CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

An Automated Method to Identify Occupant Interactions in Renovations of Occupied Buildings

By

Peggy Ho Yee

CIFE Technical Report #TR185
December 2009

STANFORD UNIVERSITY

COPYRIGHT © 2009 BY
Center for Integrated Facility Engineering

If you would like to contact the authors, please write to:

c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University
The Jerry Yang & Akiko Yamazaki Environment & Energy Building
473 Via Ortega, Room 292, Mail Code: 4020
Stanford, CA 94305-4020

AN AUTOMATED METHOD TO IDENTIFY OCCUPANT INTERACTIONS IN RENOVATIONS OF OCCUPIED BUILDINGS

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Peggy Helen Ho Yee

December 2009

ABSTRACT

Renovation projects represent an increasing percentage of building construction projects today. As the importance to utilize existing resources responsibly becomes greater, building owners are finding ways to extend the life of existing buildings (e.g., through systems upgrades), while still maintaining tenant business operations. Renovations of occupied buildings create particular management challenges because tenants and construction crews must share spaces in the building. These occupant interactions can at best be tolerable, and at worst, be disruptive to tenants and crews. Today's practice of manually identifying occupant interactions misses many disruptive interactions, which can lead to cost and schedule overruns and business disruptions for the building occupants. Therefore, this thesis addresses this challenge by developing an automated method to identify occupant interactions (IOI method).

Identifying occupant interactions is challenging because it requires the integration of spatial, organizational, and temporal information to understand where, when, and how occupants utilize building spaces over different workshifts during renovation. Furthermore, the dynamic nature of renovation projects causes the building configuration (i.e., locations of occupants) to change many times during renovation. Therefore, this thesis advances prior work in product, organization, and process modeling by formalizing the relationships between spatial, organizational, and temporal renovation planning information to enable a thorough (i.e., analysis of all building configurations) and detailed (i.e., at the space and workshift level) identification of occupant interactions. The IOI method formalizes occupants with specific organizational requirements, processes at the level of detail required for accurate identification of occupant interactions, process-space relationships to simplify model-based representation of tenant move activities, and organizational relationships that represent how occupants share spaces. These formalizations enable reasoning methods that update occupant locations and their space sharing abilities and identify interactions at a level of detail that is infeasible to achieve with manual methods. The IOI method is also representationally more efficient than existing computer-based methods to identify occupant interactions.

I implemented the IOI method in a computer prototype, 4DRenCheck, to test that the method supports automated and accurate identification of occupant interactions. I then validated the method prospectively with three renovations of large office buildings that were in their

planning stages. Prospective validation tested the power of the IOI method to identify interactions more accurately, thoroughly, and in greater detail than traditional methods and tested whether the method could be implemented in a timeframe to affect future project decisions. Based on the insights from validating the IOI method, this thesis also provides a six-criterion framework to determine when prospective validation is an appropriate method for researchers to use. The framework relates the objectives of virtual design and construction (VDC) methods (i.e., predict project performance, use on design-construction projects, and support business objectives) to six validation parameters that can demonstrate this power. This thesis also provides researchers with implementation guidelines on planning, executing, and analyzing a prospective validation test.

The results of the validation demonstrate that the IOI method analyzed all unique building configurations at the space and workshift level of detail. Consequently, the method identified occupant interactions more accurately than with traditional methods. Based on the insights from 4DRenCheck, the following interventions were made: one renovation planner corrected the start and end locations of tenant move activities, another renovation planner intended to revise the construction schedule to a greater level of detail, and the third renovation planner anticipated revising the sequencing of the renovation activities to better utilize space in the building. The results demonstrate that the concepts formalized in this thesis provide the power necessary for thorough, detailed, and accurate identification of occupant interactions on full-scale renovation projects. More broadly, the IOI method demonstrates that the integration of product, organization, and process models and the automation of planning tasks, such as identifying occupant interactions, is beneficial in managing towards desired performance objectives in renovation projects.

ACKNOWLEDGEMENTS

Earning my Ph.D. has always been a lifelong dream, but one that I could not have accomplished without many faculty, colleagues, co-workers, and family supporting me. I am grateful to the following people for helping me complete this dissertation.

First, I would like to thank my advisor, Martin Fischer, for his support and guidance. His ability to “see the forest through the trees” provided me with the necessary guidance to understand how my research could be improved when I was lost in the details. He not only has taught me how to conduct solid research, but more importantly, how to approach difficult industry problems from both a theoretical and practical perspective.

I would also like to thank my committee for their different perspectives and guidance throughout this work. Professor John Haymaker provided insights on how to organize and explain my research in a clear and meaningful way. Dr. Calvin Kam helped me to explain the observed problem and pinpoint the contribution and limitations of my work, in addition to being a wonderful mentor at GSA. I would also like to thank Dr. Ray Levitt and Dr. Banny Banerjee for serving on my defense committee and helping me to understand the broader context of my research. I would also like to thank Dr. John Kunz for all of his insights, both professional and personal. I enjoyed all of our meetings and discussions.

I could not have made this journey without the support of my friends and colleagues at CIFE. I want to thank my colleagues at Stanford: Tony Dong, Ju Gao, Victor Gane, Timo Hartmann, Atul Khanzode, Jonghoon Kim, Kathleen Liston, Tobias Maile, Claudio Mourgues, Hossein Nasseri, and Benjamin Welle. I want to especially thank Caroline Clevenger for all our late nights at CIFE and our conversations on how to best navigate through our research. I would also like to thank Teddie Guenzer for all of her administrative support.

I also want to thank my colleagues at the U.S. General Services Administration. In particular, I want to thank Charles Matta and the GSA BIM Champions for their support and understanding during my Visiting Fellowship at GSA. They allowed me to see both the future potential and practical limitations of implementing virtual design and construction methods in the AEC industry.

Finally, I am also grateful for the support from my family. I am extremely grateful to my husband, David, for his never-ending support and providing me with the motivation to finish my degree. Our time at Stanford has been a wonderful phase in our lives, from meeting each other in class to getting married at Memorial Church. I am also grateful to my sister for always providing me with a good laugh when I needed it. I hope her care packages keep coming after I leave Stanford. Finally, my parents have always known I would earn a Ph.D., and their confidence provided me with the support I needed throughout this journey. I dedicate this dissertation to my parents, Yee-Kin and Shu Ho.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 1

INTRODUCTION AND SUMMARY OF THE THESIS

1. Introduction

As the need for sustainability increases, building owners are turning towards renovating their existing buildings instead of constructing new ones. Renovation projects, however, are different from new construction. The presence of tenants during the renovation of an occupied building requires project planners to shuffle tenants and construction crews around to different locations in the building to allow tenants to continue business operations and construction crews to work. Planners must create a renovation schedule, consisting of both construction and tenant move activities that minimize occupant interactions – instances where tenants and/or crews share spaces.

As a Visiting Fellow to the United States General Services Administration (GSA), I participated in the planning process of several renovation projects by creating 4D models of the renovation schedule. For each project, I observed that the project planners had to identify occupant interactions manually and that the process was ad-hoc and error-prone. I found that the use of traditional planning methods (e.g., Excel spreadsheets, Powerpoint presentations, 2D CAD files) did not represent the building spaces, occupant behavior, or the renovation process in an integrated way or at the necessary level of detail to allow project planners to understand how occupants use building spaces during renovation. 4D models were helpful in integrating and visualizing spatial and temporal information, but the identification of occupant interactions was still performed manually. As a result, these project planners could not identify instances where tenants and crews were interacting. These experiences formed the motivation for my Ph.D. research.

This Ph.D. thesis presents an automated method to identify interactions that enables project planners to identify interactions more thoroughly and in greater detail, enabling more accurate identification of interactions than with traditional manual methods. I provide a conceptual framework and formalize representations and reasoning methods to relate building spaces, occupant behavior, and renovation process information. This research builds on prior work in renovation planning methods, occupant modeling, activity modeling, and space sharing identification methods to develop a way to identifying occupant interactions that is representationally more efficient than existing approaches. This research utilizes prospective validation, an emerging method to validate new VDC methods, to determine whether the concepts and methods developed in this thesis are powerful. This thesis also provides a framework for determining when prospective validation is an appropriate method to use and provides prospective validation implementation guidelines for researchers.

This introductory chapter provides an overview of the research problem, research questions, and contribution of this dissertation. It also provides a reader's guide to the remainder of the thesis.

2. Observed problem

Renovation projects today are increasing in importance and numbers. For example, the United States General Services Administration (GSA), the largest building owner in the United States, plans to spend $4.5 billion dollars from 2009 to 2012 on renovating federal buildings (GSA 2009). Renovation projects can vary in their scope and occupancy rate during renovation (Douglas 2006; Mansfield 2002). The scope of renovation projects can range from small maintenance projects to full building modernizations. The occupancy rate during renovation can vary from complete vacancy to full occupancy. This research focuses on renovation projects which have the most complex scheduling constraints – renovation projects that require major building renovation work (e.g., tenant build out, systems upgrades, seismic retrofits), but also require tenants to remain in the building.

Prior research indicates that renovation projects are more likely to be over budget and behind schedule. Haddad and Attala (2002) found that, when estimating the cost of a renovation, the renovation of an occupied building (versus unoccupied) accounts for approximately 30% of a contingency estimate and is the highest contributing factor to cost estimating contingencies. Other case studies have indicated significant increases in costs and schedule delays due to the presence of tenants during renovations (Attalla 1999; Department of the Treasury 2005). These prior research findings, in combination with the increasing number of renovation projects in the future, motivates the development of better methods for project planners to manage renovations of occupied buildings.

Identifying occupant interactions is a crucial aspect in managing renovations of occupied buildings because project planners must develop a renovation process that allows the building occupants (i.e., tenants and crews) to work without unnecessary disruptions. In some situations, it is tolerable for tenants and crews to share spaces. For example, a tenant does not want to share space during the day when they are working, but is willing to share the space at night to allow construction crews to work. In other situations, it is disruptive for tenants and crews to share spaces, for example, if a tenant and a crew are scheduled to work in the same space during the same workshift. Because occupant space sharing abilities can change during different workshifts, distinguishing tolerable from disruptive interactions can only be done at the workshift level. Project planners must develop a renovation schedule that minimizes tolerable occupant interactions and has no disruptive interactions.

To identify occupant interactions, project planners first need to track the locations of occupants at the space level to determine if more than one occupant is in a space. This is difficult because tenants are moving and crews are working in different spaces, creating many unique building configurations (i.e., locations of occupants) throughout the renovation. If there is more than one occupant in a space, planners then have to identify, at the workshift level, whether the occupants are sharing the space in a tolerable or disruptive manner. Identifying occupant interactions requires the synthesis of spatial, organizational, and temporal renovation planning information. It also requires thoroughness and detail because each unique building configuration must be analyzed at the space and workshift level. The result is an abundance of occupant location and space sharing data that must be updated and analyzed.

Identifying occupant interactions using today's scheduling methods is difficult because there is a lack in formalization of renovation planning information, resulting in a manual identification process. Based on a combination of literature review and participation on seven renovation projects, I identified that the process is:

- **Not Detailed** – Current renovation schedules lack the detail of organizational and activity information necessary to identify occupant interactions at the space and workshift level. Tenant move activities are not detailed to describe specific tenants and their start and end locations. This makes it difficult to determine the locations of occupants at any given time. In four of the seven projects analyzed, there was no information on the workshift of construction activities or whether these crews could share spaces. There was also no detail on the tenants' work schedules or whether they would be able to share spaces. This lack of detail not only prevents project planners from identifying whether an occupant interaction is tolerable or disruptive, but also prevents them from identifying opportunities for occupants to share space.
- **Not Thorough** – Project planners typically analyze a subset of unique building configurations for occupant interactions: the current locations of tenants, the proposed future locations of tenants after renovation, and a limited number of intermediate building configurations. On the seven

projects, project planners, on average, analyzed only half of the unique building configurations. Since occupant interactions can happen whenever the building configuration changes, a thorough analysis of all unique building configurations is needed to identify all of the occupant interactions.

- **Inaccurate** – Project planners struggle to identify when, where, and how occupant interactions occurred based on the renovation schedule. In an in-depth analysis of three of the seven projects, project planners were ready to proceed with the renovation work even though – as our detailed analysis showed – the renovation schedules contained many disruptive interactions between occupants. Project planners only identified 53% of occupant interactions. Sometimes, they completely missed or did not distinguish the correct type of interaction.

Therefore, the underlying scientific problem is to identify and formalize the relationships between spatial, organizational, and temporal renovation planning information that enables a method to identify occupant interactions more thoroughly and in greater detail, and consequently, more accurately. Furthermore, once such a method is developed, researchers and practitioners need a way to determine whether the method is better than existing methods and whether it can be implemented on a real project within a timeframe to affect future project decisions.

3. An alternative approach to manual identification of occupant interactions

My intuition is that an automated approach to identifying occupant interactions would enable a more thorough, detailed, and accurate identification of occupant interactions than manual methods. Therefore, this thesis integrates spatial (i.e., occupant locations), organizational (i.e., occupant work schedules and space sharing abilities), and process (i.e., renovation schedule) models to identify occupant interactions automatically (IOI method). The IOI method is thorough enough to analyze every unique building configuration, detailed enough to analyze occupant space sharing abilities at the workshift level, and efficient for project planners to manage. Figure 1 shows an overview of the method.

Applying a VDC method to identifying occupant interactions is interesting because the requirements of the task align well with the advantages of computer-based methods. Renovations of occupied buildings require project planners to develop a renovation schedule that coordinates the work locations of tenants and crews over time to minimize occupant interactions – instances where tenants and/or crews share spaces. Identifying interactions is challenging because it requires the synthesis of spatial, organizational, and temporal renovation planning information to understand where, when, and how occupants can or cannot share spaces. Each unique building configuration (i.e., locations of all occupants) must be analyzed at the space (i.e., room) and workshift level. Current planning tools combine, at best, two of the three types of information needed to identify occupant interactions. 4D models combine the spatial and temporal information, annotated key plans combine the spatial and organizational information, and resource-loaded schedules combine the temporal and organizational information. On one hand, this lack of integration of renovation planning information with the existing tools requires manual analysis of renovation plans. On the other hand, the requirement for thoroughness and detail makes manual identification of interactions practically impossible. Therefore, I developed the IOI method to automate the identification of interactions and improve the accuracy of this analysis.

