CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Automated Identification of Occupant Interactions in Renovations of Occupied Buildings

By

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CIFE Working Paper #WP122
December 2009

STANFORD UNIVERSITY

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CHAPTER 3

AUTOMATED IDENTIFICATION OF OCCUPANT INTERACTIONS IN RENOVATIONS OF OCCUPIED BUILDINGS

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Abstract

In renovations of occupied buildings, identification of occupant interactions, which occur when tenants and/or crews share the same space, is a critical task to ensure the timely execution of renovation work while maintaining the operational requirements of building tenants. Failure to identify occupant interactions can lead to loss in productivity for tenants and crews, as well as cost and schedule overruns. Current methods to identify occupant interactions are manual, leading to ad-hoc and inaccurate identification of occupant interactions.

This paper presents a formal representation of renovation planning information (i.e., occupant profiles, renovation schedule, and occupant interaction types) and reasoning methods that utilize this formal representation to identify occupant interactions (IOI) automatically. The IOI method builds on existing concepts and methods in product, organization, and process modeling to generate detailed occupant location and space sharing data more efficiently than existing methods. To validate the IOI method, we implemented and tested a prototype system during the planning stages of three on-going renovation projects. The results indicate that the renovation planning ontology and reasoning methods enable planners to represent renovation planning information more thoroughly, and with increased detail, leading them to identify occupant interactions more accurately than with traditional planning methods. Based on the validation results, project planners made interventions, where one project planner updated tenant move locations, another planned to update the renovation schedule in more detail, and the third planned to investigate alternative sequencing strategies.

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1. Introduction

According to the 2002 US Census (U.S. Census Bureau 2004), the renovation of commercial buildings totaled over 68 billion dollars of work and represents an increasing percentage of construction projects today. While significant, this figure represents only a small fraction of the total economic impact of a renovation on the tenants of the building. Renovations of occupied buildings are particularly complex because tenants do not completely move out of the building during the renovation, requiring tenants (i.e., permanent occupants of the building) to share spaces with construction crews (i.e., temporary occupants of the building). Project planners must actively manage space sharing interactions between occupants (i.e., tenants and crews) to identify opportunities for space sharing and, more importantly, ensure that there are no unintended space sharing situations. Failure to manage these occupant interactions can cause loss in tenant productivity and schedule delay and cost overruns for construction crews. As a result, project planners tend to assume occupants cannot share spaces, causing inefficient space utilization.

Identifying occupant interactions is practically and scientifically challenging because it requires the integrated consideration of spatial, organizational, and temporal aspects of renovation planning information to understand where and how occupants use building spaces (i.e., rooms) over time. First, project planners must determine if there is more than one occupant in the same space. This is difficult because the renovation schedule contains many tenant move activities and construction activities, which change the building configuration (i.e., location of occupants) as tenants move and construction crews work in different spaces. Second, if there are multiple occupants in a space, project planners must understand how these occupants can (or cannot) share spaces. Distinguishing tolerable from disruptive occupant interactions, however, requires knowledge of the organizational requirements of occupants and can only be accomplished at the workshift level.

Current methods to analyze renovation schedules during the planning stages do not adequately identify occupant interactions. The dynamic nature of renovation projects, in combination with the way occupants share spaces, require the generation and analysis of an abundance of occupant location and space sharing data, which is practically impossible to do manually. Based on a combination of literature review and participation on seven renovation projects, Ho et al. (2009) identified that the traditional process lacked the necessary detail of organizational and activity information to identify occupant interactions. It was also not thorough. Planners typically analyzed only a subset of unique building configurations (i.e., locations of occupants). As a result, planners struggled to identify accurately when, where, and how occupant interactions occurred. In an in-depth analysis of three of the seven renovation projects, Ho et al. (2009) found that project planners were ready to proceed with the renovation work even though – as our detailed analyses showed – the renovation schedules contained many disruptive interactions between occupants. On average on the three projects, project planners identified only 53% of all the occupant interactions. Sometimes, they completely missed or did not distinguish the correct type of interaction.

Based on these observations, Ho et al. (2009) proposed that an automated method to identify interactions automatically could be more detailed, thorough, and accurate than traditional methods. Existing research in virtual design and construction (VDC) methods has shown the benefits of visualization, integration, and automation to enable more accurate, thorough, and detailed execution of tasks for other types of architecture, engineering, and construction (AEC) planning tasks (Eastman et al. 2009; Han et al. 2000; Haymaker et al. 2003). There are, however, limitations in these existing VDC methods which inhibit the development of a method to identify occupant interactions automatically (Ho and Fischer 2009).

This paper addresses these limitations and presents a new method that relates spatial, organizational, and temporal aspects of renovation planning information to identify occupant interactions (IOI) automatically. The method is more thorough, detailed, and accurate than traditional project planning methods. The method represents a tenant move activity as a single activity and formalizes a construction activity at the workshift level to represent crew work schedules and space sharing abilities. It represents an occupant's space sharing ability as part of an occupant profile. These formalizations enable non-geometric methods to update occupant locations and occupant space sharing abilities that are simpler and more representationally efficient than prior methods. Furthermore, the formalization of an occupant interaction ontology enables a heuristic classification process to identify interactions.

The next section describes a motivating example of a renovation planning situation and highlights the limitations of current planning methods. Section 3 provides a summary review of the limitations of existing concepts and methods and Section 4 describes the IOI method.

Finally, we discuss the prospective validation of the IOI method on three on-going renovation projects.

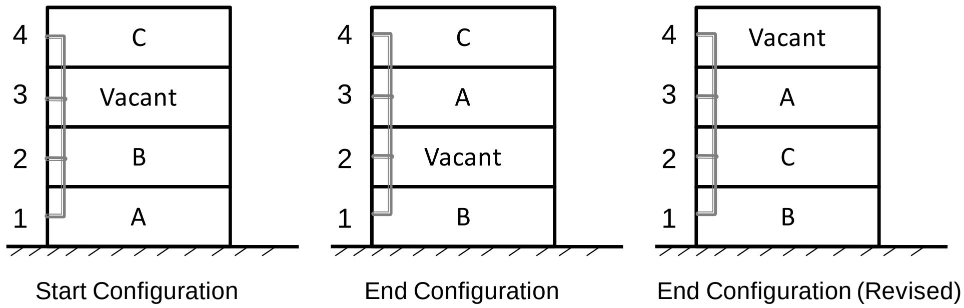
2. Motivating example

This section presents a motivating example to highlight the challenges in identifying occupant interactions. The example is a synthesis of various renovation planning situations found in the test cases and is used to illustrate the challenges associated with identifying occupant interactions.

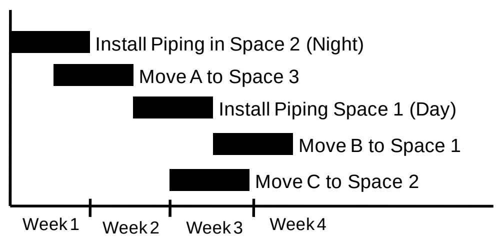
The motivating example depicts the renovation of a building which has four spaces (Space 1, 2, 3, and 4) and three tenants (Tenants A, B, and C). Figure 1-a shows the starting locations of the tenants. The scope of the renovation includes installing piping in Spaces 1 and 2 and moving tenants into different spaces. The installation of the piping requires crews to access the direct space of the pipes as well as the space above. For example, to install piping in Space 2, crews must have access to Spaces 2 and 3.

Figure 1-b shows the renovation schedule. First, piping is installed in Space 2. Since Tenant B is occupying Space 2, the renovation planner schedules the work at night. Second, the planner schedules Tenant A to move into Space 3 from Space 1. Since Space 1 will be vacant, the planner then schedules the installation of piping in Space 1 during the daytime. Once these pipes are installed, Tenant B moves into Space 1. Figure 1-a (end configuration) shows the end locations of the tenants after these activities occur.

Often, project planners are required to revise their schedules to accommodate tenant requests. To continue the motivating example, the project planner receives a last minute request from Tenant C to move into a new space. Since Space 2 is vacant (Figure 1-a, end configuration), the planner accommodates Tenant C’s request and adds an activity into the schedule to move Tenant C to Space 2. Figure 1-a (end configuration, revised) shows the resulting tenant locations after this change.



1-a.



1-b.

Figure 1a-b. Start and end building configurations showing the locations of occupants (1-a) and renovation schedule for the motivating example (1-b).

2.1. Types of occupant interactions found

Based on the renovation schedule, the project planner must determine the types of occupant interactions to inform tenants and construction crews. This example contains three types of occupant interactions. Figure 2 shows when each interaction occurs.

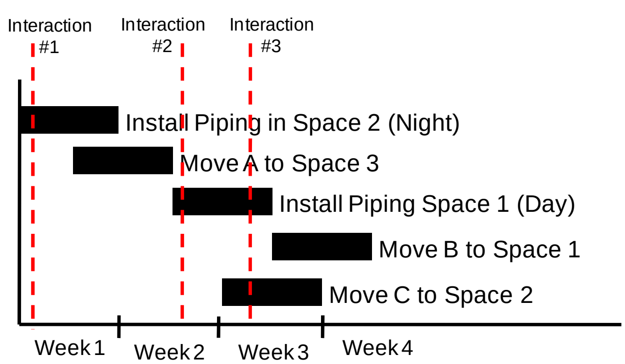


Figure 2. Occupant interactions in motivating example

2.1.1. Interaction #1 – minor tenant-crew interaction

The installation of piping in Space 2 at night creates a minor tenant-crew interaction as tenants and crews are sharing the same space, but have different space sharing abilities (Figure 3). When the condensate piping crew occupies the space at night, the crew cannot share the space with others. The tenant, however, also still occupies the space at night as well (e.g., their workspaces are ready for the tenant to work the next day) and allows the construction crews to share the space with them. During the day, the situation is reversed. The tenant is working and cannot share the space with others, while the condensate piping crew still occupies the space (e.g., their materials and equipment are stored safely off to the side in the space), but is able to share the space with the tenants. This type of occupant interaction is typical on many renovation projects.

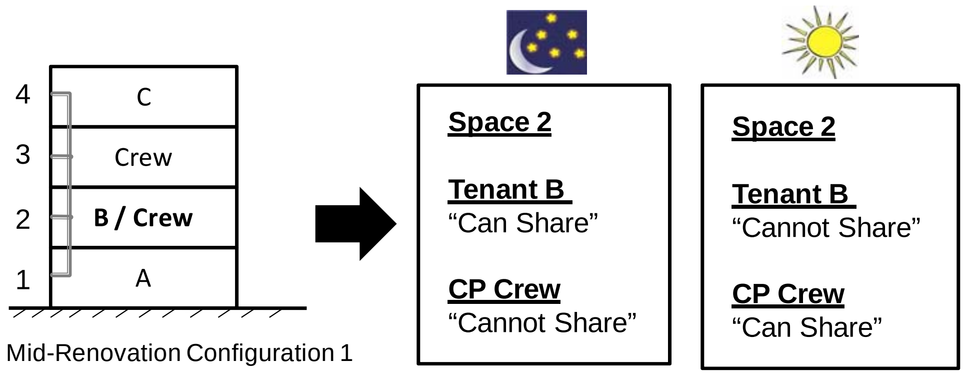


Figure 3. Locations of occupants and space sharing abilities for a minor tenant-crew interaction during day and night workshifts.

2.1.2. Interaction #2 – major tenant-crew interaction when installing piping during the day

A major tenant-crew interaction occurs because the project planner scheduled the condensate piping crew to install piping during the day in Space 1 (Figure 4). Since the crew needs access to Space 2 during the installation, this creates a major tenant-crew interaction in Space 2 because Tenant B is also working in the space during the day and both cannot share the space with each other.

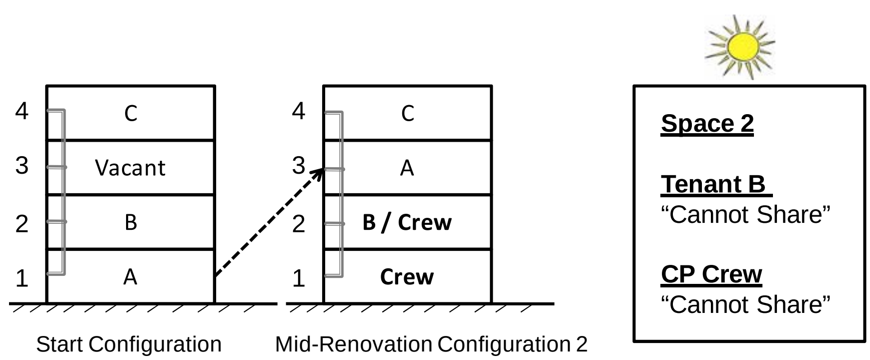


Figure 4. Locations of occupants and space sharing abilities for a major tenant-crew interaction during the dayshift

2.1.3. Interaction #3 – double booked room

A tenant-tenant interaction occurs because the project planner accommodated Tenant C's last minute request by scheduling Tenant C to move into Space 2 (Figure 5). While moving Tenant C into Space 2 is possible, the dates of Tenant C's move create a tenant-tenant interaction because Tenant B has not yet moved out of Space 2. It is often difficult for project planners to understand the possible impacts of schedule changes on other renovation activities. With today's representation of space use and renovation planning information, project planners must manually determine these impacts because the spatial information (i.e., location of occupants) is often not integrated with the temporal information (i.e., renovation schedule).