The IOI method models fixed building spaces, in which occupants move in and out of these spaces. The method requires three new formalizations of renovation planning information (i.e., renovation activity ontology, occupant profile, and occupant interaction ontology) and three associated reasoning methods (i.e., updating occupant locations, updating occupant space sharing abilities, and checking occupant interactions). This enables a representationally simpler method to identify occupant interactions than existing model-based methods because it does not require multiple geometric representations of the same space to be modeled. The method assumes that a renovation schedule and occupant-loaded spatial model (i.e., a 3D model of all building spaces and the initial locations of occupants in each space) are available as input. Once the simulation parameters (i.e., start date, start workshift, and snapshot interval) are defined by the user (e.g., the researchers), the method is a discrete event simulation that consists of two automated steps. The first step updates occupant locations and their space sharing abilities. The second step checks for occupant interactions. The resulting occupant interactions can be viewed in a spreadsheet with information on the time and location of each occupant interaction.

In the first step, I formalize a process model (i.e., renovation activity ontology) to enable project planners to relate the start and end locations of tenant move activities and represent construction activities to the workshift level. I also formalize an organization model (i.e., occupant profile) that describes an occupant's work schedule and space sharing ability. These formalizations enable two non-geometric methods to update occupant locations and update occupant space sharing abilities at the space and workshift level automatically.

In the second step, a heuristic classification process abstracts space-specific information in the updated occupant-loaded spatial model to determine the types of occupants and their space sharing abilities. I formalize an occupant interaction ontology which describes four different types of interactions between tenants and crews (i.e., tenant-tenant, crew-crew, major tenant-crew, and minor tenant-crew). The abstracted data is used in combination with the occupant interaction ontology to identify the space-specific occupant interaction. These steps are repeated for each space at the workshift level until the end of the renovation schedule.

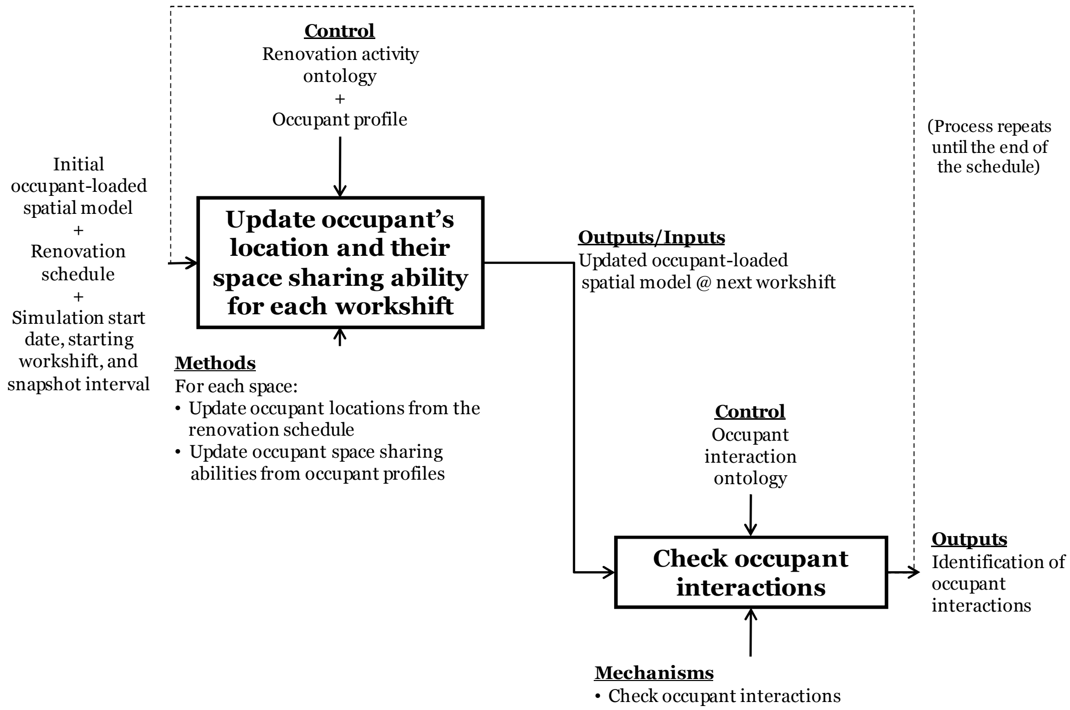


Figure 1. Method to identify occupant interactions automatically.

4. Research questions

This dissertation addresses two research questions:

RQ(1) What is a *formalization of renovation planning information* that enables automated identification of occupant interactions?

RQ(2) What *reasoning methods* can utilize the above formalization to *identify occupant interactions automatically*?

Clearly, the two research questions are related. The first research question identifies and develops a formal description of the necessary renovation planning information used to update occupant locations and their space sharing abilities. Addressing this question also requires the development of a formal classification of the different types of occupant interactions found in renovation projects. The second research question builds on the answers to the first research question by investigating how occupant locations and their space sharing abilities can be updated and how occupant interactions can be identified automatically. Prior research in renovation planning methods (Attalla 1999; Egbu 1999; Fawcett and Palmer 2004; Sanvido and Riggs 1991; Shami and Kanafani 1997; Whiteman and Irwig 1988) only provide generic guidelines to identify occupant interactions. Therefore, the development of the IOI method is a contribution to the area of renovation planning methods because it can be used in project-specific situations to identify occupant interactions.

The following sections describe each research question in detail, summarize the related theoretical points of departure, and preview my answers. These answers, collectively, form the contribution of this research in the areas of occupant modeling, activity modeling, and space sharing identification methods.

What is a *formalization of renovation planning information* that enables automated identification of occupant interactions?

Based on my participation on seven renovation projects at the GSA, I observed that spatial (i.e., locations of occupants), organizational (i.e., occupant space sharing abilities), and process (i.e., tenant move and construction activities) information are necessary to identify occupant interactions, but existing methods do not represent or integrate this information adequately. I also observed that there were only a few ways in which occupants interact, but existing formalizations do not represent all of these interactions. The purpose of this question is to formalize a computer-interpretable representation of the renovation planning information necessary to identify occupant interactions.

There are several requirements for the representation of renovation planning information. The formalization of occupant locations must be at the space level. The formalization of organization information must be generic enough to represent different occupant work schedules (i.e., day, night, weekend) and their space sharing abilities (i.e., “can share” or “cannot share”). The formalization of process information must support a method to track tenants based on tenant move activities and represent construction activities at the workshift level.

A formal representation of how tenants and crews interact is also necessary. The representation of occupant interactions must be generic enough to represent different types of interactions, but specific enough to distinguish among tolerable or disruptive interactions. This representation must include and distinguish between tenants and crews because the management approach (e.g., notifying tenants of nighttime crew work) to resolve the interaction may depend on whether the interaction involves tenants, crews, or both types of occupants.

I build on and extend existing representations of spaces, occupants, and renovation activities. For our purpose, prior research in representing spatial models (International Alliance for Interoperability 2000) is sufficient to describe the building spaces. There are several limitations, however, regarding the representation of occupants and renovation activities. Prior research in occupant modeling (Akinci et al. 2002b; Clevenger and Haymaker 2006; Jin and Levitt 1996) can represent occupant work schedules and locations, but do not represent an occupant’s space sharing ability as an attribute of the occupant. Prior representations consider an occupant’s space sharing ability as an attribute of the space. This limitation requires additional spaces to be modeled to correctly represent changes in an occupant’s space sharing ability. This is not efficient or manageable for project planners. Prior research in activity modeling (Akinci et al. 2002a; Darwiche et al. 1989) can represent an activity linked to a single space and occupant. The formalization, however, does not represent construction activities at the workshift level or allow a crew’s space sharing ability to change without modeling additional spaces and activities. Darwiche et al.’s activity formalization also does not represent the relationship between start and end locations of a tenant move and forces the project planners to model twice as many activities to represent both the start (i.e., move-out) and end (i.e., move-in) locations for a tenant move. Prior work in classifying occupant interactions (Akinci et al. 2002c) formalizes different types of crew-crew interactions, but does not represent tenants in these interactions.

To answer the first research question, this thesis formalizes a renovation planning ontology that represents: an occupant's work schedule and space sharing ability as an attribute of an occupant (i.e., occupant profile), a tenant move as a single activity and a construction activity at the workshift level of detail (i.e., renovation activity ontology), and a formalization of the different ways occupants interact (i.e., occupant interaction ontology). The formalization of an occupant profile and construction activity at the workshift level supports a simpler, non-geometric method to update occupant space sharing abilities without modeling additional occupants, spaces, or activities. The renovation activity ontology enables renovation planners to relate the start and end locations of a tenant move activity to update building configurations. The formalization of an occupant interaction ontology distinguishes four types of tolerable and disruptive interactions based on the type of occupant (i.e., tenant or crew) and their space sharing abilities.

What *reasoning methods* can utilize the above formalization to *identify occupant interactions automatically*?

The second question addresses the need to develop methods that enable a thorough, detailed, and accurate identification of occupant interactions. A thorough analysis requires a method to update occupant location data so that each unique building configuration can be analyzed. A detailed analysis requires a method to update occupant space sharing abilities at the workshift level. An accurate analysis requires a method to accommodate many different project-specific instances of tenants and crews interacting to identify each space-specific occupant interaction. These methods also need to be representationally efficient so that project planners can feasibly manage spatial, organization, and process data.

I build and extend on existing methods in reasoning about process and organizational models and space sharing identification methods. Existing 4D-modeling methods integrate product and process models (Darwiche et al. 1989), but these methods are not sufficient to update building configurations because there are no methods that relate tenant move-out and move-in activities. Prior research in reasoning about occupants is not sufficient to update occupant space sharing abilities at the workshift level without modeling additional spaces and activities. Existing approaches to identify shared spaces utilize geometric methods to identify intersections between spaces to determine if crews are interacting (Akinci et al. 2002c). For renovation projects, this is representationally inefficient because it would require additional occupants, spaces, and activities to be modeled to sufficiently represent multiple occupants in a space and each occupant's changing space sharing ability. Prior research in automating design and construction planning tasks have shown that heuristic classification is beneficial in relating project-specific data to a pre-defined set of solutions (Clancy 1985; Kim 2006). Since there are only a few ways in which tenants and crews interact, heuristic classification provides a simple and straightforward approach to identify different types of occupant interactions by abstracting project-specific information on the types of occupants and their space sharing abilities for each space.

To answer the second research question, this thesis develops three methods which correspond to the formalizations developed in the first research question. First, I develop a method to update occupant locations based on the renovation activity ontology. This method enables every unique building configuration to be analyzed. Second, I utilize the formalization of an occupant profile to develop a method to update occupant space sharing abilities. This method allows these abilities to be updated for each workshift without having to re-model each space, making the IOI method representationally more efficient that existing methods. Finally, I utilize the occupant interaction ontology to develop a space-sharing identification method using heuristic classification. Since the method uses non-geometric information (i.e., type of occupant and their space sharing abilities) to identify interactions, it is more representationally efficient than existing model-based methods.

5. Research methods

To answer these questions, I used a combination of research methods throughout this research. Since my points of departure and research questions identified the need to develop a computer-interpretable method that can utilize project-specific data, it was necessary for me to develop a computer prototype and validate the method on real renovation projects. I followed the "CIFE horseshoe method" (Kunz and Fischer 2008) to guide the overall direction of my research (Figure 2). Although the description below follows the CIFE horseshoe, the development of my research followed a non-linear approach, as I often cycled through the CIFE horseshoe, jumping to different parts of the horseshoe as necessary, following the "highest anxiety principle" (Kunz 1989). In addition to the CIFE horseshoe method, I used four different research methods throughout this research: active participation, synthetic experiments, computational modeling, and prospective validation.

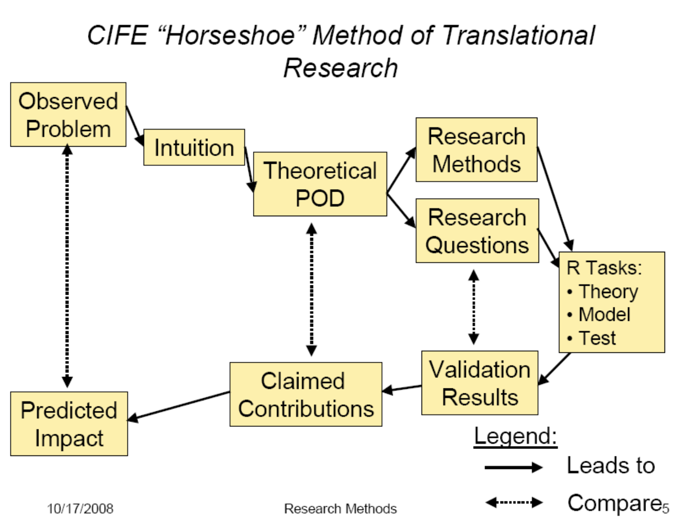


Figure 2. CIFE Horseshoe Method

I first observed that project planners had difficulties analyzing the spatial and temporal relationships among occupant locations, the renovation schedule, and occupant space sharing abilities. I actively participated in several renovation projects by building 4D models and used these models to interact with project teams to identify the necessary renovation planning information and their relationships. Active participation allowed me to understand the needs of the project planners, the use of traditional and 4D-model-based renovation planning methods, and the limitations of these methods. Based on my observations, I developed an intuition that an automated method could be developed to identify occupant interactions more thoroughly, in greater detail, and more accurately and how such a method could be used in the context of a renovation project.

Based on my intuition, I conducted a literature review in the areas of renovation planning methods, occupant modeling, activity modeling, and space sharing identification methods. The result of the literature review identified the theoretical gaps in knowledge which prevented the development of an automated method and provided the basis for my research questions and subsequent research methods.

I then used a combination of synthetic experiments and computational modeling (Thomsen et al. 1999) to formalize the renovation planning information and develop the IOI method. I developed a simple six-space test case to test various representations and reasoning methods. From these experiments, I ultimately developed the IOI method and implemented the method in a computational model, called 4DRenCheck, using Microsoft Access (Microsoft 2007).

After developing the IOI method, I used prospective validation to validate my research on three renovation projects in their planning stages. The renovation projects were chosen to determine the power and generality of the method. Each project provided different characteristics that covered a variety of scopes, sequencing of activities, mix of renovation activities, and mix of tenants and crews. The purpose of the validation was to determine whether the IOI method could identify occupant interactions more thoroughly, in greater detail, and more accurately than traditional methods. I also wanted to determine if the method could be applied in a reasonable timeframe to impact future project decisions. Prospective validation, where a new method is implemented in parallel with an existing method and the results analyzed within a timeframe for interventions, allowed me to test the power of the IOI method. Based on the insights from implementing prospective validation, this thesis also presents a six-criterion framework to evaluate whether prospective validation is an appropriate validation method for researchers to use and provides prospective validation implementation guidelines for researchers.

The validation results demonstrate that the IOI method is more detailed, thorough, and accurate in identifying occupant interactions than traditional methods. The planned and actual interventions by project planners also demonstrate the power of the method on real projects. The ability to provide thorough and detailed occupant location and space sharing information using an automated method not only allows project planners to address project challenges related to identify occupant interactions, but has the potential to support additional renovation analyses (e.g., workforce tracking, rent billing, tenant negotiations). Based on the evidence of power and generality, I claim that the IOI method is a contribution to the areas of renovation planning as a whole, and specifically to occupant modeling, activity modeling, and space sharing identification methods, which are the critical points of departure for my research.

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.

6. Reader's guide to the thesis

The remainder of this thesis is divided into three chapters that describe different aspects of my research. This thesis follows a three paper-format, where the reader can read each chapter independently. As a result, there is some repeated information among the remaining chapters.

Chapter 2 motivates the need for an automated way to track occupants and identify occupant interactions. Based on project data from seven renovation projects that I participated in, this chapter describes the characteristics of renovations of occupied buildings and the use of traditional renovation planning methods and 4D models to identify occupant interactions. Based on these insights, I propose that an automated method is necessary to identify occupant interactions and identify the requirements for such a method. This chapter also discusses the relevant points of departure in the areas of renovation planning methods, occupant modeling, activity modeling, and space sharing identification methods and identifies the theoretical limitations of existing concepts and methods. *Chapter 3* details the IOI method which addresses the limitations described in the previous chapter. This chapter describes the formalization of an occupant profile, a renovation activity ontology, and an occupant interaction ontology. It also describes the reasoning methods to update occupant locations, update occupant space sharing abilities, and identify occupant interactions automatically. It then discusses how I validated my method on three renovation projects in their planning stages using a computer prototype, 4DRenCheck, and discusses the limitations of the IOI method. *Chapter 4* examines the use of prospective validation to test new virtual design and construction (VDC) methods. Since prospective validation is an emerging validation method in the VDC domain, there are few guidelines on why and how it should be implemented. This chapter provides a framework, application, and implementation guidelines of the use prospective validation. First, I provide a six-criterion framework that VDC researchers can use to evaluate whether prospective validation is appropriate, based on the purpose of their validation. Then, I present an application of prospective validation to test the power of the IOI method and demonstrate how the validation method provides strong evidence of the power of the IOI method. Finally, based on the lessons learned from this application and a review of prior related implementation guidelines, I present a set of implementation guidelines regarding the planning, execution, and analysis of a prospective validation test.

7. References

Akinci, B., Fischer, M., and Kunz, J. (2002a). "Automated Generation of Work Spaces Required by Construction Activities." *Journal of Construction Engineering and Management*, 128(4), 306-315.

Akinci, B., Fischer, M., Kunz, J., and Levitt, R. (2002b). "Representing Work Spaces Generically in Construction Method Models." *Journal of Construction Engineering and Management*, 128(4), 296-305.

Akinci, B., Fischer, M., Levitt, R., and Carlson, R. (2002c). "Formalization and Automation of Time-Space Conflict Analysis." *Journal of Computing in Civil Engineering*, 6(2), 124-135.

Attalla, M. (1999). "Reconstruction of Operating Facilities, A model for Project Management," Ph.D. Thesis, University of Waterloo, Waterloo.

Clancy, W. J. (1985). "Heuristic Classification." *Report Number STAN-CS-85*, Stanford University, Palo Alto.

Clevenger, C., and Haymaker, J. (2006). "The Impact of the Operant on Building Energy Simulations." Joint International Conference on Computing and Decision Making in Civil and Building Engineering, ISCCBE & ASCE, Montreal, Canada, 3637-3646.

Darwiche, A., Levitt, R., and Hayes-Roth, B. (1989). "OARPLAN: Generating Project Plans by Reasoning about Objects, Actions and Resources." *AI EDAM*, 2(3), 161-181.

Department of the Treasury. (2005). "TBARR: Cost of Employee Move Delays During Main Treasury Building Renovation Could Not Be Determined." Department of the Treasury, ed., Washington.

Douglas, J. (2006). *Building Adaptation*, Butterworth-Heinemann, Burlington, MA.

Egbu, C. O. (1999). "Skills, knowledge and competencies for managing construction refurbishment works." *Construction Management and Economics*, 17(1), 29-43.

Fawcett, W., and Palmer, J. (2004). "Good Practice Guidance for Refurbishing Occupied Buildings." *Report Number C621*, CIRIA, London.

GSA. (2009). "GSA Plans for Recovery Act Funding Increase." Washington DC.

Haddad, S., and Attalla, M. (2002). "Cost Overrun in Reconstruction/Rehabilitation of Institutional Community Centers." Annual Conference of the Canadian Society for Civil Engineering, Montreal.

International Alliance for Interoperability. (2000). "IFC Technical Guide."

Jin, Y., and Levitt, R. (1996). "The Virtual Design Team: A Computations Model of Project Organizations." *Computational and Mathematical Organization Theory*, 2(3), 171-195.

Kim, J. (2006). "Temporary Structure Planning Ontology," Stanford University, Stanford, CA.

Kunz, J. (1989). "Concurrent Knowledge Systems Engineering." *CIFE Working Paper #5*, Stanford University, Stanford.

Kunz, J., and Fischer, M. (2008). "CIFE Research Questions and Methods." CEE 320 Presentation, 17 October 2008, Stanford University, Stanford.

Mansfield, J. (2002). "What's in a name? Complexities in the definition of "refurbishment"." *Property Management*, 20(1), 23-30.

Microsoft. (2007). "Microsoft Office Access 2007." Microsoft Office, Redmond.

Sanvido, V. E., and Riggs, L. S. (1991). "Managing Retrofit Projects." *Technical Report #25*, University of Texas at Austin.

Shami, M., and Kanafani, A. (1997). "Coping with Construction at Operational Airports: SFIA Case Study." *Journal of Transportation Engineering*, 123(6), 417-428.

Thomsen, J., Levitt, R., Kunz, J., Nass, C., and Fridsma, D. (1999). "A Trajectory for Validating Computational Emulation Models of Organizations." *Journal of Computational & Mathematical Organization Theory*, 5(4), 385-401.

Whiteman, W., and Irwig, H. (1988). "Disturbance Scheduling Technique for Managing Renovation Work." *Journal of Construction Engineering and Management*, 114(2), 119-213.

CHAPTER 2

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

Peggy Ho[1], Martin Fischer[2]

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.

[1] Center for Integrated Facility Engineering, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, peggyhho@stanford.edu

[2] Professor, Department of Civil and Environmental Engineering, Director, Center for Integrated Facility Engineering, Stanford University, Stanford, CA 94305, fischer@stanford.edu

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.

[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).

- 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.

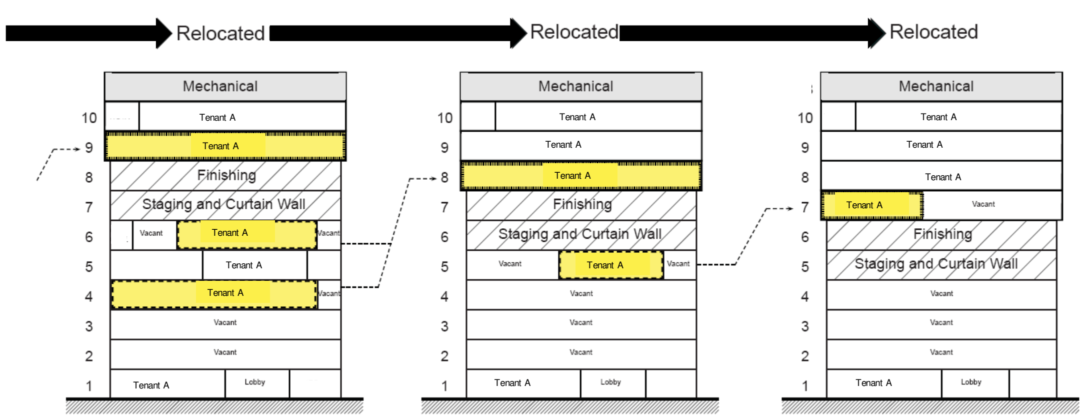


Figure 2. Renovation sequencing plan from Project 6 (modified to remove identifying information)

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.

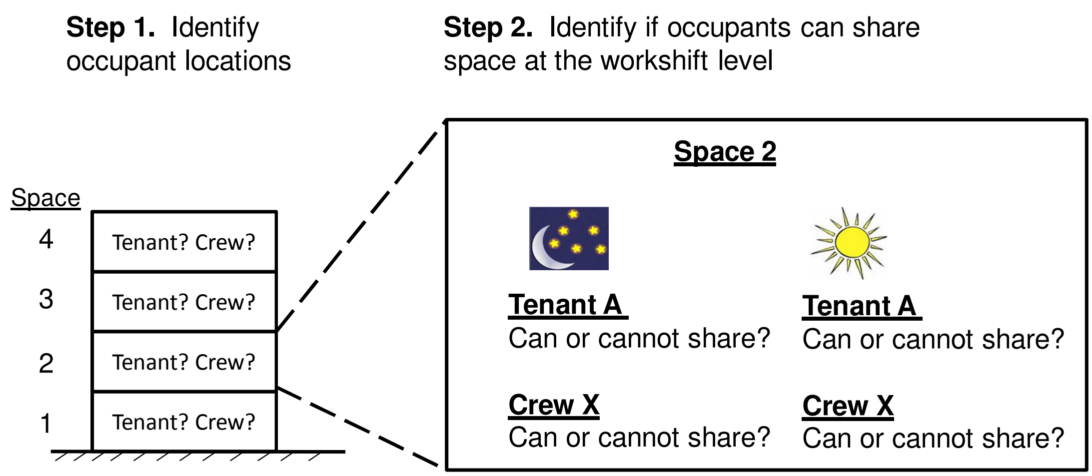


Figure 3. Identification of occupant interactions requires integration of spatial (e.g., Space 1, 2, 3, 4), organizational (e.g., Tenant A, Crew X), and temporal (e.g., nighttime and daytime workshifts) information**.**

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.

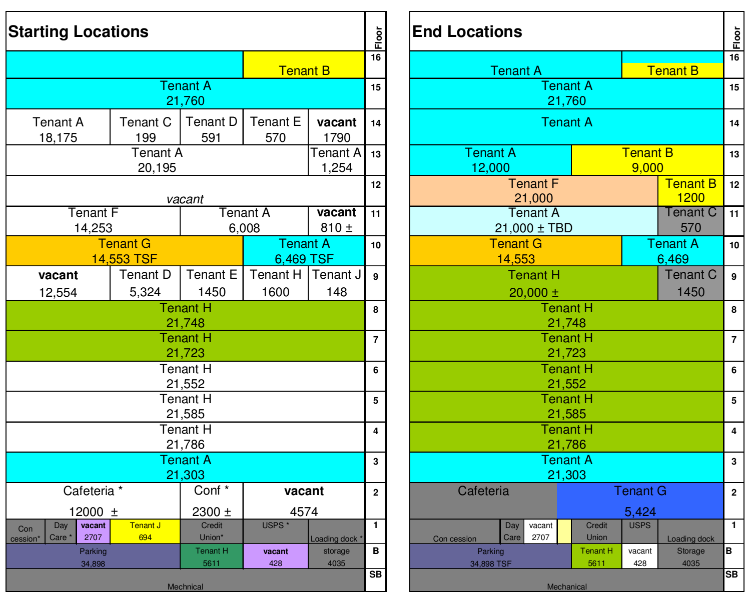


Figure 4. Start and end locations of tenants for Project 3

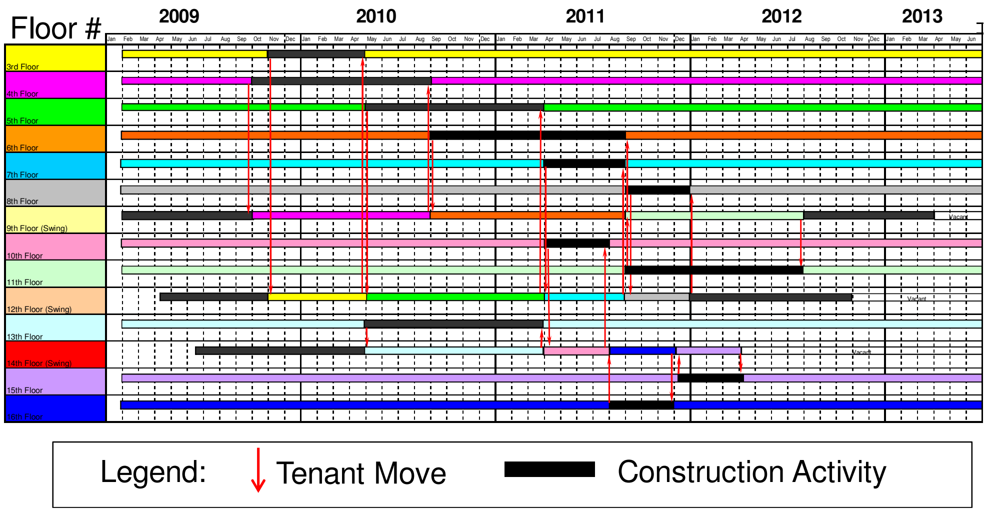


Figure 5. Excel spreadsheet of renovation activities by floor for Project 3

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.

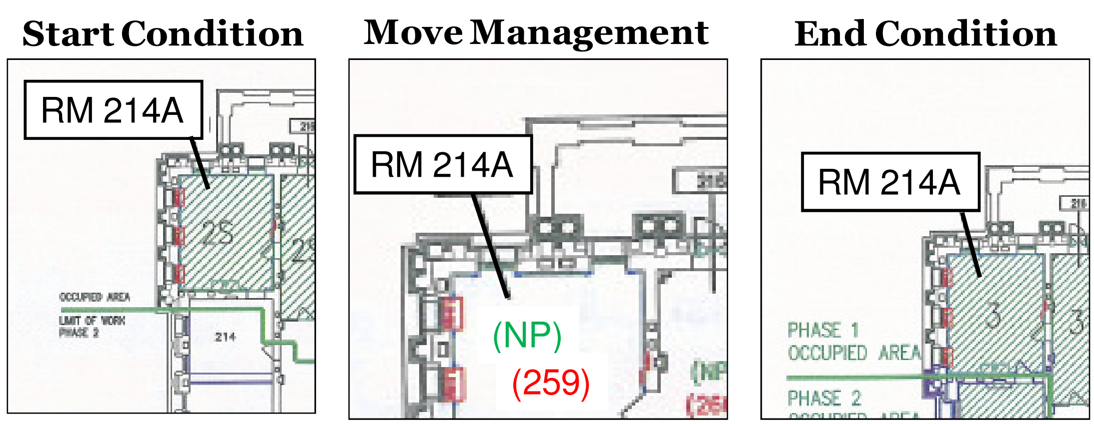


Figure 6. Three sets of 2D CAD documents for Project 1 were used to manage tenant move activities. The documents were inconsistent; the starting conditions and the move management information did not result in the same locations shown on the end condition drawings.