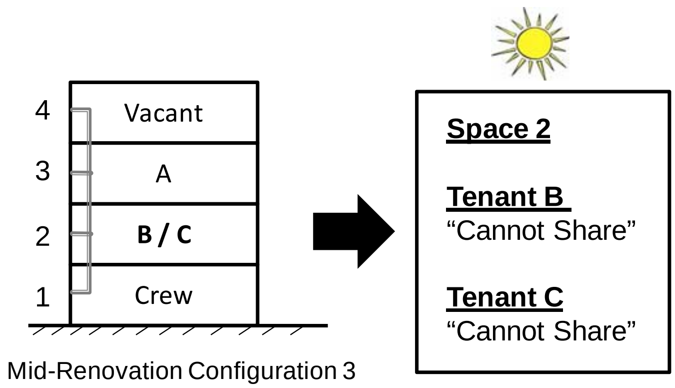


Figure 5. Locations of occupants and space sharing abilities for a tenant-tenant interaction during the dayshift

2.1.4. Identification of space sharing opportunities

The motivating example above also highlights the opportunities available when project planners understand how construction crews and tenants can share space at the workshift level. The opportunity for tenants and crews to share space during the installation of piping in Space 2 is predicated on two pieces of organizational information:

- The crew installing condensate piping has a work schedule and space sharing ability that allows the construction crew to work at night, while the tenant works during the day.
- Tenant B has a work schedule and space sharing ability that allows the tenant to work during the day, while the construction crew works at night.

In the absence of knowledge of space sharing abilities at the workshift level, however, renovation planners have to assume the most restrictive scenario: that Tenant B and the condensate piping crew cannot share spaces. This can result in inefficient space utilization and lengthen the renovation schedule. Figure 6 shows the resulting schedule under these circumstances. During Week 1, the condensate piping crew is waiting for Tenant A to move to begin their work, while Tenant B's space is available at night, but not utilized. The construction crew waits until Tenant B moves out of Space 2 to begin the work. As a result, the scheduled is about half a week longer than necessary.

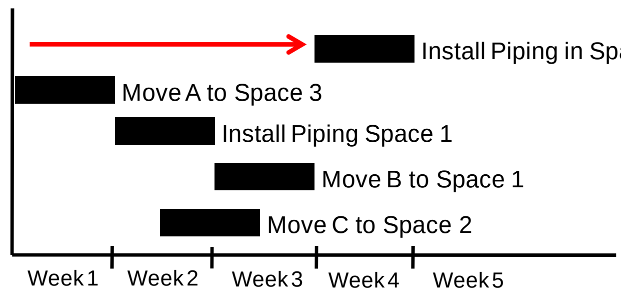


Figure 6. A lack of knowledge of space sharing at the workshift level would under-utilize space and extend the project schedule.

While it is easy to identify project-specific instances of space sharing opportunities in such simple examples, it is difficult to identify them on real projects. For example, in TC#3, there were 13 different occupants, 46 renovation activities, and 92 unique building configurations. As a result, the project planner missed a potential space sharing opportunity which could have saved three months on the duration of the installation of structural spandrels. This opportunity was missed because there was no integrated spatial-organizational-temporal model of the renovation work and its building context and detailed information on whether the structural spandrel work could occur at night or whether tenants were okay with crews working at night was missing. As a result, the planner had to assume that tenants would have to move out of the space before the renovation.

2.1.5. Requirements for an automated method to identify interactions

The motivating example demonstrates that project planners must integrate spatial (e.g., occupant locations), organizational (e.g., occupant work schedules and their space sharing abilities), and temporal (e.g., renovation activities) information to identify occupant interactions. Ho et al. (2009) formalized requirements for an automated, more thorough, and detailed method to identify occupant interactions:

> ***Representation of renovation activities*** – Tenant move activities describe when and where tenants move from their start locations to their end locations. Construction activities need to describe during which workshift the work will be performed to distinguish impacts of daytime versus nighttime activities and identify opportunities to share spaces with other occupants.
>
> ***Representation of occupants and space sharing abilities*** – Knowledge of each organization's work processes is necessary to understand where, when, and how each organization utilizes space and to identify potential space sharing opportunities. The following aspects of each occupant organization must be formalized:
>
> - Where an occupant is in the building (i.e., location) at the space level
> - When the occupant is active or idle in the building (i.e., work schedule)
> - What the occupant's space sharing abilities are over different workshifts
>
> Organizational information must be represented at the workshift level, since active workshifts can have different space sharing abilities than idle workshifts. An active workshift means that an occupant is physically working in a space, whereas an idle workshift means that an occupant is temporarily not working in a space, but plans to return during their designated workshift. These situations need to be distinguished because the space sharing ability of an occupant changes based on its active or idle status. For example, the condensate piping crew working at night does not want to share space with tenants during that workshift. During the day, however, when and where the crew is idle, it would be acceptable for Tenant B to occupy the space. The inverse situation exists for Tenant B.
>
> In an idle workshift situation, a crew needs to be represented as occupying a space, even through the crew is not physically present in the space during that workshift. This enables the distinction between an idle workshift and the situation where a crew is not working in a space at all. In the former situation, project planners would need

to notify the tenant that a construction crew will be in their space. In the latter case, project planners would not need to notify the tenant at all.

Representation of occupant interactions **–** A formalization of different types of occupant interactions is needed to enable a software tool to distinguish between tolerable and disruptive interactions because the management approaches to resolve interactions can differ. For example, a crew-crew interaction may be resolved by notifying the general contractor of the interaction, whereas a tenant-tenant interaction may be resolved by contacting each tenant organization.

Reasoning about occupant interactions during renovation activities – A thorough analysis of the interactions would require project planners to analyze each building configuration whenever a change in occupant locations or space sharing ability occurs, Project planners need a method to update the locations of occupants and their space sharing abilities described by a formalization of renovation activities and occupant organizations. Based on this updated information, project planners then need a method to identify occupant interactions based on a formalization of occupant interactions. The method must be able to examine all project-specific instances of occupants sharing spaces. It must also be representationally efficient to enable project planners to manage the data at the space and workshift level.

In summary, the research challenge addressed in this paper is to develop a renovation planning ontology and an automated method that is thorough enough to analyze many unique building configurations and detailed enough to enable identification of interactions at the space and workshift level.

3. Points of departure

While existing ontologies and methods serve as fundamental points of departure in meeting the representation and reasoning requirements outlined above, they do not allow the process to be automated. Ho et al. (2009) reviewed prior work in product modeling, occupant modeling, 4D-based activity modeling, and space sharing identification methods. These findings indicate that prior representations of product models (International Alliance for Interoperability 2000; Yang 2003) are able to represent occupant locations at the space level, but prior organization and activity representations are not sufficient to identify interactions automatically. These representational limitations consequently limit the reasoning methods that can be developed to identify interactions. Therefore, automated identification of occupant interactions requires, first, and extension of existing representation schemata and, second, the formalization of reasoning methods leveraging the new representation schema to detect occupant interactions automatically This section summarizes existing approaches and their limitations in the areas of occupant modeling, 4D-based activity models, and space sharing identification methods.

In the area of occupant modeling, prior representations of organizations describe work schedules and provide a link to locations in a building (Hoes et al. 2009; Jin and Levitt 1996), but do not represent the space sharing abilities of occupants. An occupant's space sharing ability has previously been represented as an attribute of the space, but not of the occupant (Akinci et al. 2002b). This existing formalization requires that a new space must be modeled each time an occupant's space sharing ability changes, which is inefficient for project planners to manage.

In the area of 4D-based activity modeling, Darwiche et al.'s (1989) ontology represents activities that have a resource <R> that acts <A> on a specific object <O>. While this representation integrates a single activity, occupant, and space, the <OAR> tuple does not detail construction activities and changing crew space sharing requirements to the workshift level efficiently. In combination with the limitation of the representation of space sharing ability as an attribute of a space, this requires additional spaces and dummy activities to be modeled. For example, a 10-day condensate piping activity would require twenty different activities and two different spaces to represent the changing space sharing abilities of the condensate piping crew (Figure 7).

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

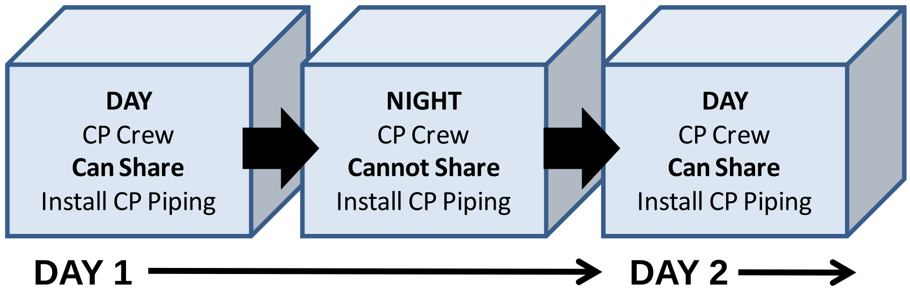


Figure 7. For a condensate piping (CP) activity, additional activities and spaces need to be added to distinguish the space sharing abilities in active and idle workshifts.

Furthermore, Darwiche et al.'s representation associates only a single object <O> to a single activity <A>. As a result, the representation cannot link two spaces (i.e., start locations and end locations) to a single activity or occupant. A tenant move activity must be represented as two separate activities, which would create additional dummy activities for project planners to manage. This becomes problematic to manage (e.g., if the dates of one activity are changed, there is no link to update the other activity). This representation also complicates the development of a method to update building configurations unnecessarily because the tenant move is represented as two separate activities with no explicit relationship to each other.

In the area of space sharing identification methods, existing methods utilize geometric methods, which have significant limitations when applied to the identification of occupant interactions. To utilize geometric methods, separate spaces would need to be created for each occupant to determine if spaces are overlapping, similar to 3D clash detection methods (Khanzode et al. 2008; Leite et al. 2009). Furthermore, as mentioned above, these spaces would need to be created for each workshift to represent the changing space sharing abilities of each occupant. In the context of the challenge to manage an abundance of occupant location and space sharing data, the use of geometric methods is representationally inefficient and creates an unmanageable process.

Ho et al. (2009) found that there are no existing formalizations of interactions that include tenants. They also identified that there are only four ways in which occupants interact on renovations of office buildings. Therefore, a generic representation of these four occupant interaction types can be used to distinguish interactions based on the type of occupant (i.e., tenant or crew) and how they share spaces (i.e., can share, cannot share). Heuristic classification (Clancy 1985) can then be applied to identify tenant and crew interactions. The benefits of heuristic classification are discussed in the following section.

4. Method to automatically identify occupant interactions

This section presents the renovation planning ontology and method to identify occupant interactions (IOI) automatically. The IOI method differs from existing approaches because it considers renovation projects as buildings with pre-defined spaces, in which occupants change locations in the building resulting from tenant moves or construction activities. It does not require new spaces to be generated as occupant locations change. This approach requires several new formalizations of renovation planning information and new methods which utilize these formalizations.

An IDEF diagram of the IOI method is shown in Figure 8. The method is a discrete event simulation where a project planner first defines a simulation start date, starting workshift, and snapshot interval for the analysis. The snapshot interval determines when the analysis of occupant interactions will occur and how many different building configurations are analyzed. For each snapshot date, the analysis occurs at the workshift level of detail. This enables the distinction between impacts on daytime, nighttime, and weekend workshifts. Once the simulation parameters are entered, the method consists of two automated steps. The first step updates occupant location and space sharing abilities. The second step checks for occupant interactions.