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.

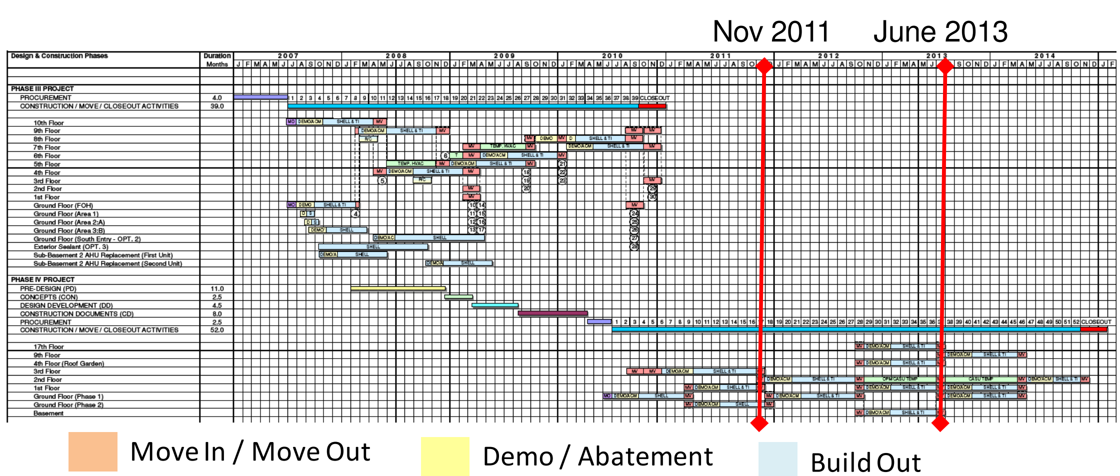
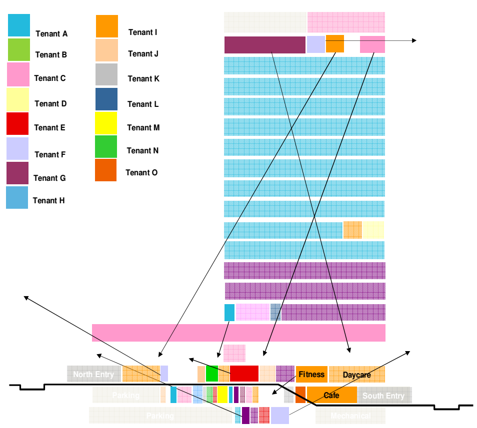


Figure 7. Renovation schedule for an office building renovation. The bold vertical lines correspond to the building configurations shown in Figure 8.



November 2011 **June 2013**

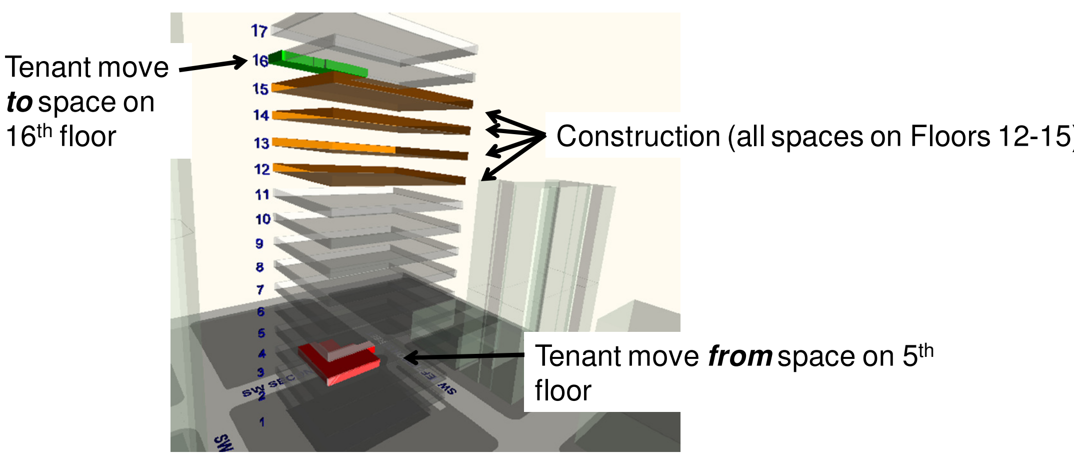
Figure 8. Building configurations corresponding to vertical lines in Figure 7 show where tenants are during the renovation. The arrows indicate tenant moves. While the names and locations of tenants are detailed, the timing of the moves is not indicated, making it necessary for project planners to synthesize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

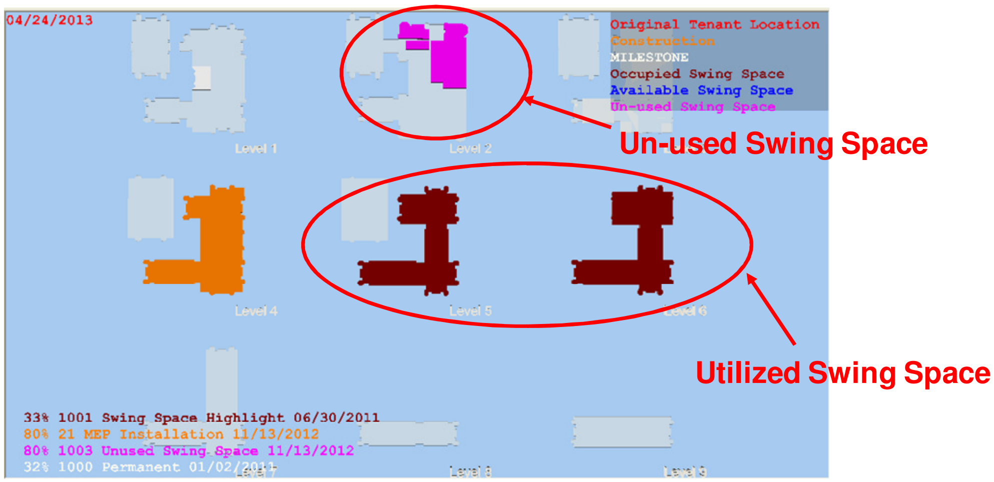


Figure 10. Use of 4D model on Project 6 to visualize vacant space over time

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.

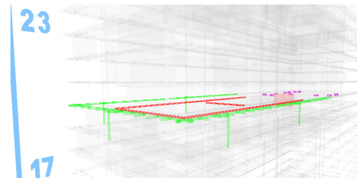
- The identification of occupant interactions is still manual. The models only show changes in occupant locations, but do not show the complete updated building configurations. For example, in Figure 9, the project planner was not able to see whether a tenant was already occupying a space since non-moving 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.

[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.

Daytime Installation of Condensate Piping on 19th Floor

19th Floor	**320 days**	**Wed 12/19/07**	**Mon 3/9/09**
19-Install FA Risers & Panels	3 days	Wed 12/19/07	Fri 12/21/07
19-Move 19th Floor Tenants to Swing Space - Start	6 days	Mon 12/22/08	Mon 12/29/08
19-Move 19th Floor Tenants to Swing Space - End	6 days	Mon 12/22/08	Mon 12/29/08
19-Demo & Abatement - North	16 days	Fri 12/26/08	Fri 1/16/09
19-Install FA Branch Conduit, Pull FA Wire, Install FA Devices - I	14 days	Mon 1/19/09	Thu 2/5/09
19-Replace VAVs - North	11 days	Mon 1/19/09	Mon 2/2/09
19-Toilet Renovations - North	24 days	Mon 1/19/09	Thu 2/19/09
19-Install Condensate Piping - North	10 days	Mon 1/19/09	Fri 1/30/09
19-Patch & Paint Columns - North	5 days	Mon 2/2/09	Fri 2/6/09
19-Replace PIUs - North	12 days	Mon 1/19/09	Tue 2/3/09



Nighttime Installation of Condensate Piping on 16th Floor

16th Floor	**570 days**	**Wed 1/31/07**	**Tue 3/17/09**
16-Install FA Risers & Panels	3 days	Thu 12/6/07	Mon 12/10/07
16-Install FA Branch Conduit, Pull FA Wire, Install FA Devices	22 days	Wed 1/31/07	Thu 3/1/07
16-Demolition of Columns - North	1 day	Sat 10/6/07	Sun 10/7/07
16-Install Condensate Piping Risers - North	11 days	Mon 10/8/07	Fri 10/19/07
16-Replace PIUs - North	12 days	Thu 2/12/09	Fri 2/27/09
16-Demolition of Columns - South	1 day	Sat 10/13/07	Sun 10/14/07
16-Install Condensate Piping Risers - South	10 days	Mon 10/22/07	Fri 11/2/07
16-Replace PIUs - South	12 days	Mon 3/2/09	Tue 3/17/09

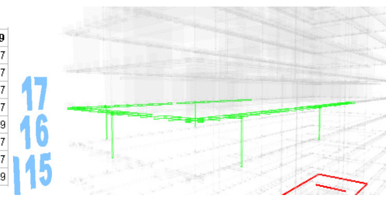


Figure 11. The 4D model of the condensate piping activity does not allow project managers to distinguish the impact of construction workshifts on tenants.

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 / **Link start and end spaces**	**Construction activity** / **Crew space sharing abilities at workshift LOD**	**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**
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

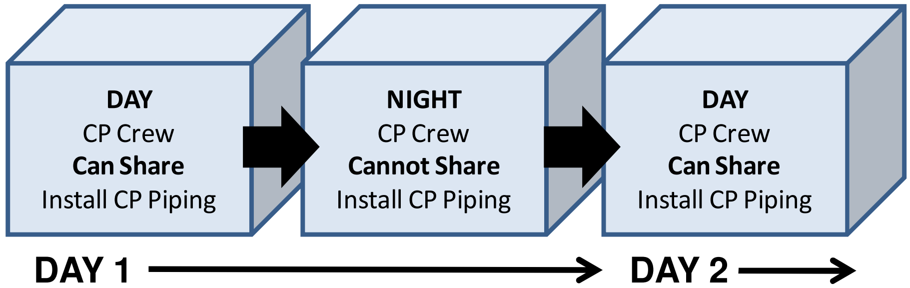


Figure 12. For a condensate piping (CP) activity, additional activities and spaces would need to be added to distinguish the space sharing abilities in active and idle workshifts.

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

Aalami, F. (1998). "Using Method Models to Generate 4D Production Models," Ph.D. Thesis, Stanford University, Stanford, CA.

Akbas, R. (2004). "Geometry-based Modeling and Simulation of Construction Processes," Ph.D. Thesis, Stanford University, Stanford, CA.

Akinci, B., Fischer, M., and Kunz, J. (2002a). "Automated Generation of Work Spaces Required by Construction Activities." *Journal of Construction Engineering and Management*, 128(4), 306-315.

Akinci, B., Fischer, M., Kunz, J., and Levitt, R. (2002b). "Representing Work Spaces Generically in Construction Method Models." *Journal of Construction Engineering and Management*, 128(4), 296-305.

Akinci, B., Fischer, M., Levitt, R., and Carlson, R. (2002c). "Formalization and Automation of Time-Space Conflict Analysis." *Journal of Computing in Civil Engineering*, 6(2), 124-135.

Ali, M. S. A. D., Babu, R., and Varghese, K. (2005). "Collision Free Path Planning of Cooperative Crane Manipulators Using Genetic Algorithm." *Journal of Computing in Civil Engineering*, 19(2), 182-193.

Boukamp, F., and Akinci, B. (2007). "Automated processing of construction specifications to support inspection and quality control." *Automation in Construction*, 17(1), 90-106.

Carley, K. (1995). "Computational and Mathematical Organization Theory: Perspective and Directions." *Computational and Mathematical Organization Theory*, 1(1), 39-56.

Clancy, W. J. (1985). "Heuristic Classification." *Report Number STAN-CS-85*, Stanford University, Palo Alto.

Clevenger, C., and Haymaker, J. (2006). "The Impact of the Operant on Building Energy Simulations." Joint International Conference on Computing and Decision Making in Civil and Building Engineering, ISCCBE & ASCE, Montreal, Canada, 3637-3646.

Collier, E., and Fischer, M. "Visual based scheduling: 4D modelling on the San Mateo County Health Centre." *3rd ASCE Congress on Computing in Civil Engineering*, Anaheim, CA, 800-805.

Darwiche, A., Levitt, R., and Hayes-Roth, B. (1989). "OARPLAN: Generating Project Plans by Reasoning about Objects, Actions and Resources." *AI EDAM*, 2(3), 161-181.

Douglas, J. (2006). *Building Adaptation*, Butterworth-Heinemann, Burlington, MA.

Fawcett, W., and Palmer, J. (2004). "Good Practice Guidance for Refurbishing Occupied Buildings." *Report Number C621*, CIRIA, London.

Fiedler, K. (1987). "Special conditions for time scheduling of building modernization process." *Project Management*, 5(1), 35-38.

Greenberg, L. (2000). "A Clinician's Guide to Construction/Renovation Project Success." *Herman Miller for Healthcare*, Herman Miller, 6.

Hassanain, M. A., and Al-Mudhei, A. (2006). "Business continuity during facility renovations." *Journal of Corporate Real Estate*, 8(2), 62-72.

Heesom, D., and Mahdjoubi, L. (2004). "Trends of 4D CAD applications for construction planning." *Construction Management and Economics*, 22, 171-182.

Hoes, P., Hensen, J., Loomans, M., De Vries, B., and Bourgeois, D. (2009). "User Behaviour in Whole Building Simulation." *Energy and Buildings*, 41(3), 295-302.

Holm, M. (2000). "Service management in housing refurbishment: a theoretical approach." *Construction Management and Economics*, 18(5), 525-533.

International Alliance for Interoperability. (2000). "IFC Technical Guide."

Jin, Y., and Levitt, R. (1996). "The Virtual Design Team: A Computations Model of Project Organizations." *Computational and Mathematical Organization Theory*, 2(3), 171-195.

Jongeling, R., Kim, J., Mourgues, C., Fischer, M., and Olofsson, T. (2005). "Quantitative Analyses using 4D Models - An Explorative Study." 1st International Conference on Construction and Engineering Management, C. Park, ed., KICEM Korea Institute of Construction Engineering and Management, Seoul, Korea, 830-835.

Jongeling, R., and Olofsson, T. (2006). "A method for planning of work-flow by combined use of location-based scheduling and 4D CAD." *Automation in Construction*, 16(2), 189-198.

Kim, J. (2006). "Temporary Structure Planning Ontology," Stanford University, Stanford, CA.

Koo, B., and Fischer, M. (2000). "Feasibility study of 4D CAD in commercial construction." *Journal of Construction Engineering and Management*, 126(4), 251-260.

Mansfield, J. (2002). "What's in a name? Complexities in the definition of "refurbishment"." *Property Management*, 20(1), 23-30.

McKim, R., Hegazy, T., and Attalla, M. (2000). "Project Performance Control in Reconstruction Projects." *Journal of Construction Engineering and Management*, 126(2), 137-141.

Messner, J. I., and Lynch, T. "A Construction Simulation Model for Production Planning at the Pentagon Renovation Project." *International Workshop on Information Technology in Civil Engineering 2002*, November 2-3, 2002, Washington, D.C.,USA.

National Institute of Building Sciences. (2007). "United States National Building Information Modeling Standard." Facilities Information Council, ed., National Institute of Building Sciences, Washington, DC, 183 pages.

Pritscher, C. (1998). "Stealth renovation is key in occupied areas." *Facilities Design and Management*, 17(6), 34.

Shami, M., and Kanafani, A. (1997). "Coping with Construction at Operational Airports: SFIA Case Study." *Journal of Transportation Engineering*, 123(6), 417-428.

Stouffs, R., Krishnamurti, R., Lee, S., and Oppenheim, I. J. (1994). "Construction process simulation with rule-based robot path planning." *Automation in Construction*, 3, 79-86.

Sze, E., Kumaraswamy, M., Fung, A., Palaneeswaran, E., and Wong, S. (2004). "Partering with the tenants - Hong Kong experience." 20th Annual ARCOM

Conference, F. Khosrowshahi, ed., Association of Researchers in Construction Management, Heriot Watt University, 309-320.

U.S. General Services Administration. (2009a). "GSA Project Information Portal." Internal Website, Accessed 15 September, Washington DC.

U.S. General Services Administration. (2009b). "GSA Submits Economic Recovery Plans to Congress." Accessed 11 May, Washington DC.

Whiteman, W., and Irwig, H. (1988). "Disturbance Scheduling Technique for Managing Renovation Work." *Journal of Construction Engineering and Management*, 114(2), 119-213.

Yamaguchi, Y., Shimoda, Y., and Mizuno, M. (2003). "Development of District Energy System Simulation Model Based on Detailed Energy Demand Model." Eighth Annual IBPSA Conference, Building Simulation, Eindhoven, Netherlands, 1443-1450.

Yang, Q. (2003). "IFC-compliant design information modelling and sharing." *Journal of Information Technology in Construction*, 8, 1-14.

Zhang, C., Hammad, A., Zayed, T., and Wainer, G. (2005). "Representation and Analysis of Spatial Resources in Construction Simulation." 2005 Winter Simulation Conference, M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Jones, eds., IEEE, Orlando, FL, 1541-1548.

CHAPTER 3

AUTOMATED IDENTIFICATION OF OCCUPANT INTERACTIONS IN RENOVATIONS OF OCCUPIED BUILDINGS

Peggy Ho[1], Martin Fischer[2], John Haymaker[3]

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.

[1] Center for Integrated Facility Engineering, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, peggyhho@stanford.edu

[2] Professor, Department of Civil and Environmental Engineering, Director, Center for Integrated Facility Engineering, Stanford University, Stanford, CA 94305, fischer@stanford.edu

[3] Assistant Professor, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, haymaker@stanford.edu

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.

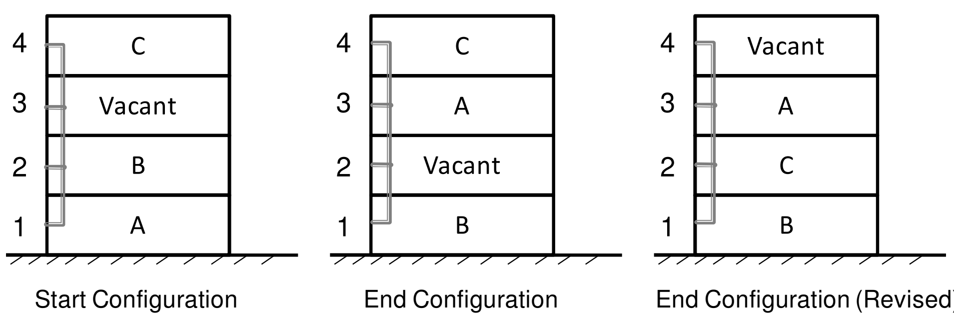
2. Motivating example

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.

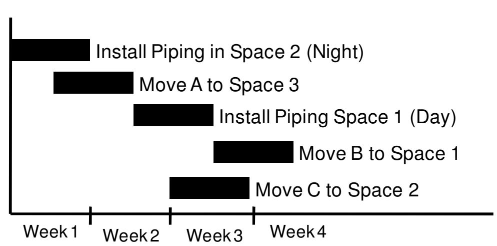
The motivating example depicts the renovation of a building which has four spaces (Space 1, 2, 3, and 4) and three tenants (Tenants A, B, and C). Figure 1-a shows the starting locations of the tenants. The scope of the renovation includes installing piping in Spaces 1 and 2 and moving tenants into different 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.

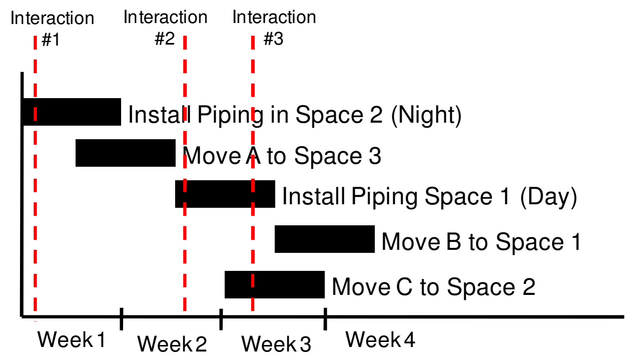


Figure 2. Occupant interactions in motivating example

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.

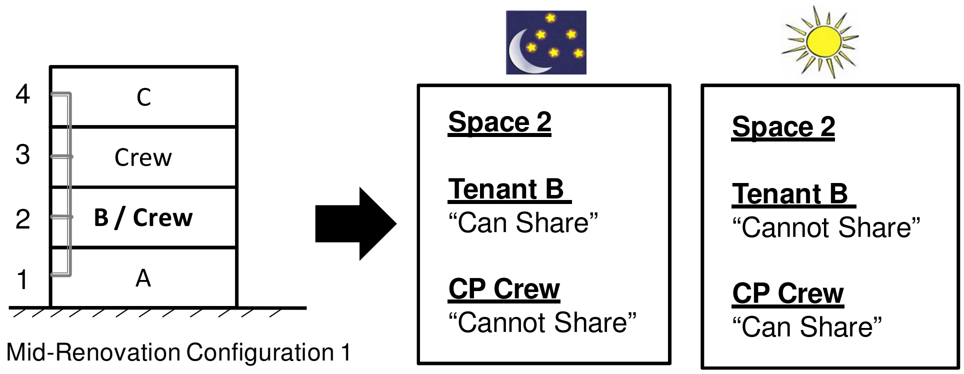


Figure 3. Locations of occupants and space sharing abilities for a minor tenant-crew interaction during day and night workshifts.

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.

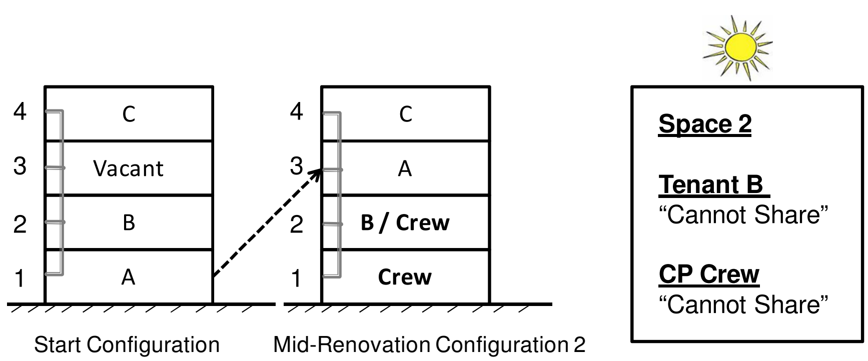


Figure 4. Locations of occupants and space sharing abilities for a major tenant-crew interaction during the dayshift

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).

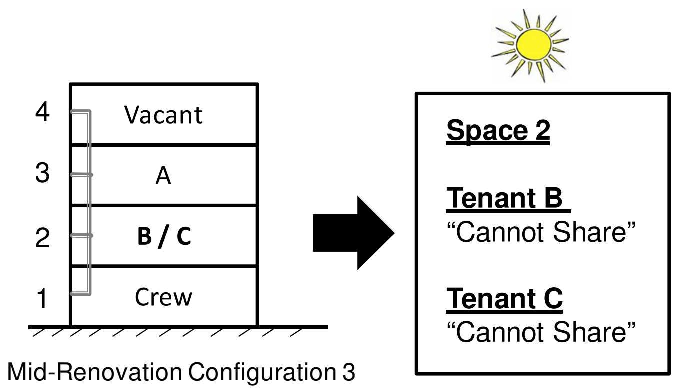


Figure 5. Locations of occupants and space sharing abilities for a tenant-tenant interaction during the dayshift

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.

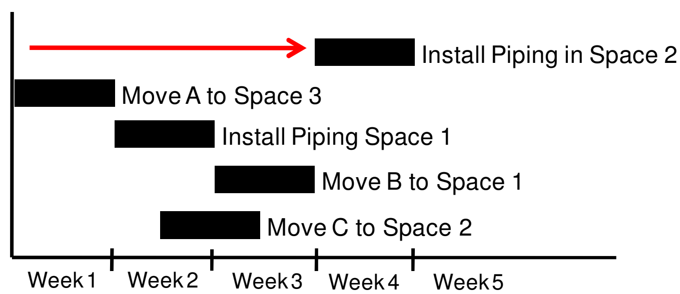


Figure 6. A lack of knowledge of space sharing at the workshift level would under-utilize space and extend the project schedule.

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

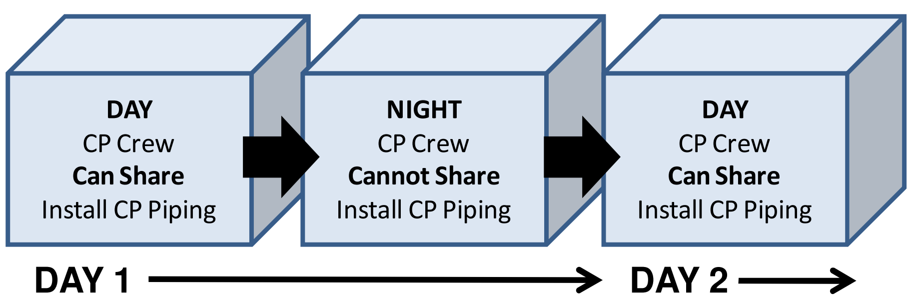


Figure 7. For a condensate piping (CP) activity, additional activities and spaces need to be added to distinguish the space sharing abilities in active and idle workshifts.

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.

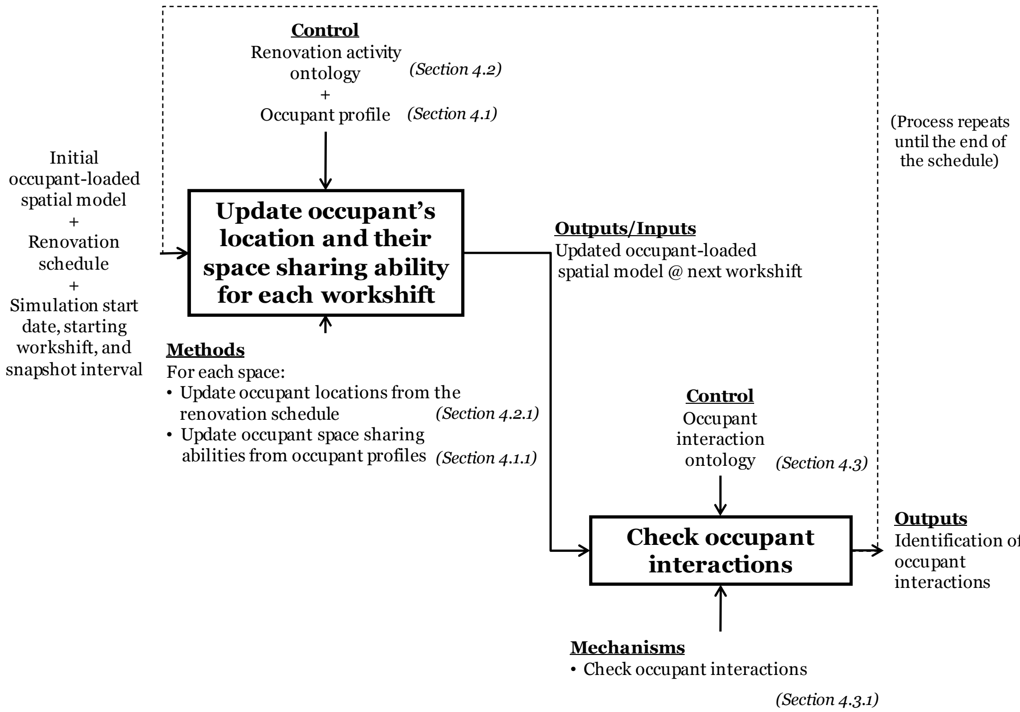


Figure 8. IDEF diagram of method to identify occupant interactions automatically

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.