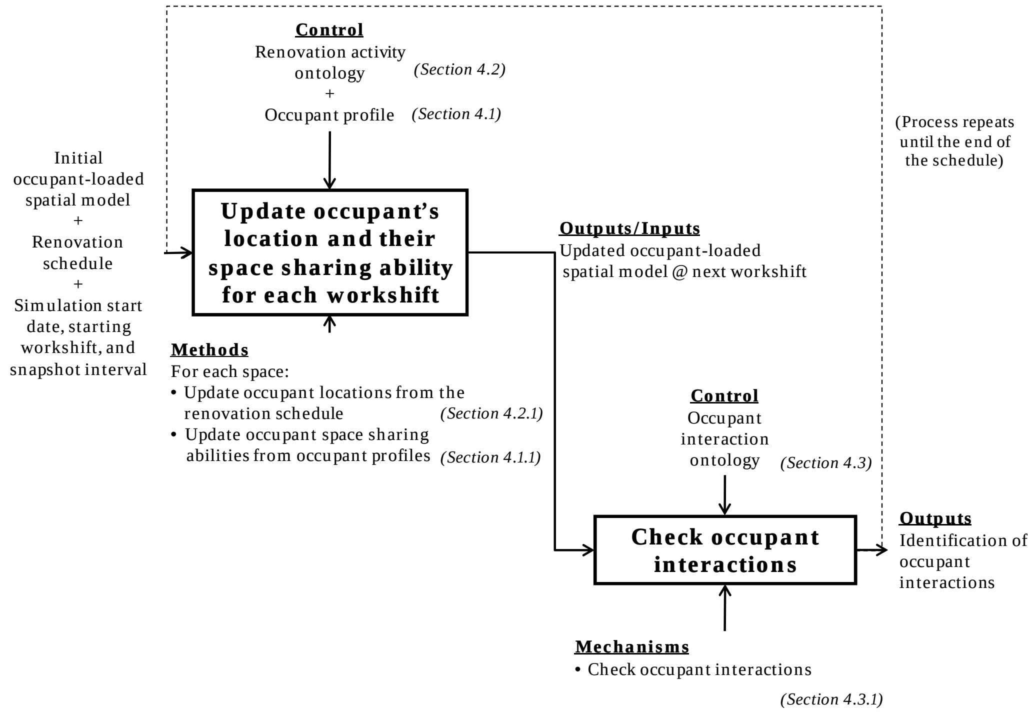


Figure 8. IDEF diagram of method to identify occupant interactions automatically

The first step requires new formalizations of tenant move and construction activities (i.e., a renovation activity ontology), to enable a non-geometric method to update occupant locations. Instead of creating a new space each time an occupant moves, the IOI method only needs to track in which existing space an occupant is located. The first step also requires a new formalization of occupant requirements (i.e., occupant profile). The occupant profile represents the ability to share space as an attribute of the occupant, not the space. This de-coupling of the organizational attribute from the space allows another non-geometric method to update an occupant's space sharing ability at the workshift level without modeling additional spaces and activities as occupant's space sharing abilities change.

Figure 9 depicts the integrated representation of renovation planning information required in the first step of the IOI method. The ontology relates product (i.e., spaces), organization (i.e., occupant profiles), and process (i.e., renovation activity ontology) models to eliminate multiple sources of information for the analysis.

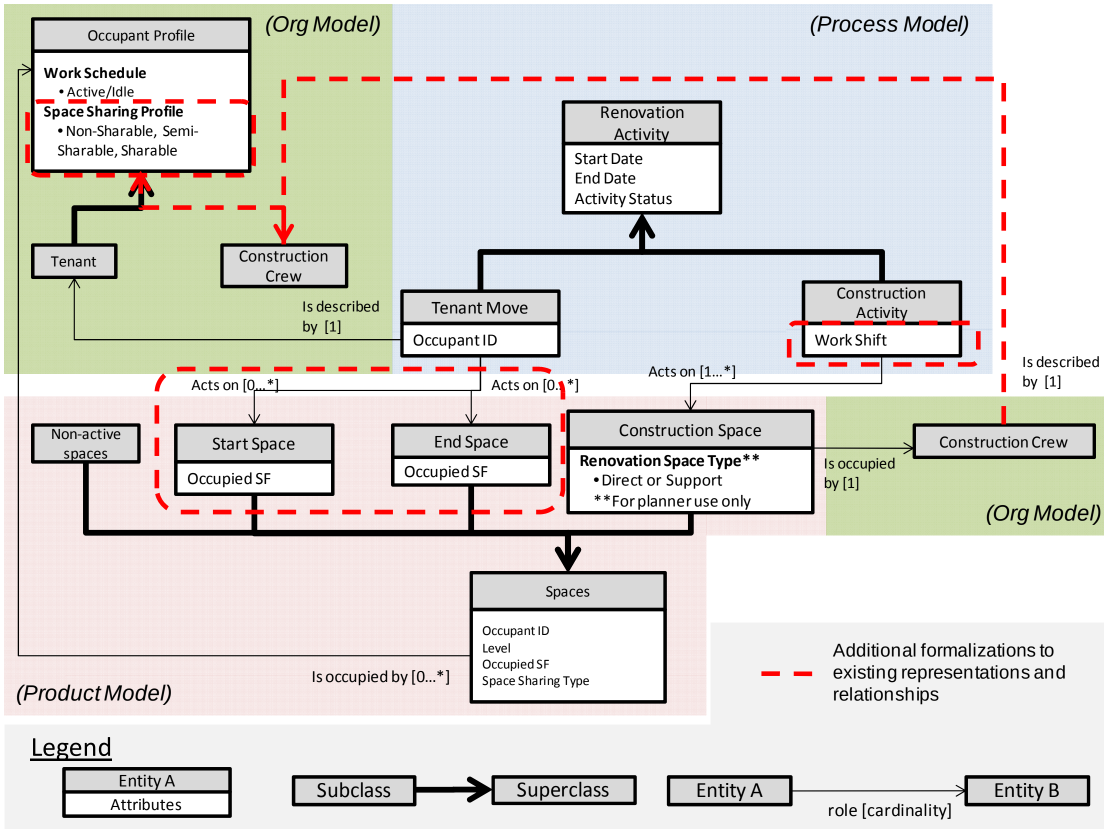
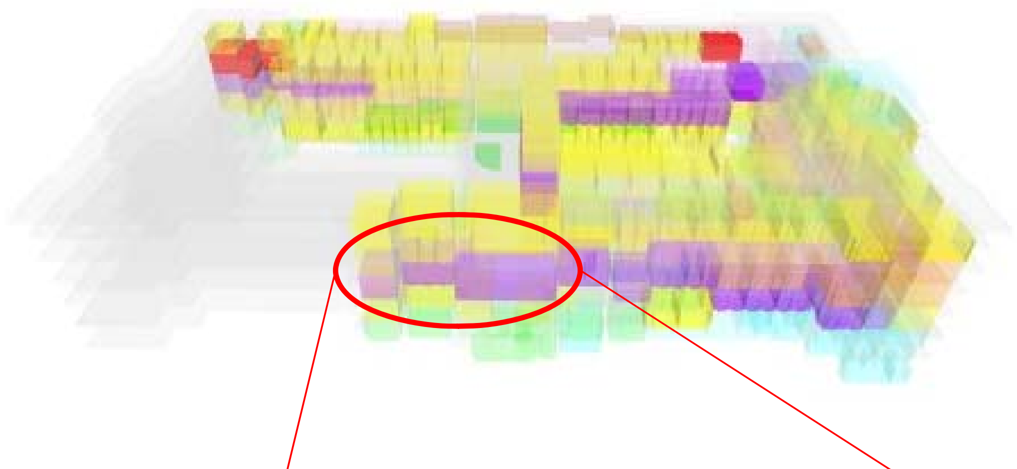


Figure 9. The occupant profile and renovation activity ontology formalize renovation planning information and integrate product, organization, and process models.

The product model section of the renovation planning ontology formalizes an occupant-loaded spatial (OLS) model. An example of an OLS model is shown in Figure 10. The OLS model describes the locations of all occupants detailed to the space level. While each space is associated with 3D geometry, the geometric dimensions and coordinate locations of the space are not necessary for the analysis. The only geometric property utilized in the analysis is the square footage of each space. Each record about a space contains its occupant(s) and their occupied square footage(s). Each occupant has its own space sharing ability that is documented in the OLS model. Each space can range from having no occupants (i.e., vacant) to having multiple occupants (e.g., two tenants sharing a space). Multiple occupants indicate a potential occupant interaction that is identified in the second step of the IOI method. The OLS model is a snapshot of the building configuration at a particular time. Reasoning methods in the first step (i.e., update occupant locations and update occupant space sharing abilities) utilize the occupant profile and renovation activity ontology formalizations to determine the renovation status (RS) of each activity, which then determines how the OLS model (i.e., occupant location, square footage, and space sharing abilities) is updated. As a result, only the initial OLS model needs to be created because the OLS model is updated automatically for future building configurations based on the renovation activity ontology, occupant profile, and associated reasoning methods in step 1.



SpaceID	OccupantID	OccupiedSF	Space Sharing Ability
470	Group 1F	503	Cannot Share
472	Group 1G	355	Cannot Share
474	Group 1G	274	Cannot Share

Figure 10. An example of an occupant-loaded spatial model used for analysis of potential occupant interactions. Each space in the model contains information on the square footage, the occupants in the space and each occupant's ability to share that space.

In the second step, the IOI method analyzes the updated OLS model using the occupant interaction ontology and a heuristic classification process. Although there are many different project-specific ways occupants can possibly use each space (e.g., different tenants, crews, and space sharing abilities), heuristic classification abstracts project-specific occupant information into project-independent information regarding the type of occupant (i.e., tenant or crew) and the occupant's space sharing ability (i.e., sharable or non-sharable). This information is used to identify the space-specific occupant interactions. The reasoning method in this step enables the IOI method to identify occupant interactions more thoroughly than traditional methods. The process is also more representationally efficient because no geometric spaces need to be modeled to identify interactions. The following sections describe the formalizations and reasoning methods in detail.

4.1. Occupant profile and reasoning methods

A disruptive occupant interaction occurs when a tenant's work schedule conflicts with a construction activity. To recognize such a conflict, one must know about the work schedules and space sharing abilities of the two organizations. We formalize an occupant's organizational requirements, as related to identifying occupant interactions, by defining an occupant work schedule and space sharing profile for each tenant and construction crew.

In renovations, tenants and crews share the same spatial and temporal attributes regarding where, when, and how they can share spaces with others. This commonality enables tenants and crews to be formalized using a single representation – an occupant profile. Project planners define tenant profiles based on tenants' preferences and business operations and define construction crew profiles based on the construction activity.

Work Schedule: An occupant's work schedule is defined by assigning an "Active" or "Idle" value for day, night, and weekend shifts. We chose to decompose the work week to day, night, and weekend shifts because typical construction workshifts are detailed to this level. Tenant work schedules are also defined to the workshift level. Defining exact start and end times for tenants for each workshift is not necessary to identify disruptive occupant interactions.

Space Sharing Profile: The space sharing profile of an occupant is classified as either "Non-sharable", "Sharable", or "Semi-Sharable." A non-sharable profile indicates that the tenant is unwilling to share the space whether or not the occupant is active or idle. A semi-sharable profile indicates that the occupant is unwilling to share the space when the occupant is active, but willing to share the space when the occupant is idle. A shareable profile indicates that an occupant is willing to allow other occupants to use its space during active and idle times. Ho et al. (2009) found the semi-sharable profile to be the most common space sharing profile for tenants, where a tenant is only active during the day and permits crews to work only at night. This type of tenant was found on all seven renovation projects examined.

4.1.1. Determining space sharing abilities from space sharing profiles

Based on the space sharing profile and occupant work schedule, reasoning methods can determine the space sharing ability for each occupied space for each occupant (Table 2).

Table 1. Space sharing profile and work schedule matrix determine the space sharing ability for each occupant for all workshifts.

Space Sharing Profile	Work Schedule	
	Active	***Idle***
Non-Sharable	Cannot Share	Cannot Share
Semi-Sharable	Cannot Share	Can Share
Sharable	Can Share	Can Share

The combination of the space sharing profile and work schedule allows the IOI method to determine the occupant space requirement (i.e., space sharing ability) for any given workshift without additional modeling of spaces or activities (Figure 11).

Occupant Profile Example

Work Schedule	
Daytime Shift Status	Active
Nighttime Shift Status	Idle
Weekend Shift Status	Idle
Space Sharing Profile	
Semi-Sharable	

↓

Daytime Shift Space Sharing Ability	Cannot Share
Nighttime Shift Space Sharing Ability	Can Share
Weekend Shift Space Sharing Ability	Can Share

→

Space 1 on 2/10/2010 Daytime Shift		
Space ID	**Occupant ID**	**Space Sharing Ability**
101	Tenant A	Can Share

Figure 11. An occupant's profile is transformed to space-specific sharing abilities.

4.2. Activity representation and reasoning methods

A renovation schedule contains tenant move activities and construction activities. The spatial, organizational, and temporal aspects of a tenant move activity can be formalized by describing:

- ***Who*** is moving (i.e., Occupant ID)
- ***From where*** (i.e., Start Space ID) and how much square footage the tenant will vacate from the start location
- ***To where*** (i.e., End Space ID) and how much square footage the tenant will occupy after the move

This representation extends prior activity representations to relate the start and end locations of tenant moves in a single activity representation. It also provides flexibility for different start and end move situations (e.g., one-to-one, many-to-many) and different square footages between start spaces and end spaces to represent situations where a tenant is expanding or consolidating. The formalization allows the IOI method to update building configurations by tracking tenant locations and the amount of square footage they occupy in each space. As a result, the IOI method is more thorough than manual methods in the number of building configurations it analyzes. Figure 12 shows an example of a tenant move activity and method to track tenant locations.

Tenant Move Activity:

Activity ID	Activity Description	Start Date	End Date
30	Move Tenant A to Space 3	2/10/2010	2/12/2010

Activity ID	Occupant ID	Move Space Type	Space ID	Occupied SF
30	Tenant A	Start	1	367
30	Tenant A	End	3	503

Update changes to spatial model:

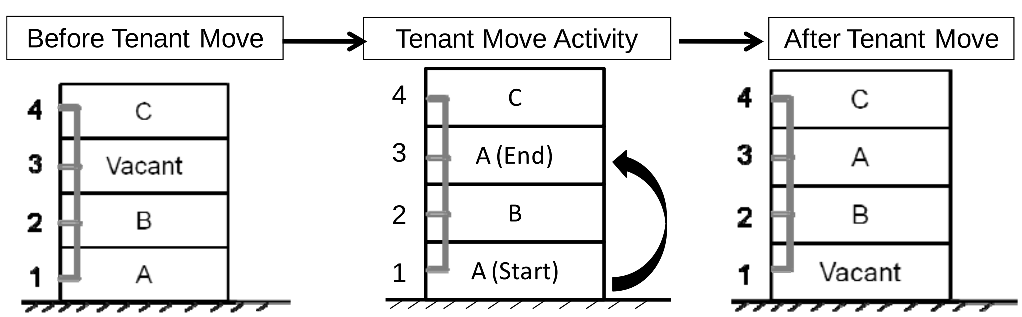


Figure 12. Example of a tenant move activity representation and resulting updates to an occupant-loaded spatial model

We build on Darwiche et al.'s <OAR> ontology to define a construction activity and add the workshift when the work will be performed and the construction crew space sharing profile as part of the activity representation. A construction activity is formalized by describing:

- ***Which crew*** is working (i.e., Crew ID)
- ***Where*** the crew is working (i.e., Space ID) and type of space (direct or support)
- ***Space Sharing Profile*** of the crew (which formalizes the active workshift and crew's space sharing ability)

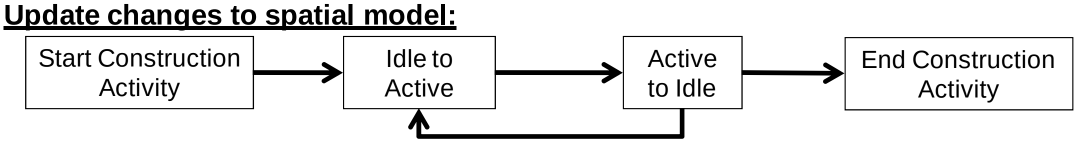
While the type of construction space (i.e., direct or support) is not directly used in the IOI method, it allows project planners to distinguish these types of spaces. Including the space sharing profile of the crew allows the IOI method to update the crew's space sharing ability for each workshift without modeling additional spaces or activities. Using this representation of a construction activity and method to update the crew's space sharing ability, only one activity and one space need to be modeled (Figure 13) vs. many activities and spaces with the current methods (Figure 7).

Construction activity representation:

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

Activity ID	Space ID	Space Type	Crew ID	Space Sharing Profile
117	2	Direct	CP Crew	Semi-Sharable
117	3	Support	CP Crew	Semi-Sharable

Update changes to spatial model:



Night Shift		
SpaceID	**OccupantID**	**Space Sharing Ability**
2	CP Crew	Cannot Share
2	Tenant A	Can Share
3	CP Crew	Cannot Share
3	Tenant A	Can Share

Day Shift		
SpaceID	**OccupantID**	**Space Sharing Ability**
2	CP Crew	Can Share
2	Tenant A	Cannot Share
3	CP Crew	Can Share
3	Tenant A	Cannot Share

Figure 13. Example of a construction activity representation and resulting updates to an occupant-loaded spatial model

4.2.1. Reasoning method to update an occupant-loaded spatial model from renovation activities

To update the occupant-loaded spatial model for the renovation activities, the IOI method contains a non-geometric reasoning method which defines how to update the spatial, organizational, and temporal changes that result from the renovation activities. The method automatically elaborates renovation activities to the workshift level and determines the status of each activity based on the snapshot date, snapshot shift, and current renovation activity status (RS). There are nine (9) possible renovation activity statuses. Figure 14 depicts a flowchart of the method to determine the renovation status of each activity. All activities have a "Not Started" status (RS-1) at the beginning of the analysis and have a "Completed" status (RS-2) at the end of the analysis. Throughout the analysis, a tenant move activity progresses through the following activity statuses: Start Tenant Move Activity (RS-3), Active Tenant Move Activity" (RS-4), and Complete Tenant Move Activity (RS-5). A construction activity progresses through the following activity statuses: Start Construction Activity (RS-6), Active Construction Activity (RS-7), Idle Construction Activity (RS-8), and Complete Construction Activity (RS-9).

The method enables a thorough and detailed analysis of all unique building configurations because it records every building configuration for the entire renovation schedule for each analysis snapshot. By distinguishing renovation activity statuses as "active" or "idle," the method utilizes the occupant profile representation to update occupant space sharing abilities at the workshift level. The following sections describe the renovation activity statuses in detail.

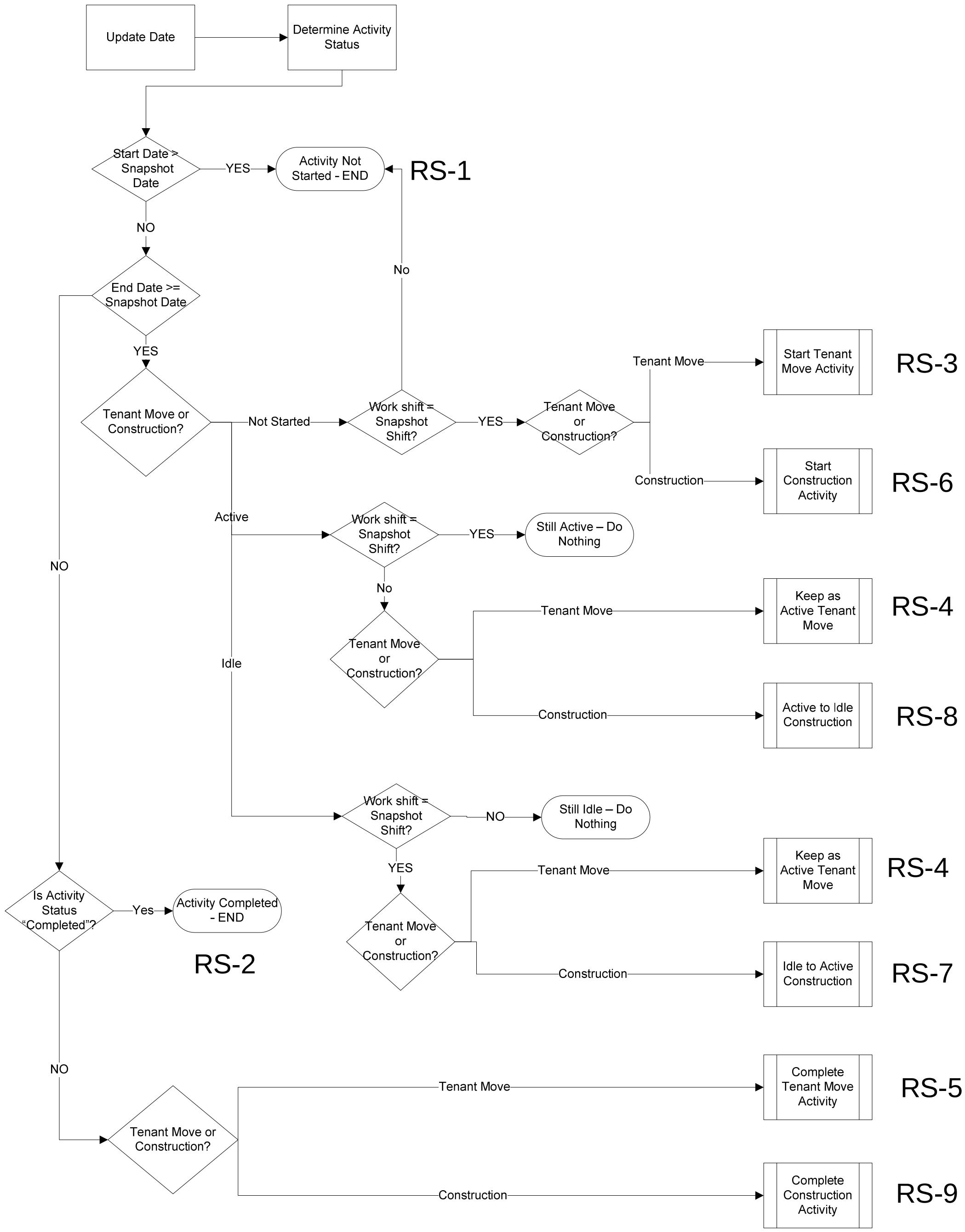


Figure 14. Flowchart describing reasoning method to determine activity status

RS-1 represents an activity that is not scheduled to start yet and RS-2 represents an activity that has already been completed. If the activity is in one of these two statuses no additional reasoning methods about occupant locations or space sharing abilities need to be executed.

(RS-1) Not Started – At the beginning of the simulation, all activities' status is "Not Started." If the start date for an activity is later than the snapshot date, the activity status is still "Not Started." Nothing in the occupant-loaded spatial model is updated.

(RS-2) Completed – If the end date of the activity is earlier than the snapshot date, the activity is already completed and has the activity status "Completed." In this situation, nothing in the occupant-loaded spatial model is updated.

4.2.1.1. Activity situations related to updating the occupant-loaded spatial model from a tenant move activity

This set of renovation situations defines a process that describes a tenant move. Figure 15 depicts the reasoning method used to update the occupant-loaded spatial model.

(RS-3) Start Tenant Move Activity – Once the reasoning method determines that a tenant move activity has started, all of the end spaces are updated to show that the tenant has occupied the space with the specified square footage. The space-sharing ability of the start and end spaces are set to "Cannot Share" for all workshifts to indicate that no other activities should be occurring in the spaces during the move.

(RS-4) Active Tenant Move Activity **–** During the tenant move, the status of the tenant move activity remains active. Since the representation of the tenant move activity links an activity to two spaces, the IOI method can depict the tenant occupying the start and end spaces throughout the activity duration. No changes occur in the occupant-loaded spatial model.

(RS-5) Complete Tenant Move Activity – Once the tenant move activity is completed, the IOI method checks each start space location to determine if there is remaining occupied square footage that the tenant continues to occupy in the start location. If so, the occupied square footage in the start space is updated by subtracting the amount of occupied square footage that was moved to the end location. Otherwise, if the tenant does not have any occupied square footage remaining in the space, the instance of the tenant in the start space is deleted from the OLS model.