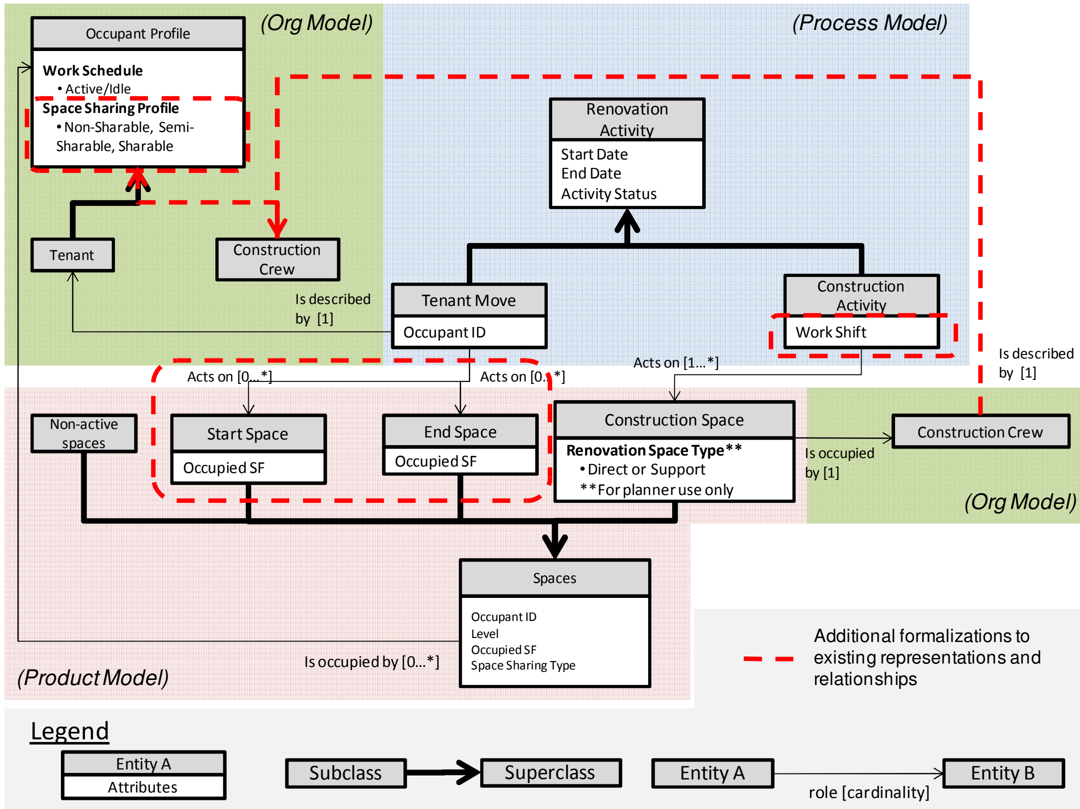
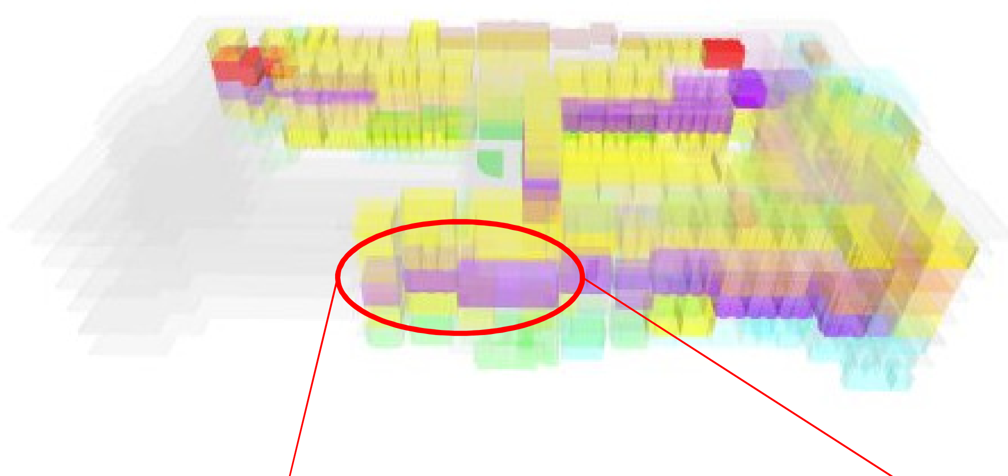


Figure 9. The occupant profile and renovation activity ontology formalize renovation planning information and integrate product, organization, and process models.

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 1).

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).

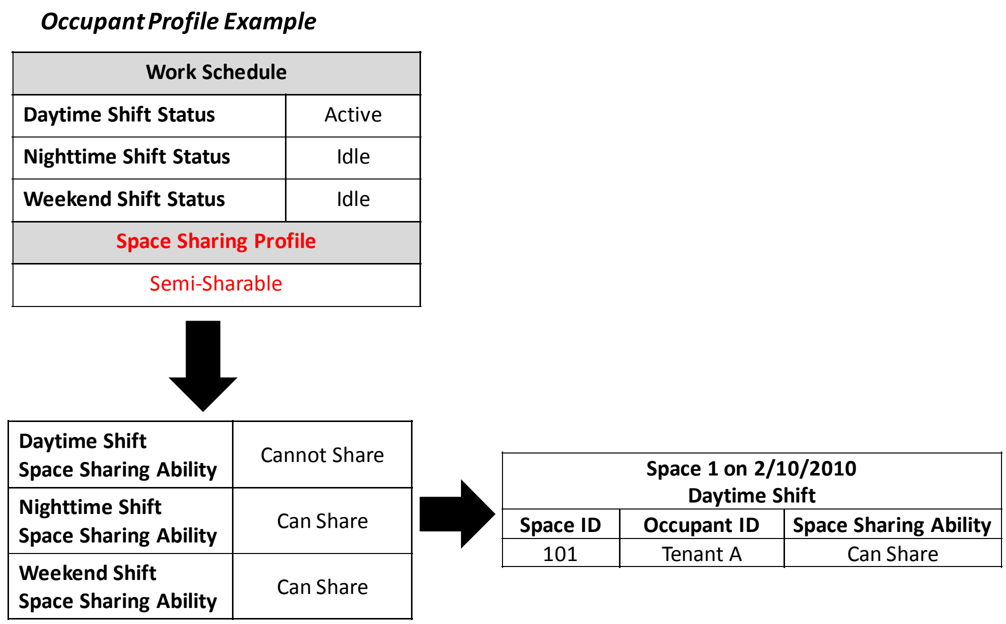


Figure 11. An occupant's profile is transformed to space-specific sharing abilities.

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:

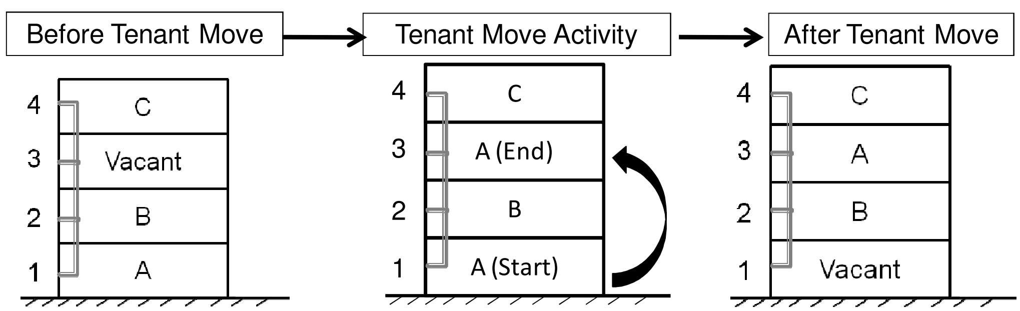


Figure 12. Example of a tenant move activity representation and resulting updates to an occupant-loaded spatial model

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)

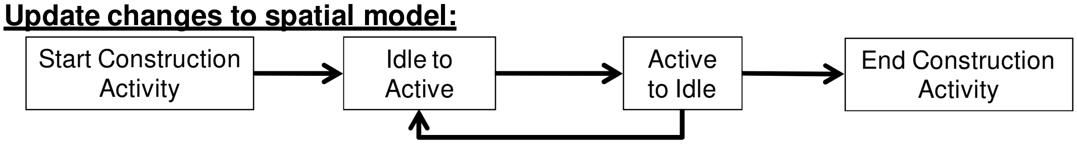
While the type of construction space (i.e., direct or support) is not directly used in the IOI method, it allows project planners to distinguish these types of spaces. Including the space sharing profile of the crew allows the IOI method to update the crew's space sharing ability for each workshift without 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.

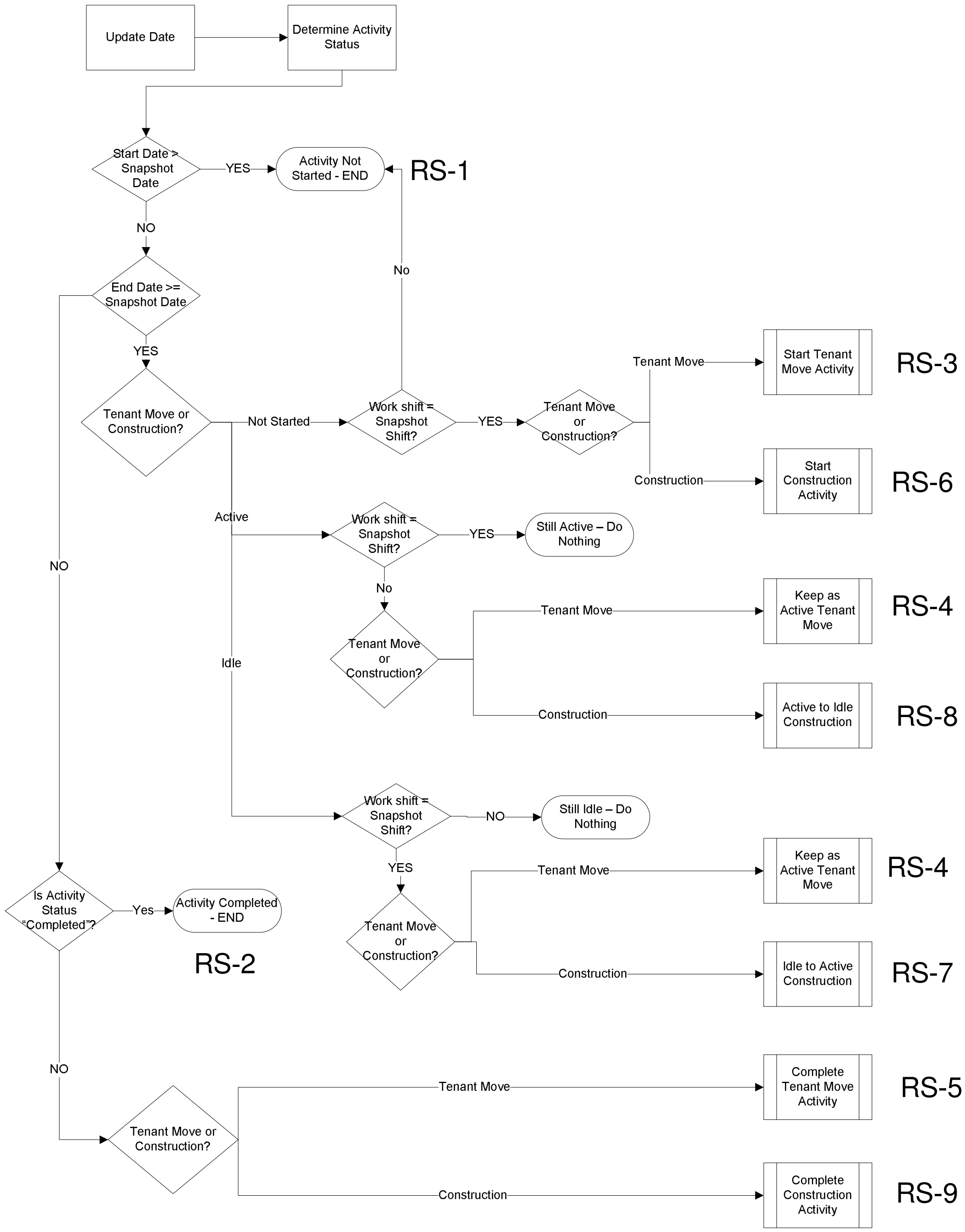


Figure 14. Flowchart describing reasoning method to determine activity status

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.

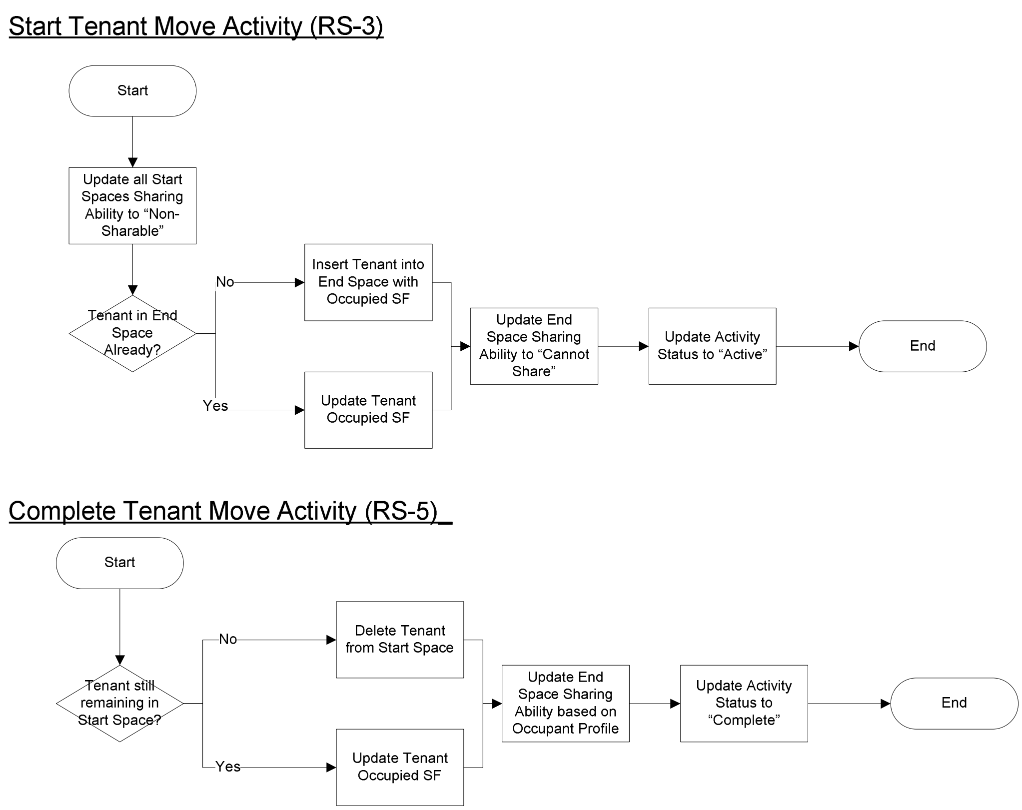


Figure 15. Flowcharts describing update scenarios from a tenant move activity

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.