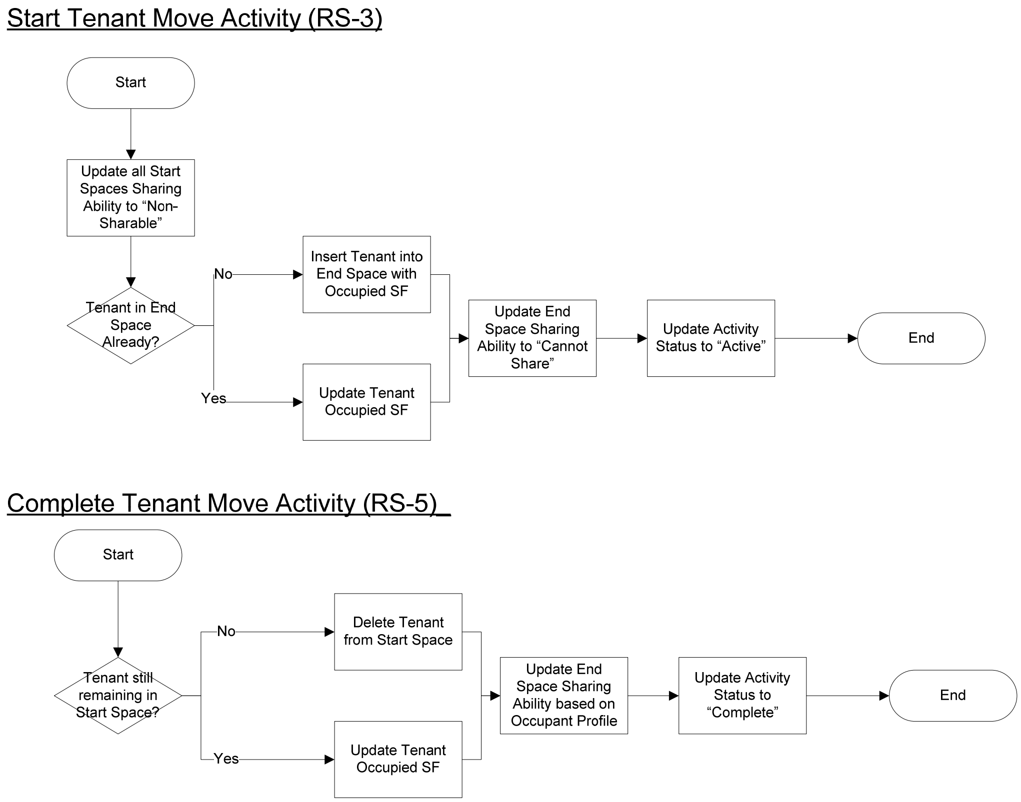


Figure 15. Flowcharts describing update scenarios from a tenant move activity

4.2.1.2. Activity situations related to updating the occupant-loaded spatial model from a construction activity

This set of renovation situations describes a construction activity. The method assumes that a construction crew occupies the entire space (equal to the square footage of the space) for every activity. Since planners only specify the type of crew needed for an activity, the crew representation formalizes a generic crew type (e.g., build out crew) and does not specify the particular crew e.g., (build out crew number 1, 2, etc,). Therefore, multiple crews of the same type in the same space are represented by multiplying the amount of occupied square footage. For example, two build out crews working in the same space would result in double the occupied square footage. This limitation is addressed at the end of this paper. Figure 16 depicts the reasoning method used to update the occupant-loaded spatial model.

***(RS-6) Start Construction Activity* –** When a construction activity is started, the occupant-loaded spatial model is updated to show construction crews in the specified construction spaces. If there is no crew of the same type in the space the method inserts a new instance of the crew, with an occupied square footage of the crew equal to the total square footage of the space. There may be situations where other construction crews of the same type, working on other construction activities, occupy the same space. Since the crew representation is at the crew type level of detail, the IOI method updates the occupied square footage of the crew by adding additional square footage (equal to the square footage of the space). The OLS model then indicates a greater amount of occupied square footage than the total square footage of the space for that type of crew. This allows project planners to not only understand which crews are in which spaces, but also the number of the crews of the same type in each space. Based on the construction crew space sharing profile, the space sharing ability is updated in the occupant-loaded spatial model.

***(RS-7) Active to Idle Construction Activity* –** A switch in construction activity status from active to idle indicates that a crew has left, but plans to return for the next scheduled workshift. The space sharing ability is updated for each crew in each space.

***(RS-8) Idle to Active Construction Activity* –** An idle to active construction activity indicates that a crew has come back to the space to continue work. Only the space sharing ability is updated.

***(RS-9) Complete Construction Activity* –** Once a construction activity is completed, the reasoning method determines if there are other crews of the same type remaining in the space (that are still working on other activities). If so, the method deletes only one crew from the space by subtracting the occupied square footage of one crew. Otherwise, if no remaining crews of the same type are scheduled in the space the crew is deleted from the OLS model.

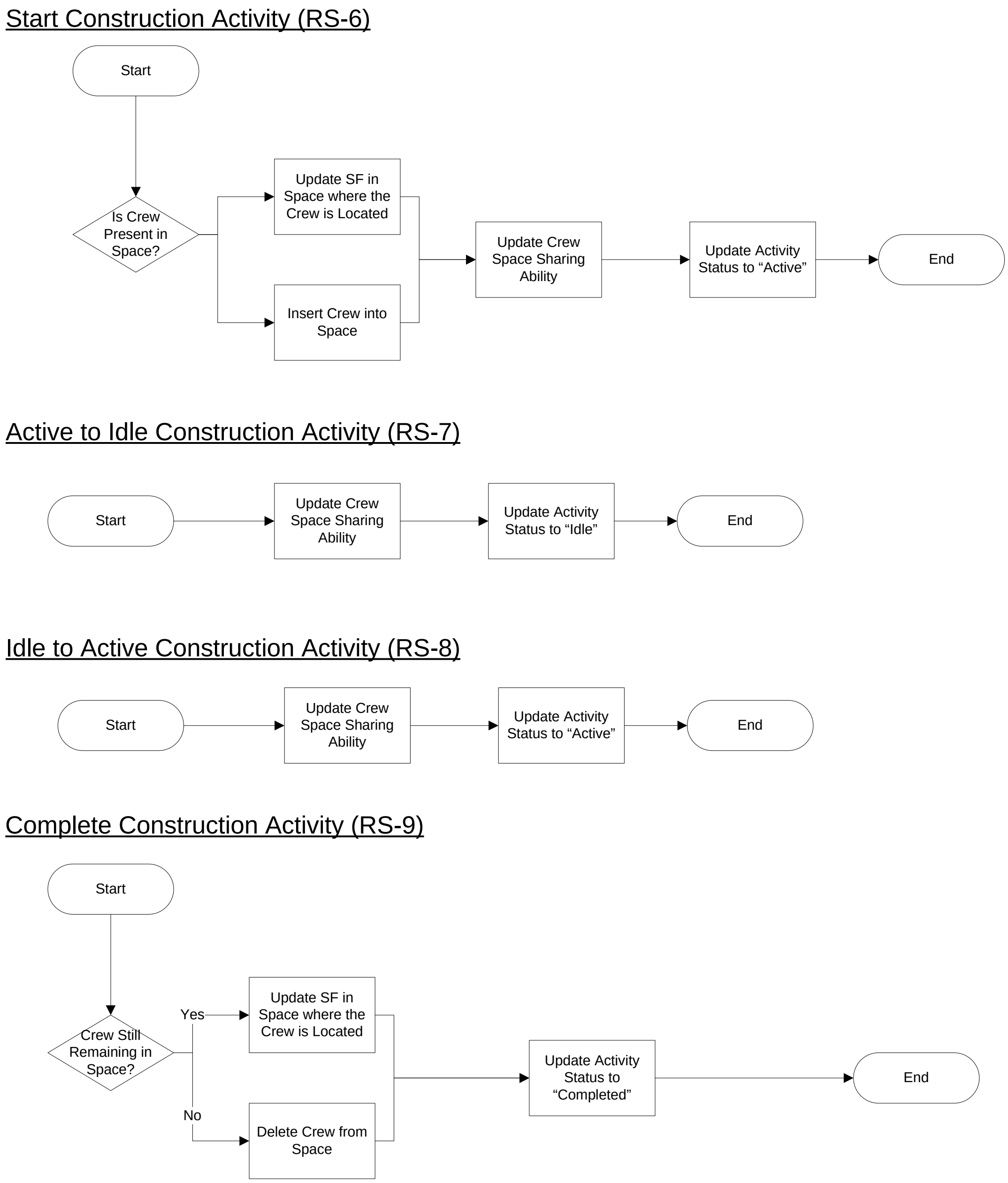


Figure 16. Flowcharts describing all update scenarios from a construction activity

4.3. Identification of occupant interactions

The second step of the IOI method is to identify occupant interactions in the updated OLS model. Once the OLS model is updated, the IOI method checks each space for each workshift to identify occupant interactions. The IOI method utilizes a heuristic classification process (Clancy 1985) in combination with the occupant interaction ontology to determine the type of occupant interaction in each space for any point in time. This enables project-specific occupant space sharing instances to be abstracted and classified into different types of occupant interactions. This heuristic classification process allows the IOI method to identify occupant interactions thoroughly and in detail at the space and workshift level of detail.

4.3.1. Occupant interaction ontology

The occupant interaction ontology formalizes the four ways in which occupants interact in a space, as observed in practice (Ho and Fischer 2009). The ontology is based on the types of occupants involved in the interaction (i.e., tenant and/or crews) and the types of occupant space sharing abilities (i.e., can share or cannot share). Each interaction type requires project planners to respond differently to manage the interaction effectively. These responses range from communicating with tenants and crews about planned interactions to adjusting the scope or schedule to avoid interactions.

- ***Crew-Crew Interaction*** – These interactions occur when more than one crew is occupying the same space. Often, project planners intentionally schedule multiple crews in one space to minimize the number of disruptions to tenants. Management of crew-crew interactions is typically the responsibility of the general contractor. The analysis only identifies crew-crew interactions, which could then be further classified with the method developed by Akinci et al. (2002b). However, the integration of their method into this analysis was out of the scope of the research.
- ***Tenant-Tenant Interaction*** – These interactions are considered double-booked spaces as described in the motivating example. Management of tenant-tenant interactions involves moving tenants to a different location or changing tenant move dates to eliminate the interaction.
- ***Minor Tenant-Crew Interaction*** – These interactions occur when tenants and crews occupy the same space, but there is at most one "cannot share" space sharing ability at any time. In practice, these interactions occur when tenants occupy spaces during the day while crews occupy the space at night. 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 tenant-occupied spaces to ensure that the spaces are left in an acceptable condition after their workshift.

- ***Major Tenant-Crew Interaction*** – This interaction indicates that there are at least one tenant and one crew each that have a “cannot share” space sharing ability. These interactions must be avoided. Management of major tenant-crew interactions involves re-sequencing activities, deleting scope, or changing construction methods to avoid this interaction.

4.3.2.Method to automatically identify occupant interactions

The IOI method utilizes heuristic classification to identify an occupant interaction. For each workshift and each space in the occupant-loaded spatial model, the IOI method abstracts project-specific occupant information on the type of occupant (i.e., tenant or crew) and the space sharing ability (i.e., can share or cannot share) of each occupant. An occupant interaction type can be determined from the abstracted data. Table 3 shows the relationship between the abstracted data and project-independent occupant interaction type.

Table 2. Identification of occupant interaction types from abstracted data in the occupant-loaded spatial model

Abstracted Data				Occupant interaction type
# of crews that "cannot share"	**# of crews that "can share"**	**# of tenants that "cannot share"**	**# of tenants that "can share"**	
>0	N/A	N/A	N/A	Crew-crew interaction
>0	N/A	>0	N/A	Major tenant-crew interaction
>0	N/A	0	>0	Minor tenant-crew interaction
0	>0	>0	NA	Minor tenant-crew interaction
N/A	N/A	>0	N/A	Tenant-tenant interaction

Once the IOI method determines the type of occupant interaction, the method utilizes the project-specific data (i.e., space ID and snapshot date) to identify the specific interaction. Figure 17 provides an example of this classification process on a single space from the motivating example.

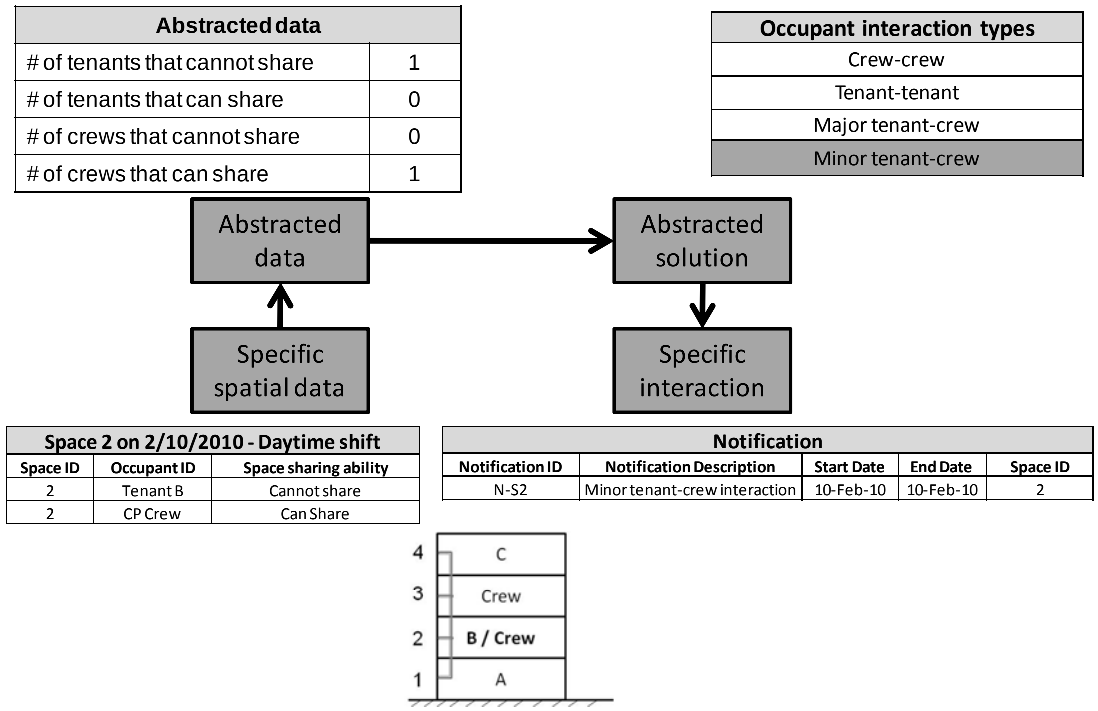


Figure 17. Heuristic classification process for identifying occupant interactions. The occupant-loaded spatial model indicates that a tenant and crew are assigned to the same space in the same workshift. The IOI method abstracts the data to determine that a minor tenant-crew interaction occurs in space 2 because the crew can share the space with the tenant. The method then determines the specific date and space of the interaction.

This identification process is repeated for each space in the occupant-loaded spatial model, for every building configuration at each snapshot date. Since the IOI method examines each building configuration, a specific interaction may be repeatedly identified if the interaction occurs over several snapshot dates. Therefore, the project planner must post-process the interactions manually to determine the underlying renovation activity which causes the interaction. This limitation is discussed later in this paper.

5. Validation

Ho et al. (2009) observed that the requirement for a thorough and detailed analysis of occupant locations and their space sharing abilities makes it infeasible for project planners to identify interactions manually at the scale of real projects. The number of activities, tenants and crews make the use of traditional methods ad-hoc and inaccurate. 4D models were used only for visualization and were also ad-hoc and inaccurate. With these challenges in mind, the researchers used prospective validation to observe how the method could be used within the context and scale of real renovation projects (i.e., in an uncontrolled environment, with large sets of data) to understand the power and generality of a more detailed and thorough analysis. Ho et al. (2009) further describe the reasons for using prospective validation and its implementation on each of the test cases. We implemented the IOI method in a computer prototype, 4DRenCheck, and tested it on three on-going renovation projects. The power of the IOI method is determined by whether or not the method supports identification of occupant interactions that is more accurate, more thorough, and more detailed than achieved by the project planners.

The project planners on the selected renovation projects each have 15+ years of experience on public and private design and construction projects . The planners from private industry come from internationally recognized construction management firms. Most importantly, at the time of the prospective validation, the project planners had worked on the selected renovation projects for over two years and were intimately familiar with the project context and information. For example, on test case (TC) #1, the planner's main duty was to manage the tenant moves in the building. Therefore, the comparison with these project experts provides a solid benchmark of the power of the IOI method.

The three test cases provide evidence of the generality of the method. Table 4 describes the characteristics of the validation test cases, which cover a variety of scopes, sequencing plans, mix of renovation activities, mix of tenants and crews, and analysis needs. The renovation schedule in TC#1 sequenced construction activities separately from tenant move activities, allowing a focus on the tenant move activities. The schedule in TC#2 did not emphasize moving tenants into swing space, but instead planned much of the work during night shifts. There were only a few tenant moves, allowing a focus on analyzing the construction activities. The schedule in TC#3 alternates between the renovation activities by cycling between a tenant move activity and a construction activity (e.g., when a tenant moves out, a construction crew renovates the space, and a new tenant moves in).

Table 3. Overview of validation test cases and comparison of the traditional, 4D model-based, and 4DRenCheck methods

	Test Case	**1**	**2**	**3**
Project characteristics	**Project size (in thousand sf)**	335	1,300	419
	Scope of renovation	Historic preservation, building systems upgrades	Building systems upgrade, tenant build out	Seismic upgrades, asbestos abatement, tenant build out
	Number of tenants	114	8	10
	Number of crews	0	6	3
Characteristics of schedule	**Characteristics of renovation schedule**			
	Number of tenant move activities	97	16	23
	Number of construction activities	0	292	23
	Number of different building configurations	3	628	92
	Sequencing plan	Separated tenant move and construction activities	Integrated tenant moves to swing space during construction	Integrated tenant moves to swing space during construction
	Analysis needs	Track tenants over time, identify double booked rooms	Identify number of times crews are in tenant spaces	Track amount of vacant square footage; track tenants and crews
Characteristics of scheduling methods (Traditional, 4D Model, 4DRenCheck)	**Traditional method**			
	Detail of organization information			
	Location	Yes	No	No
	Work schedule	No	Tenants - No, Crews - Yes	No
	Space sharing	No	No	No
	Number of building configurations analyzed	2	0	54
	Frequency of analysis (i.e., snapshot interval)	Start/End	N/A	Monthly
	Number of interactions found	0	77	0
	4D Model			
	Purpose of 4D model **	1	2	1,2,3
	Detail of 4D model			
	Number of spaces	1098	59	102
	Number of activities	97	308	46
	Number of dummy activities	97	16	23
	Detail of organizational information			
	Location	Yes	Yes	Yes
	Work schedule	No	No	No
	Space sharing	No	No	No
	Frequency of analysis (i.e., snapshot interval)	Daily	Every 2 days	Daily
	4DRenCheck			
	Detail of organizational information			
	Location	Yes	Yes	Yes
	Work schedule	Yes	Yes	Yes
	Space sharing	Yes	Yes	Yes
	Number of building configurations analyzed	17	1234	962
	Frequency of analysis (i.e., snapshot interval)	Daily	Every 2 days	Daily
	Number of total interactions identified and confirmed by project planner	11	119	17

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

Each test case also had different analysis needs, all of which required the identification of occupant interactions. Project planners in TC#1 needed to track tenants over time and identify double-booked rooms. Planners in TC#2 needed to understand how often crews would be in tenant spaces to aid in communication with the tenants. Planners in TC#3 needed to track tenants and crews to validate the renovation schedule and track vacant square footage to determine if there was enough swing space in the building.

Table 4 provides a comparison of the traditional planning methods, 4D modeling methods, and 4DRenCheck (IOI method). Across the three cases, 4DRenCheck was able to identify occupant interactions more accurately and thoroughly than traditional methods. 4DRenCheck was also more detailed than traditional and 4D-model-based methods. All project planners confirmed the power of the IOI method through the actual and planned changes in each project's renovation planning information. Based on the validation results, one project planner changed end space tenant locations to eliminate double-booked rooms. Project planners on the remaining two test cases planned to update their renovation planning workshift schedules and sequencing plans based on the analysis.

5.1. Accuracy

Accuracy is measured by the number of occupant interactions identified. Table 4 summarizes the results from the test cases. 4DRenCheck was more accurate than traditional planning methods in all test cases. In two of the three test cases, all of the interactions found were valid interactions that were confirmed by the project planner.

To compare the accuracy of the traditional method versus the automated method, we first asked the project planners to identify all occupant interactions using their current planning methods (Table 5, traditional). We then showed them the results of the 4DRenCheck analysis and asked them to confirm whether the results were accurate (Table 5, 4DRenCheck and true positives). In TC#1, there were 2 false positives, where the project planner indicated that it was intentional to move two different tenants into the same space. We then asked the planners to re-examine the renovation planning information to determine if any additional interactions were present, but not identified by either the planners original traditional analysis or the 4DRenCheck (Table 5, false negatives). In all three test cases, the project planner did not indicate any false negatives. The determination of false positives and negatives is based on the project planner's expert judgment because the validation cases were done prior to the actual execution of the renovation. Due to the duration of these projects, it was not possible to determine the actual number of interactions found. A future area of research could be to compare the planned and actual number and type of interactions.

Table 4. Total number of interactions found using traditional methods and 4DRenCheck

	Type of Interaction	# of interactions found **(Traditional)**	# of interactions found **(4DRenCheck)**	# of 4DRenCheck interactions confirmed by project planners **(True Positives)**	# of 4DRenCheck interactions not confirmed by project planner **(False Positives)**	# of 4DRenCheck interactions missed **(False Negatives)**
Test case #1	Tenant-Tenant **(TOTAL)**	0	13	11	2	0
Test case #2	Minor Tenant-Crew	77	101	101	0	0
	Major Tenant-Crew	0	18	18	0	0
	TOTAL	77	119	119	0	0
Test case #3	Major Tenant-Crew	0	13	13	0	0
	Tenant-Tenant	0	4	4	0	0
	TOTAL	0	17	17	0	0

In Test Case (TC) #1, the project planner stated that she was unable to identify the tenant-tenant interactions based on her project documents, resulting in zero interactions found using the traditional method. 4DRenCheck, however, identified thirteen double-booked rooms. The project planner confirmed that eleven of these were disruptive interactions. There were two false positives which resulted from the project planner consolidating two different tenant groups into a single space on purpose. She also confirmed that there were no additional double-booked spaces that had not been identified by 4DRenCheck. The project planner used the information from 4DRenCheck to update her project documents to eliminate the double-booked spaces.

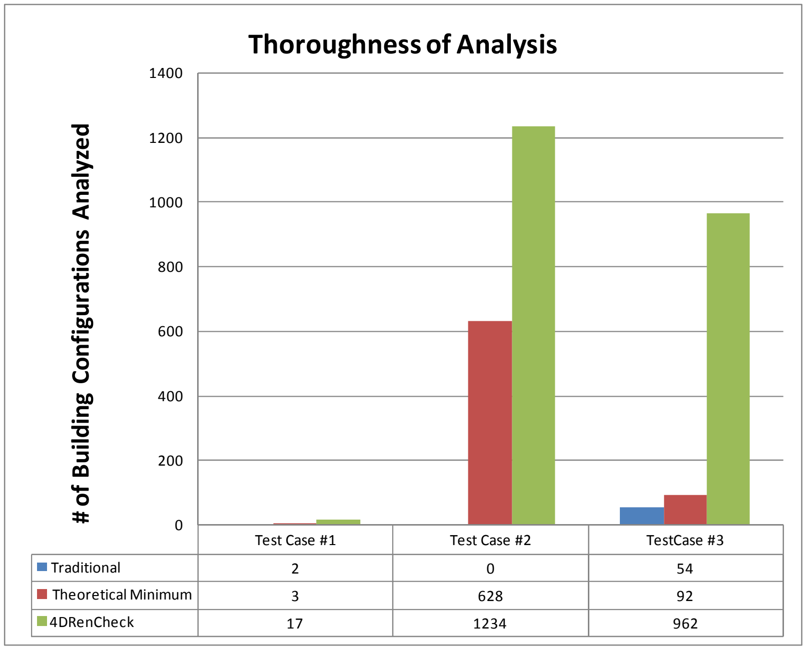
In TC#2, there were three project planners who validated the IOI method collectively. The project planners had identified most of the minor tenant-crew interactions, but had missed all of the major tenant-crew interactions associated with the support space needs of one of the construction activities. The project planners had also not identified minor tenant-crew interactions associated with a tenant that was occupying the north side of the 8th floor, while the south side of the 8th floor remained vacant. Since the day/night/weekend activity matrix was only to the floor detail, the planners did not identify any interactions associated with the 8th floor tenant. After the 4DRenCheck analysis was shown to the project planners, they verified that these were valid interactions that needed to be addressed and confirmed that no additional interactions were missed by 4DRenCheck. Based on the results of the analysis, the project planners also indicated that they would need to update the project documents to reflect a greater level of detail in the day/night/weekend matrix on the 8th floor.

In TC#3, the project team did not know initially that they had any issues with occupant interactions. After the results of the 4DRenCheck analysis were shown, they agreed that all interactions found were valid and that there were no additional interactions missed by 4DRenCheck. Based on the interactions identified and an analysis of the vacant square footage, described below, the project planners decided to consider alternative sequencing strategies to address the occupant interactions identified and better utilize the vacant square footage.

5.2. Thoroughness

We measure the thoroughness of the analysis by the number of building configurations analyzed. In TC#1, we found that the project planner analyzed only the start condition and end condition of the building. She did not analyze any interim building configurations. In TC#2, there was no formal documentation of analyzing any building configurations. In TC#3, the planner analyzed building configurations on a monthly interval.

We define the theoretical minimum as the minimum number of building configurations required to identify all the true positive occupant interactions. Figure 18 shows the results of the validation. While 4DRenCheck was more thorough than traditional planning methods, it was also more thorough than necessary. As discussed previously, the IOI method requires post processing of the interaction results to determine the underlying activity which causes a particular interaction. This post-processing step is discussed in the limitations section.



	Test Case #1	Test Case #2	TestCase #3
Traditional	2	0	54
Theoretical Minimum	3	628	92
4DRenCheck	17	1234	962

Figure 18. Comparison of thoroughness of identification of occupant interactions from traditional methods, 4DRenCheck, and the theoretical minimum

5.3. Level of detail

The level of detail of the analysis is compared by:

- the detail of organization information (i.e., does the method utilize occupant locations, work schedule, and space sharing abilities?) and
- the frequency and detail of analysis of the building configurations (i.e., are building configurations analyzed at regular intervals at the space level?).