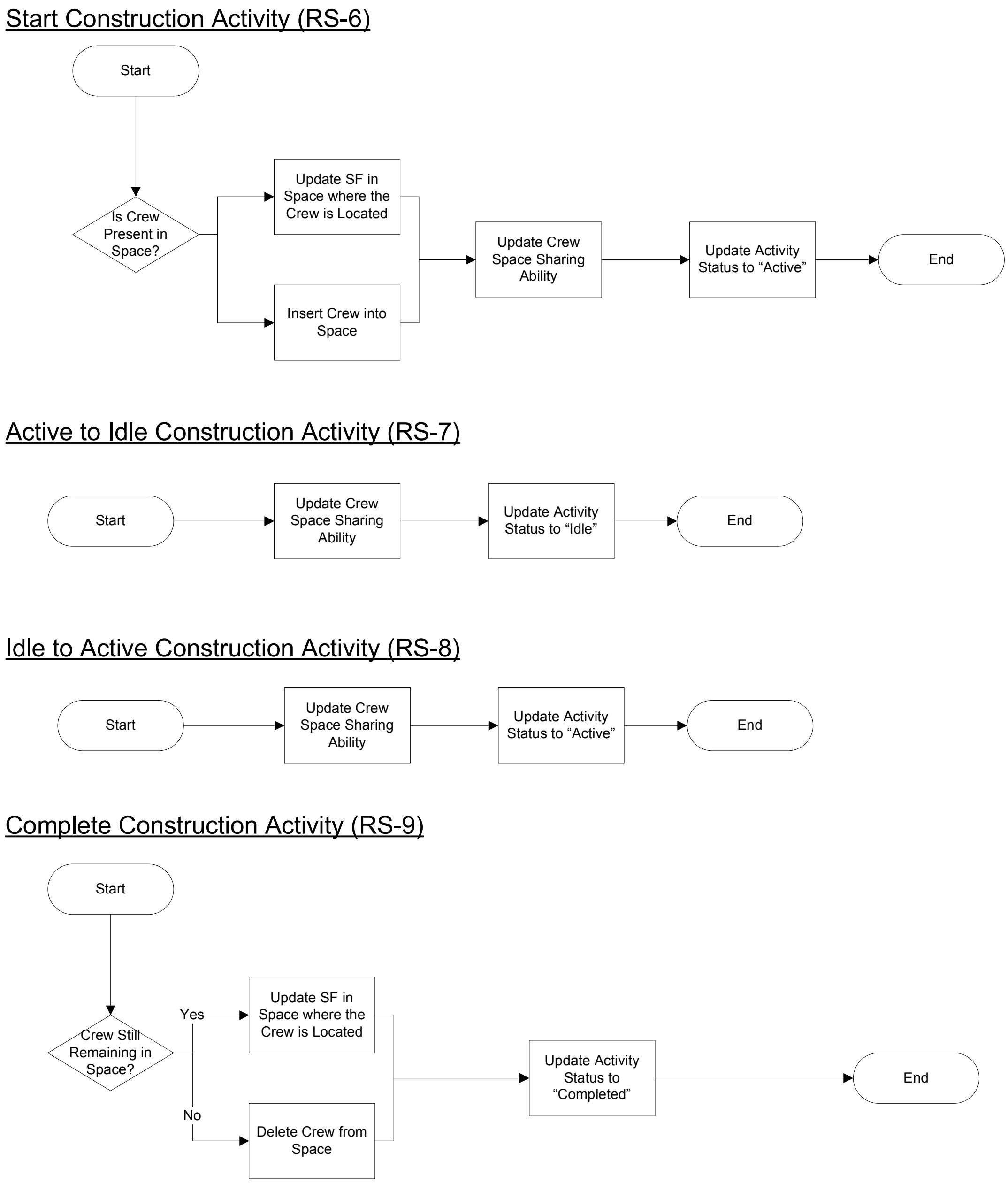


Figure 16. Flowcharts describing all update scenarios from a construction activity

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 2 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.

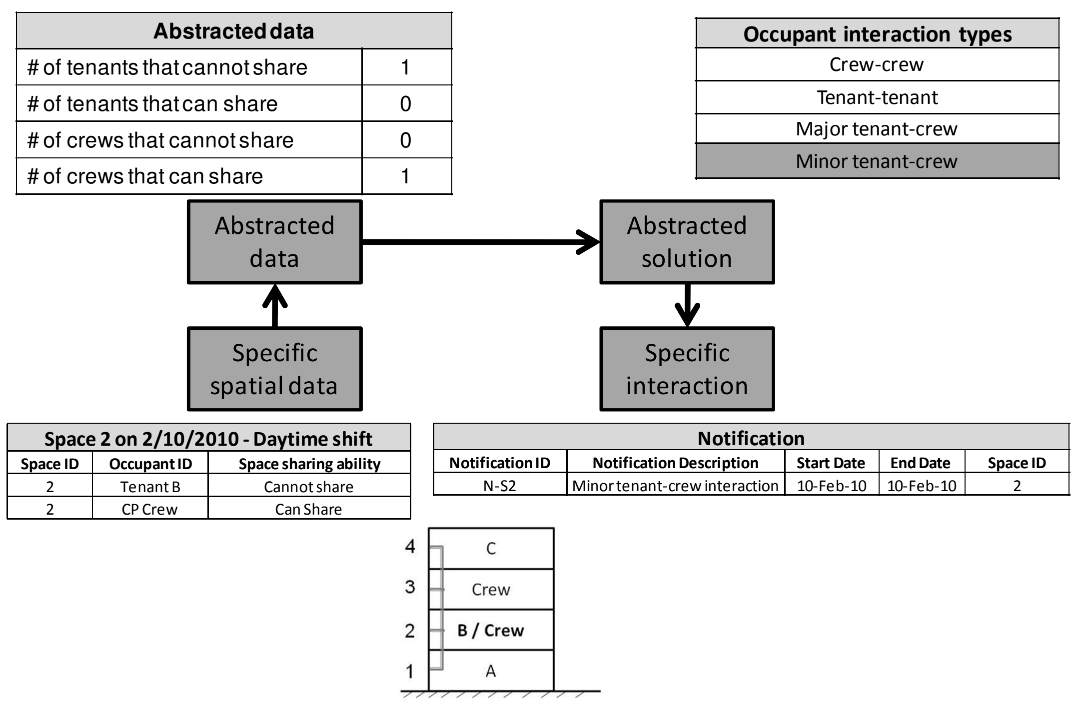


Figure 17. Heuristic classification process for identifying occupant interactions. The occupant-loaded spatial model indicates that a tenant and crew are assigned to the same space in the same workshift. The IOI method abstracts the data to determine that a minor tenant-crew interaction occurs in space 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 3 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

Section	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 3 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 4, traditional). We then showed them the results of the 4DRenCheck analysis and asked them to confirm whether the results were accurate (Table 4, 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 4, 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.

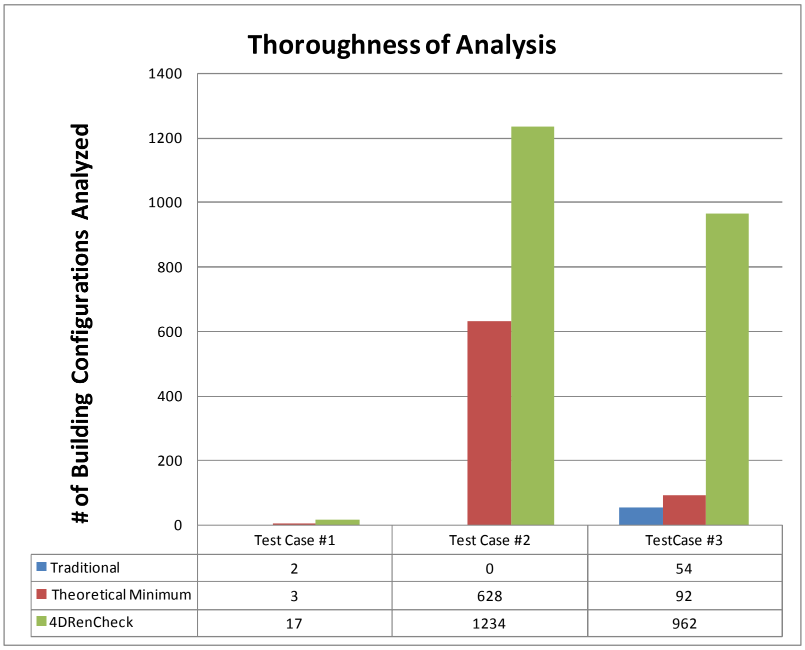


Figure 18. Comparison of thoroughness of identification of occupant interactions from traditional methods, 4DRenCheck, and the theoretical minimum

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

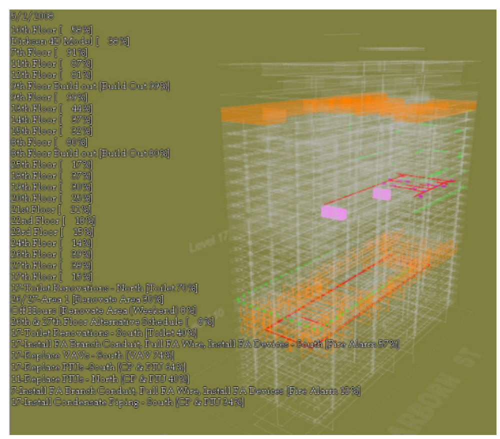
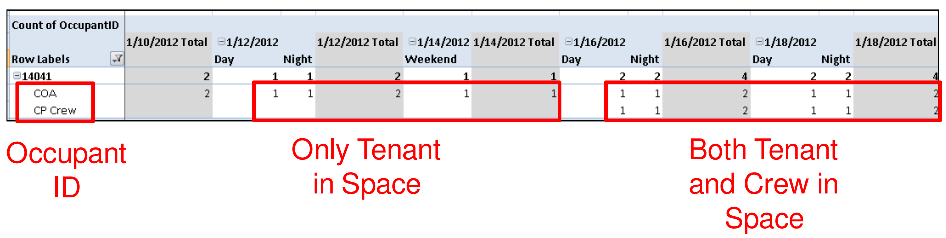


Figure 19. The traditional planning methods used on TC#2 included a Primavera schedule, day/night/weekend activities matrix, and 4D model

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.



Count of OccupantID												
Row Labels	1/10/2012 Total	1/12/2012 Day	Night	1/12/2012 Total	1/14/2012 Weekend	1/14/2012 Total	1/16/2012 Day	Night	1/16/2012 Total	1/18/2012 Day	Night	1/18/2012 Total
14041	2	1	1	2	1	1	2	2	4	2	2	4
COA	2	1	1	2	1	1	1	1	2	1	1	2
CP Crew							1	1	2	1	1	2

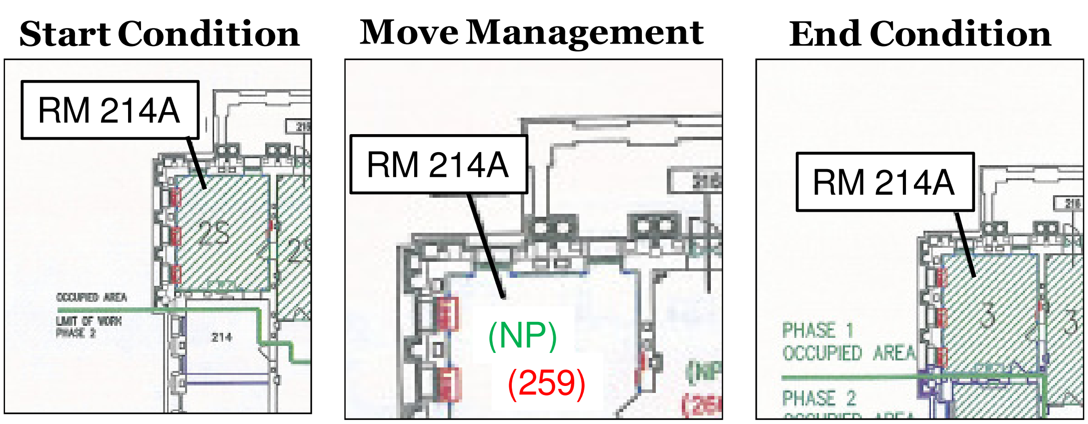
Start Date	End Date	Shift	Space ID	Occupant ID	Space Sharing Ability
1/16/2012	1/16/2012	Day	14041	COA	Cannot Share
1/16/2012	1/16/2012	Day	14041	CP Crew	Cannot Share

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.

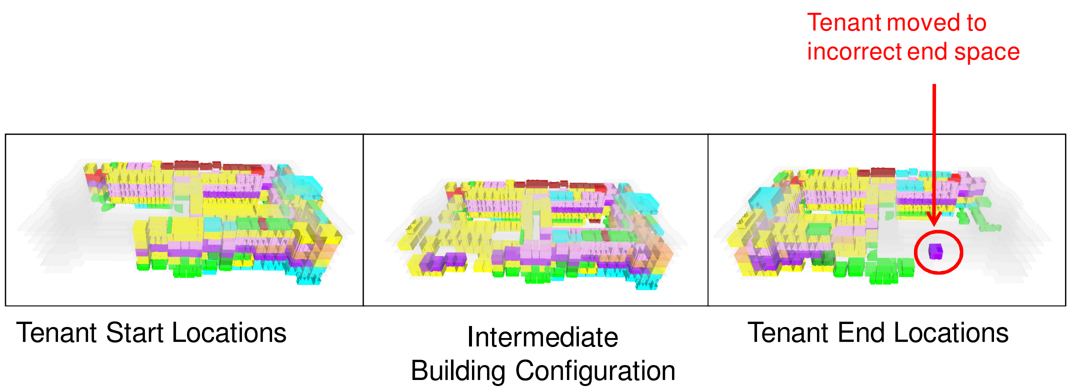


21-a. **21-b.** **21-c.**

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.