5.3.1. Detail of organization information

In all three test cases, 4DRenCheck had detailed organization information about occupant locations, work schedule, and space sharing abilities. In the traditional method, none of the projects had work schedules or space sharing abilities for the tenants. Only TC#2 had workshift information for the construction crews. Figure 19 shows the traditional documentation for TC#2. The day/night/weekend matrix contained details about crew workshifts, but the Primavera schedule did not provide this detail, requiring the planners to reconcile this information. Furthermore, information about the location of crews and their space sharing abilities was not detailed enough, which prevented the project team from identifying the major occupant interactions. In the 4D model, changes to occupant locations were at the space level, but the model did not represent occupant work schedules or space sharing abilities. 4DRenCheck provided detailed information on occupant work schedules and space sharing abilities that allowed project planners to determine how occupants were sharing spaces during each workshift.

ACTIVITIES MATRIX

	Floors SB-B	Floors 1-7	Floors 8-10	Floors 11-16	Floors 17-19	Floor 20
DEMOLITION (8, 9, & 10)						
Demolition (Below Ceiling)	N/A	N/A	Night	N/A	N/A	N/A
Abatement (VCT, Ceilings & Above)	N/A	N/A	Night	N/A	N/A	N/A
PERIMETER INDUCTION UNITS						
Abatement of Flexible Duct @ PIUs	N/A	Night	Day	Night	Day	Night
Drywall - Install Gypsum Board	N/A	Night	Day	Night	Day	Night
Drywall - Taping & Sanding	N/A	Night	Day	Night	Day	Night
Plastering	N/A	Night	Day	Night	Day	Night
Painting	N/A	Night	Day	Night	Day	Night
Mech. Piping Rough-in	N/A	Night	Day	Night	Day	Night
PIU Replacement	N/A	Night	Day	Night	Day	Night
Ductwork Rough-in	N/A	Night	Day	Night	Day	Night
Ductwork Trim	N/A	Night	Day	Night	Day	Night
Controls Rough-in	N/A	Night	Day	Night	Day	Night
Controls Trim	N/A	Day	Day	Day	Day	Day
Controls Programming	N/A	Day	Day	Day	Day	Day
Commissioning	N/A	Day	Day	Day	Day	Day
PIU CONDENSATE PIPING						
Abatement @ Column and above ceilings	N/A	Weekend	Day	Weekend	Day	Weekend
Patching and Painting @ Columns	N/A	Night	Day	Night	Day	Night
Patching and Painting @ Ceiling	N/A	Night	Day	Night	Day	Night
Mech. Piping Rough-in (Condensate Drain)	N/A	Night	Day	Night	Day	Night

Activity ID	Activity Name	Original Duration	Remaining Duration
09920	Demolition & Abatement	20	20
09410	Install Condensate Piping Risers - North	10	10
09420	Replace PIUs - North	10	10
09926	Install pipe hangers/ racks	15	15
09440	Install Condensate Piping Risers - South	10	10
09450	Replace PIUs - South	10	10
09930	Install VAV boxes	20	20

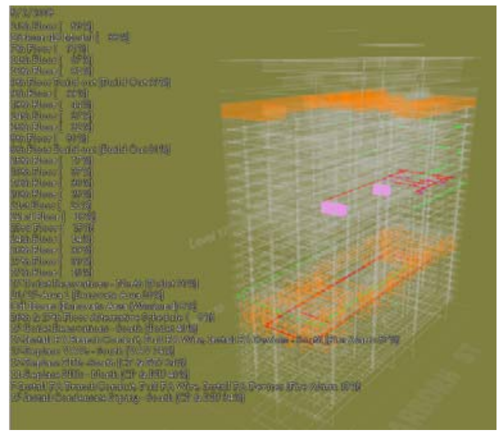
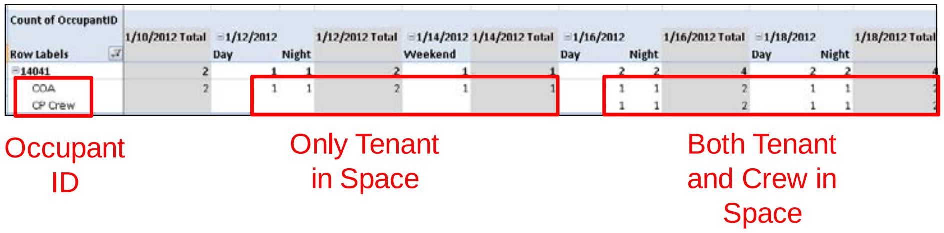


Figure 19. The traditional planning methods used on TC#2 included a Primavera schedule, day/night/weekend activities matrix, and 4D model

4DRenCheck provides additional detail of occupant locations and space sharing abilities. A pivot table (Figure 20) allows project planners to see which occupants are in each space over time. This pivot table shows how planners could have identified one of the 18 major tenant-crew interactions they missed initially. The example shows that a tenant (i.e., Tenant COA) occupies Space 14041. It also indicates that a condensate piping crew occupies the same space starting on 1/16/2012. Upon further inspection of the data, both occupants have a "cannot share" space sharing ability, indicating a major tenant-crew occupant interaction throughout the entire 10-day duration of the condensate piping activity. The detail of this information allows project planners to drill down for any specific date and workshift to identify what types of occupant interactions are occurring and determine the underlying activities that cause the interactions. This type of detail could also enable project planners to identify occupant space sharing opportunities. The data could also be used to find tenants who can share their space, but do not have a crew sharing a space.



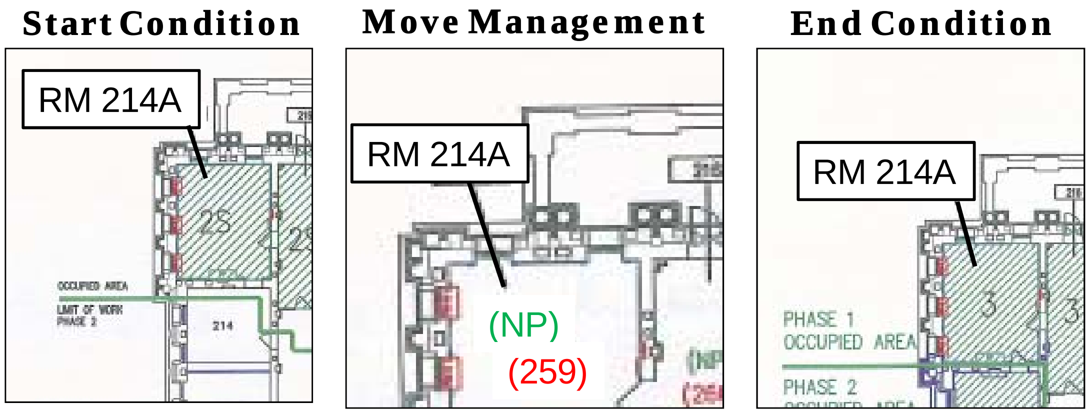
Start Date	End Date	Shift	Space ID	Occupant ID	Space Sharing Ability
1/16/2012	1/16/2012	Day	14041	COA	Cannot Share
1/16/2012	1/16/2012	Day	14041	CP Crew	Cannot Share

Figure 20. Building configuration information organized in a pivot table, with underlying project information available

5.3.2.Frequency and detail of analysis of building configurations

On the test cases, 4DRenCheck provided greater frequency of recording building configurations than the traditional methods. With the traditional method, on TC#1 the project planner only examined the start and end locations. On TC#2, the project planners did not examine any building configurations. On TC#3, the planner had locations of occupants on a monthly basis in an Excel spreadsheet, but the detail was at the floor level, not the space level. The 4D models allowed project planners to see changes to occupant locations at the same frequency as 4DRenCheck if the snapshot intervals of both models were equal. 4D models, however, did not enable visualization of changing building configurations. 4DRenCheck was able to visualize every building configuration at regular intervals at the space level. This enabled planners to analyze where occupants were, which could not have been done with traditional or 4D methods.

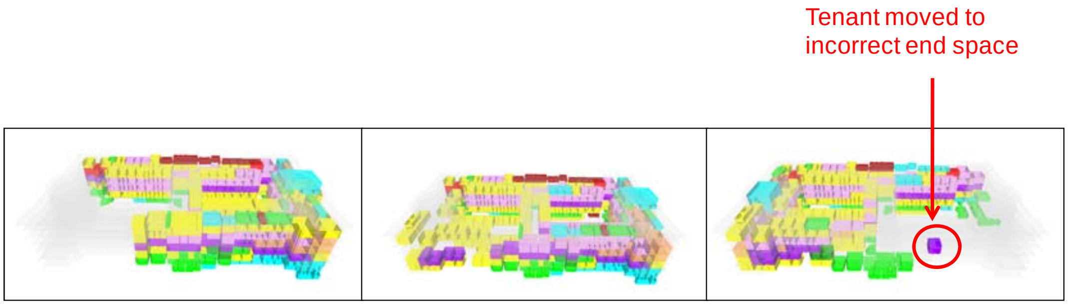
In TC#1, the frequency of analysis was not detailed enough for every interim snapshot date; only the start and end conditions were provided. Figure 21 shows the traditional planning documents used in TC#1. From these documents, the project planner was not able to track tenants or vacant space over time.



19-a. **19-b.** **19-c.**

Figure 21a-c. Traditional move management documents. Starting locations of tenants (21-a), move activities (21-b), and final locations (21-c) are managed in three separate sets of 2d CAD drawings. For each space, one label (e.g., NP) indicates to which space a tenant will be moving, and another label (e.g., 259) indicates from which space a tenant will be moving.

By documenting building configurations at regular intervals, 4DRenCheck tracks tenants automatically based on the renovation schedule. Figure 22 shows the progression of tenants from the Phase 3 and 1 locations (Figure 22-a), through the move (Figure 22-b), to their final locations (Figure 22-c). From this analysis, the researchers identified that one tenant in the Phase 3 area was incorrectly moved because the visualization showed a tenant in a space that was supposed to be vacant. The project planner confirmed that the tracking was accurate and that the identification of the incorrectly moved tenant in Phase 3 was accurate. As a result, the project planner changed the end location of the tenant. The project planner also indicated that this information was useful to determine vacant spaces throughout the moves.



Tenant Start Locations | Intermediate Building Configuration | Tenant End Locations

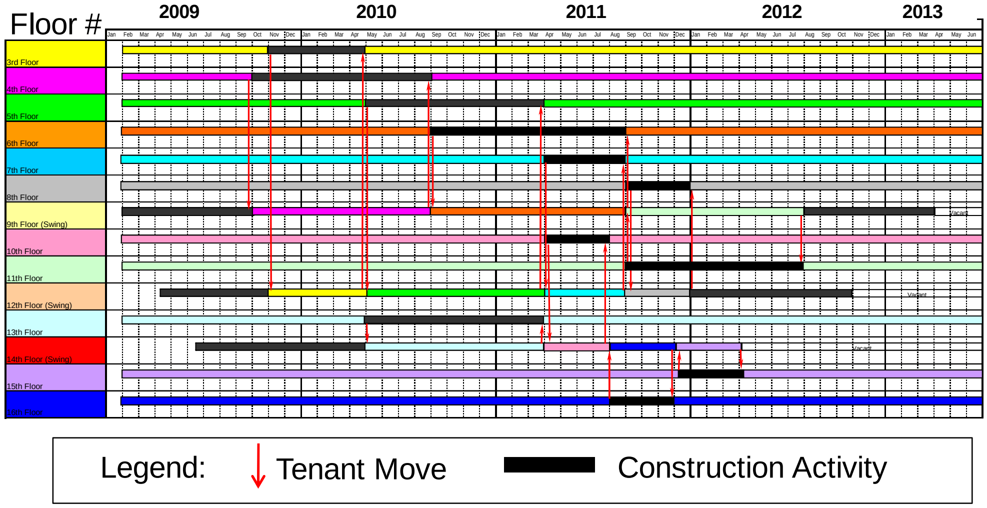
20-a. ***20-b.*** ***20-c.***

Figure 22a-c. Snapshots of tenant locations throughout the TC#1 move schedule show the start locations of tenants (22-a), an intermediate building configuration (22-b), and end tenant locations (22-c). The locations of occupants in the intermediate and end building configurations are determined automatically, eliminating inconsistencies between the move schedule and the end locations of tenants.

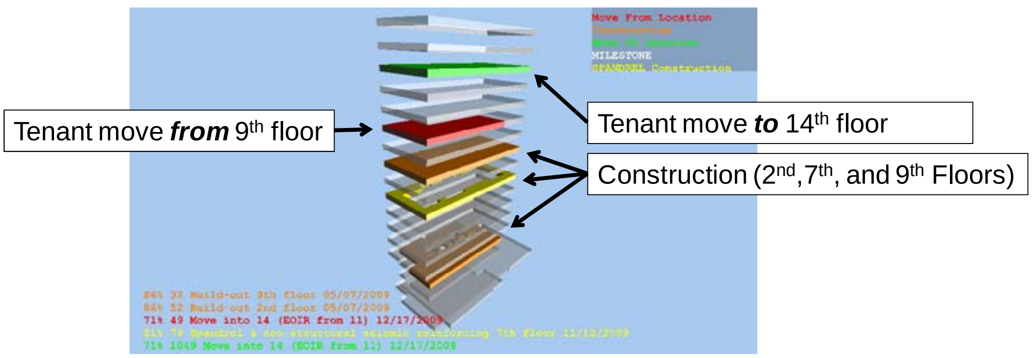
5.4. Analysis of vacant square footage

The tracking of occupants also enables another related analysis – the identification of vacant square footage (i.e., swing space) in the building. Of the seven projects analyzed by Ho et al. (2009), this type of analysis was required on two projects. On TC#3, planners needed to analyze the amount of vacant square footage to determine if the amount of swing space (i.e., temporary tenant space) in the building was adequate for the duration of the renovation, or if additional lease space needed to be rented.

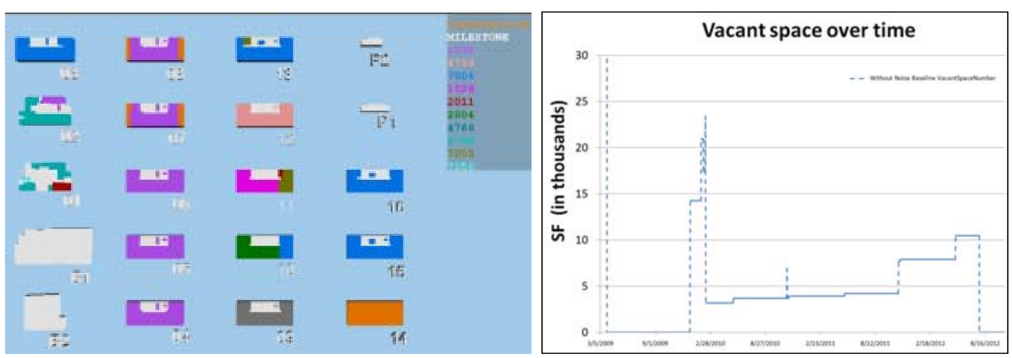
In TC#3, the traditional planning information did not detail the tenant move activities to the space level, making it impossible to track occupants and the amount of vacant space over time. In contrast, 4DRenCheck analyzes the locations of occupants and tracks vacant square footage. Figure 23 compares the level of detail of information between traditional planning information and 4DRenCheck for TC#3. In the traditional planning documents, the tenant move schedule is at a floor-by-floor level of detail (Figure 23-a), which does not have enough information to track vacant square footages over time. The 4D model (23-b) shows changes in occupant locations, but does not show changes to building configurations over time. 4DRenCheck tracks the occupant locations and square footage information over time (23-c, left) to analyze the amount of vacant space in the building (23-c, right).



23-a



23-b



23-c

Figure 23a-c. Comparison of level of detail of the traditional method, 4D model, and 4DRenCheck (IOI method) for TC#3. The traditional method (23-a) does not enable the tracking of tenants or calculating the amount of vacant space over time. The 4D model (23-b) does not enable visualization of changing building configurations. 4DRenCheck can track tenants to visualize changing building configurations and determine the amount of vacant square footage over time automatically (23-c).

In summary, the IOI method is powerful and general based on the evidence of increased accuracy, thoroughness, and detail in identifying occupant interactions. The prospective validation on real renovation projects and the interventions planned and made by the project planners show the power of an automated process to identify occupant interactions that can be used at the scale of real renovation projects.

5.5. Limitations

We identified several limitations to this research. As with any model, information is abstracted and simplified. While the method captures the information necessary to identify occupant interactions, occupants and construction activities could be modeled in greater detail to incorporate additional renovation planning information. The analysis method could also be further developed to enable greater automation and flexibility in representing non-typical renovation situations.

5.5.1. Limitations in representation

Representation of tenants – This research has shown that an organization's requirements can be formalized and considered in scheduling decisions. Currently, the renovation planning ontology only represents the work schedule and space sharing abilities of an occupant for a typical work week. While this representation will identify most interactions, there are additional organizational requirements for each tenant that could be refined or modeled.

First, the representation may not accurately represent the occupant during certain times of the year. For example, a tenant may have a "busy season" in which they work during the weekends, where their space sharing abilities become "cannot share" during that period, or their business operations inhibit them from moving during certain months. Similarly, there may be certain unique spaces that a tenant occupies for which the tenant has different space sharing abilities. For example, a tenant may occupy a library space for which the organization would have different space sharing abilities than office spaces. An area of follow-on research could be to identify and formalize these non-typical occupant situations.

Second, tenants may have additional tenant-specific requirements that should be addressed during the planning stage. Table 6 shows some tenant-specific requirements found in the seven projects examined by Ho et al. (2009). These tenant-specific requirements have spatial and temporal aspects, making it necessary for project planners to ensure that these requirements are met over the entire renovation schedule. With respect to the tenant-specific requirements related to spaces, some tenants had unique functional spaces (e.g., specialized conference rooms) which were used on a daily basis. The tenant required a minimum number of these functional spaces to continue the tenant's business operations during the renovation. The temporal requirements were also related to the tenants' operations. For example, a tenant had business operations which were difficult to relocate (i.e.., the tenant operated large equipment) and required a maximum of one tenant move.

Table 5. Examples of tenant-specific requirements

Examples of Tenant-Specific Requirements
Spatial Requirements
We must have at least six work stations operational at all times.
A new functional space on the 14th floor needs to be constructed before the current functional space on the 13th floor is eliminated.
Occupant B needs five conference rooms available at all times.
Temporal Requirements
The best time for Occupant A to move would be June - November.
Occupant B cannot move in April.
Occupant C can only move once.
Occupant D needs to move in by a certain date beause their lease runs out at a different location.

Third, tenants may be willing to be flexible and negotiate different renovation conditions. For example, on TC#2, one tenant was willing to move into swing space if it meant that their renovated space would be finished early in the renovation. Therefore, a tenant's space sharing profile could be extended to represent tenant flexibility based on different renovation conditions. A future area of research could be to determine what types of conditions (e.g., reduced renovation time) could influence a tenant's preferences to move or affect the ability to share spaces with construction crews.

Representation of construction activities – The IOI method requires project planners to identify the direct and support spaces for each construction activity manually. There could be additional renovation parameters that could define additional spatial relationships from construction activities. For example, a pile driving activity could have a vibration parameter which determines which spaces in the building would be affected by the activity. Akinci et al. (2002a) utilize a generic representation of workspaces to automatically determine the volume of space needed for different types of work (e.g., hazard, equipment). A future area of research could be build on this prior work to identify and formalize the geometric concepts necessary for renovation planning (e.g., above, below, adjacent, etc.) to represent construction activity support spaces.

The IOI method represents crews at the crew-type level of detail, although there may be multiple instances of the same crew type during renovation. A future area of research could develop representation and reasoning methods to detail the specific instance of a crew automatically, such that each instance of a crew is considered a separate organization. This would allow planners to further understand the resource utilization of crews at the instance level in addition to the aggregate crew-type level.

Prior research has identified that renovation projects have higher product uncertainty (e.g., unknown information about what is behind a wall) than new construction projects (Sanvido and Riggs 1991). Monte Carlo simulations could also be incorporated in each construction activity to represent this uncertainty. This would enable project planners to understand which activities have the most risk to develop alternative plans or communicate better with tenants. The impact of using the IOI method to decrease process uncertainty (i.e., from having more accurate information about occupant interactions) could also be examined further and incorporated in Monte Carlo simulations.

5.5.2. Limitations in analysis method

Non-geometric analysis **-** The method is not a true 4D-model based analysis since it does not include geometric methods as part of the IOI method. While the IOI method contains non-geometric methods that are representationally efficient to identify interactions, it creates two main limitations.

First, project planners must manually determine which support spaces are affected by a construction activity. For example, if a construction activity requires access from the space above, the project planner has to identify the space above manually and include it in the inputs to the analysis. A future area of work would be to utilize formal representations of support spaces in construction activities (Akinci et al. 2002b) to develop a method to determine which spaces would be affected by a construction activity automatically.

Second, the method assumes that all spaces are pre-defined and unique. Therefore, all individual spaces need to be represented and tenants need to move into all individual spaces to represent several individual spaces being combined into a larger space for a tenant. There is no additional space representing the larger space. This limitation also exists if a construction crew occupies only a portion of the space. The IOI method represents the crew occupying the entire space. A future area of work would be to build on prior work in geometry-based construction process modeling to separate and combine building spaces (Akbas 2004). This would give project planners more flexibility in specifying different spatial configurations for the occupants when analyzing renovation schedules.

However, implementation of these geometric methods would not affect the method to automatically identify occupant interactions since the identification is based on the occupant's space sharing ability, which is a non-geometric property.

Simulation is too thorough – As explained in the validation, the IOI method unnecessarily checks building configurations that have not changed from the previous configuration. This limitation requires manual post-processing of the interactions to identify unique interactions. This thoroughness concept is not uncommon when computer-interpretable analysis is used. For example, in 3D clash detection software, project engineers must routinely post-process computer-identified clashes to determine which ones are unique and need to be addressed (Leite et al. 2009). Follow-on research could improve this reasoning method in two ways. First, better reasoning methods could be developed to only identify interactions when there is a change from the previous building configuration. Second, post-processing reasoning methods could be developed to automatically combine similar instances of interactions into a single unique interaction.

6. Conclusion

The presence of tenants during renovation projects creates the need for project planners to analyze renovation schedules to identify possible occupant interactions. Failure to identify these interactions can result in loss of productivity for tenants and construction crews. Current renovation planning methods do not represent the spatial, organizational, and temporal aspects of renovation planning information to allow project planners to identify occupant interactions thoroughly and in detail, leading to inaccurate identification of these interactions. This research developed a method to identify occupant interactions automatically. The method formalizes the following renovation planning information:

(1) Occupant Profiles,
(2) Renovation Activity Ontology (i.e., tenant move and construction activities), and
(3) Occupant Interaction Ontology.

This formalization provides the level of detail needed by project planners to analyze renovation schedules and identify occupant interactions. The reasoning methods utilizing the above formalization can:

(1) update the occupant-loaded spatial model information from renovation activities,
(2) update occupant space sharing abilities from occupant profiles, and
(3) automatically identify occupant interactions from the occupant-loaded spatial model.

These reasoning methods enable project planners to identify occupant interactions more thoroughly, in greater detail, and more accurately than traditional planning methods.

Based on the evidence of power and generality from the validation cases, the scientific contributions of this research are the formalization of renovation planning information and a method to identify occupant interactions automatically. This research provides a new, representationally efficient approach which integrates spatial, organizational, and temporal renovation planning information to identify shared spaces. This research integrates and extends existing concepts and methods in product modeling, occupant modeling, activity modeling, and space sharing identification methods. It extends prior research in occupant and organizational modeling by representing an occupant's space sharing ability as an attribute of the occupant, not the space. It extends prior research in activity modeling by formalizing a tenant move activity as a single activity even though it relates to two (sets of) spaces. It also represents the construction activities and occupants at the workshift level, so that occupant locations and their space sharing abilities can be updated at the space and workshift level. Finally, it extends prior research on space sharing analysis by developing a non-geometric method to check interactions that is more representationally efficient and manageable than existing space sharing identification methods because it does not require additional spaces or activities to be modeled.

The scientific implication of this research is that virtual design and construction methods which integrate all aspects of the product, organization, and process models for a planning task, such as identifying interactions, and automate the task can improve the management of renovation projects. Formalized relationships between organizational requirements and project performance demonstrate that building occupants are key stakeholders to a successful project. Automated checking of process models, such as the IOI method, indicates that schedule performance objectives can be explicitly defined and measured.

The practical implication of this research is the ability for renovation planners to ensure that disruptive interactions between tenants and construction crews do not occur. The ability to track occupant locations over time more thoroughly and in detail not only provides the necessary data to perform additional analyses, but could also be used to identify potential occupant space sharing opportunities. As the number of renovation projects increases, the active management and analysis of the renovation schedule, including identification of occupant interactions, will become even more critical to minimizing schedule delays and loss in occupant productivity. More broadly, this research demonstrates that the use of integrated planning information and automated methods, such as the IOI method, has the potential to improve existing renovation management practices.

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