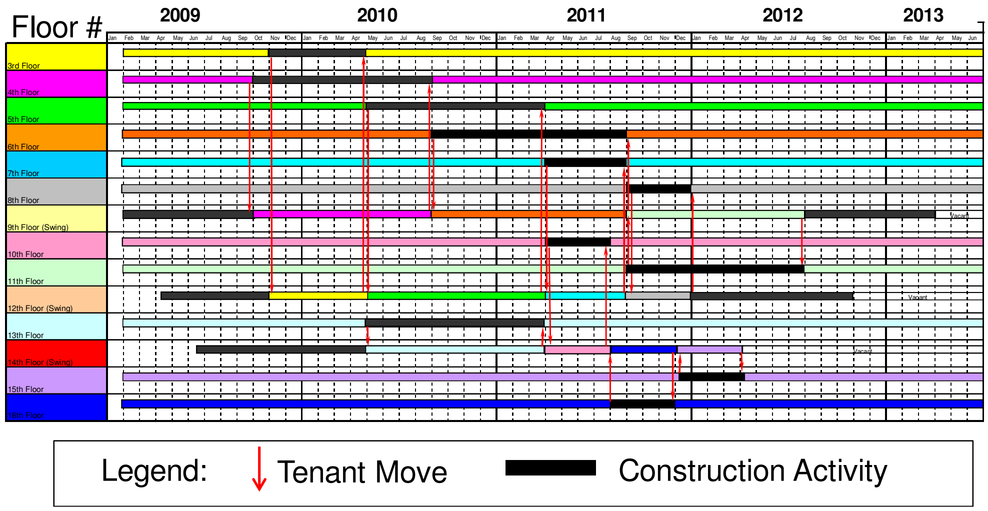
22-a. ***22-b.*** ***22-c.***

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.

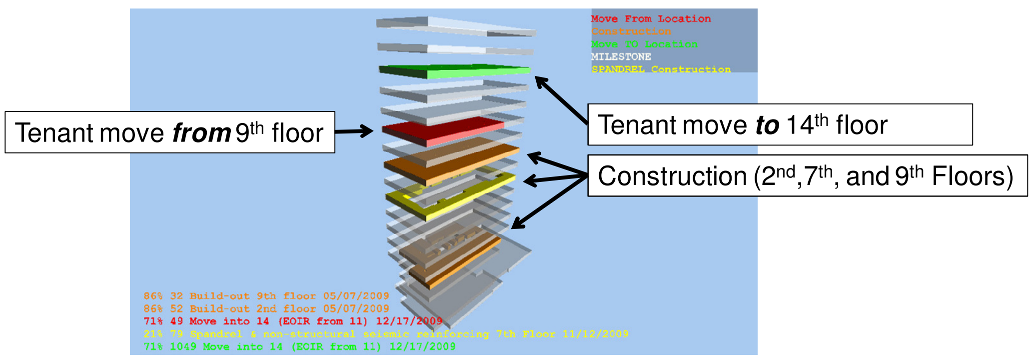
5.4. Analysis of vacant square footage

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.

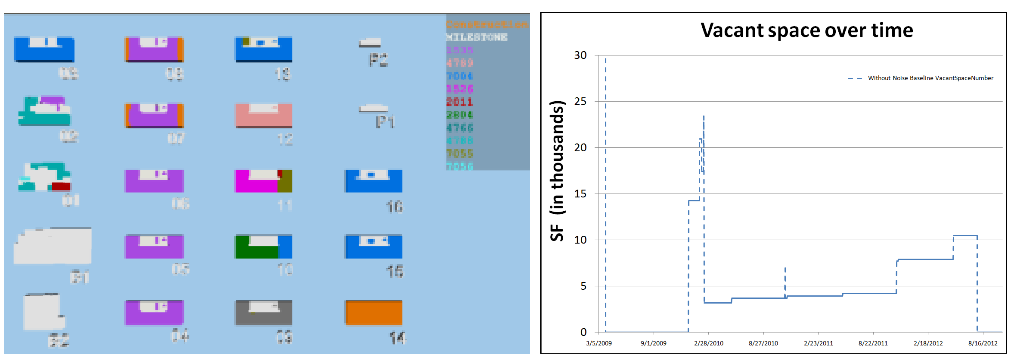
In TC#3, the traditional planning information did not detail the tenant move activities to the space level, making it impossible to track occupants and the amount of vacant space over time. In contrast, 4DRenCheck analyzes the locations of occupants and tracks vacant square footage. Figure 23 compares 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 5 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.

7. References

Akbas, R. (2004). "Geometry-based Modeling and Simulation of Construction Processes," Ph.D. Thesis, Stanford University, Stanford, CA.

Akinci, B., Fischer, M., Kunz, J., and Levitt, R. (2002a). "Representing Work Spaces Generically in Construction Method Models." *Journal of Construction Engineering and Management*, 128(4), 296-305.

Akinci, B., Fischer, M., Levitt, R., and Carlson, R. (2002b). "Formalization and Automation of Time-Space Conflict Analysis." *Journal of Computing in Civil Engineering*, 6(2), 124-135.

Clancy, W. J. (1985). "Heuristic Classification." *Report Number STAN-CS-85*, Stanford University, Palo Alto.

Darwiche, A., Levitt, R., and Hayes-Roth, B. (1989). "OARPLAN: Generating Project Plans by Reasoning about Objects, Actions and Resources." *AI EDAM*, 2(3), 161-181.

Eastman, C., Lee, J.-m., Jeong, Y.-s., and Lee, J.-k. (2009). "Automatic rule-based checking of building designs." *Automation in Construction*, 18(8), 1011-1033.

Han, C. S., Law, K., and Kunz, J. (2000). "Computer Models and Methods for Disabled Access Analysis Design Environment." *Technical Report #123*, Stanford University, Stanford.

Haymaker, J., Suter, B., Fischer, M., and Kunz, J. (2003). "The Perspective Approach: Enabling Engineers to Construct and Integrate Geometric View to Generate and Evolving Project Model." *Working Paper #081*, Center for Integrated Facility Engineering, Stanford University.

Ho, P., and Fischer, M. (2009). "An examination of current practices in identifying occupant interactions in renovation projects." *CIFE Working Paper #121*, Stanford University, Stanford.

Ho, P., Fischer, M., and Kam, C. (2009). "Prospective validation of VDC methods: Framework, application, and implementation guidelines." *CIFE Working Paper #123*, Stanford University, Stanford.

Hoes, P., Hensen, J., Loomans, M., De Vries, B., and Bourgeois, D. (2009). "User Behaviour in Whole Building Simulation." *Energy and Buildings*, 41(3), 295-302.

International Alliance for Interoperability. (2000). "IFC Technical Guide."

Jin, Y., and Levitt, R. (1996). "The Virtual Design Team: A Computations Model of Project Organizations." *Computational and Mathematical Organization Theory*, 2(3), 171-195.

Khanzode, A., Fischer, M., and Reed, D. (2008). "Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project." *ITcon*, 13(Special Issue: Case studies of BIM use), 324-342.

Leite, F., Akinci, B., and Garrett, J. (2009). "Identification of data items needed for automatic clash detection in MEP design coordination." 2009 Construction Research Congress, ASCE, Seattle, WA, 416-425.

Sanvido, V. E., and Riggs, L. S. (1991). "Managing Retrofit Projects." *Technical Report #25*, University of Texas at Austin.

U.S. Census Bureau. (2004). "Industrial Building Construction: 2002." 2002 Economic Census, U.S. Department of Commerce, ed., Washington, DC, 21 pages.

Yang, Q. (2003). "IFC-compliant design information modelling and sharing." *Journal of Information Technology in Construction*, 8, 1-14.

CHAPTER 4

PROSPECTIVE VALIDATION OF VIRTUAL DESIGN AND CONSTRUCTION METHODS: FRAMEWORK, APPLICATION, AND IMPLEMENTATION GUIDELINES

Peggy Ho[1], Martin Fischer[2], Calvin Kam[3]

Abstract

As new virtual design and construction (VDC) methods are developed, researchers and practitioners alike must understand the power of these methods before dedicating effort and resources towards further development or implementation on real projects. One particular aspect of power – external validation – is a challenge in VDC research because of the unique nature of projects and long waiting times for actual data on project performance. With the increased use of VDC in practice, however, prospective validation is an emerging validation method where researchers can test new VDC methods on real projects within a reasonable time frame.

This paper examines how researchers can use prospective validation. It presents a framework for understanding the purpose of prospective validation, an application of prospective validation, and implementation guidelines for researchers utilizing prospective validation. The results show that prospective validation should be used when researchers want to test a new method against an existing method used by practitioners on a real project. Researchers should also want to test whether the new method can be performed within a reasonable time frame and if so, whether the results could influence future project decisions. The implementation guidelines describe the necessary steps in the planning, execution, and analysis of a prospective validation test. More broadly, prospective validation represents a new way in which researchers and practitioners can collaborate that benefits the advancement of science as well as the management of real projects.

[1] Center for Integrated Facility Engineering, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, peggyhho@stanford.edu

[2] Professor, Department of Civil and Environmental Engineering, Director, Center for Integrated Facility Engineering, Stanford University, Stanford, CA 94305, fischer@stanford.edu

[3] Consulting Assistant Professor, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, calvin.kam@stanford.edu

1. Introduction

Virtual design and construction (VDC) is becoming an important part of architecture, engineering, and construction (AEC) practice and research. Kunz and Fischer (2009) define VDC as the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives. Existing VDC methods have demonstrated the benefits of visualization, integration, and automation of AEC tasks, in particular to predict project outcomes and manage towards the desired performance (Eastman et al. 2009; Hagan et al. 2009; Haymaker and Fischer 2001; Jongeling et al. 2008; Khanzode et al. 2008). As new concepts and methods are developed which further integrate and automate these tasks, researchers and practitioners must determine the power (i.e., whether the new method is better than existing methods) of these advancements on real projects. Specifically, researchers must demonstrate external validation to claim a new VDC method is powerful.

There has been much prior literature written on validation in general (Cook and Campbell 1979) and within the AEC industry (Abowitz and Toole 2009; Flood and Issa 2009; Kunz and Fischer 2008; Lucko and Rojas 2009). To validate any new method, researchers must show its power and generality (i.e., the range of problems the method applies to). While both are important, researchers must typically first demonstrate the power of a method. Without power, there is usually no motivation to determine generality.

Prior literature has examined different external validation methods to demonstrate that a new method can be used in real world applications (Carley 1995; Lynch 1982; Thomsen et al. 1999). While this prior work serves as useful points of departure, researchers can benefit from a VDC-specific framework to evaluate different validation methods. First, the unique combination of a facility design, stakeholders, and process of each project creates an un-controlled environment where practitioners do not know if a VDC method that has been shown to work in a controlled environment (e.g., laboratory experiments) will work in a real project situation. Second, the objectives of VDC methods (i.e., to predict performance, to be used on real projects, and to support business objectives) create a set of specific criteria to evaluate the power of VDC methods. Finally, with the increase in VDC research and practice, it is becoming a growing reality that researchers can validate new methods on real projects.

Prospective validation, where a VDC method is tested by predicting future project performance of a real project and the results are given to practitioners in a timeframe to affect future project decisions, is an emerging method for external validation. But how can researchers use prospective validation? In what situations is prospective validation an appropriate method to validate new VDC methods? What is a process to implement prospective validation? This paper provides answers to these questions by first developing a six-criterion framework to evaluate and select an appropriate VDC validation method, such as prospective validation. Then, an application of prospective validation to test an automated method to identify occupant interactions (IOI method) in renovation projects is described to demonstrate how prospective validation can provide strong evidence of external validity. Finally, based on prior literature and lessons learned from its application, implementation guidelines are presented for researchers who want to use prospective validation.

This paper will be of interest to VDC researchers who are interested in external validation and how to develop a validation trajectory throughout the course of their research. This paper will be of interest to practitioners who need to analyze whether a new VDC method is powerful to justify effort and resources to implement it on real projects.

2. Selecting a validation method

Validation is a recurring process throughout a research project, and therefore, has different purposes depending on the stage of the research (Carley 1995; Pedersen et al.

2000). Researchers select a validation method based on the purpose of the validation, constraints of the research, and preferences of the researchers. For example, during early stages of developing a new VDC method, researchers may only want to test whether the method works with simplified, simulated data. As the method develops further, more difficult tests for external validation are done (e.g., using real project data). It is important for researchers to understand the purpose of the validation before selecting a validation method.

There may also be constraints regarding the feasibility of different types of validation. For example, it may not be feasible to test a new method using real project data if the state-of-the-art research has not yet developed methods to handle the advanced complexities of real data (Maile et al. 2007). Where there are no constraints, researchers have a choice regarding the parameters of the validation. These choices affect the strength of the evidence for power. For example, researchers can use students to validate a new method (Clayton et al. 1998; Mourgues 2009). A method that is validated using students, however, provides weaker evidence of power than a method that is validated utilizing practitioners. Therefore, researchers must choose a validation method that meets the purpose of the validation and provides the strongest evidence as possible within the constraints of the research.

Kunz and Fischer's definition of VDC provides a starting point for defining a good validation method to test a new VDC method. To claim that a VDC method is powerful, researchers must demonstrate three facets:

- The method predicts project performance.
- The method can be used on design-construction projects.
- The method supports business objectives.

There are six criteria in selecting a validation method that relate to the three facets above. For each criterion, researchers must decide which parameter to use for the validation. Figure 1 provides an overview of the relative strength of evidence each parameter provides for each criterion. The purpose, parameters, and constraints of each criterion are discussed in detail below.

Range of evidence for external validity

VDC objective	Less →		More
Predicts project performance	Prediction is compared indirectly to past performance		Prediction is compared directly between new and existing method
	Prediction is compared to existing predictive methods		Prediction is compared to actual results
Can be used on real projects by practitioners	Simulated data		Real project data
	Controlled environment		Un-controlled environment
	Researchers	Students	Practitioners
Supports business objectives	Results have no impact on a project		Results can create intervention

Figure 1. Six-criterion framework for selecting a VDC validation method

2.1. Criteria related to predicting project performance

Direct or indirect comparison – Indirect comparison occurs if a task is performed using a new method and the results are compared to the same task performed in similar situations (e.g., comparable projects) in the past. In contrast, direct comparison occurs if the same task is performed with the same data using both an existing method and the new method. Researchers can then compare the performance of the existing method with the performance of the new method directly. The evidence is stronger if researchers use direct comparison rather than an indirect comparison to past performance.

Actual or predicted data – The predictions (i.e., performance) of a new method (e.g., 3D clash detection methods) can be compared to actual project performance data (e.g., the actual number of clashes during installation of HVAC ductwork

(Khanzode 2007)) or data from existing prediction methods used by practitioners (e.g., estimated number of clashes predicted by subcontractors). Obtaining actual data, however, is often difficult, due to the long durations of construction projects (El-Diraby and O'Connor 2004). On the other hand, since existing prediction methods are typically not perfect in predicting actual performance, a method that can predict actual project performance provides stronger evidence than a method which can perform equal or better than an existing prediction method because, in our experience, few prediction methods have been validated thoroughly for their accuracy in the AEC industry (Persson 2005).

2.2. Criteria related to demonstrating a method can be used on real projects

Real or simulated data – Researchers can either use real project data or simulated data. Simulated data, while often based on real project data, often simplifies and removes variables (e.g., reducing a complex building design to a design which only contains walls, slabs, and windows) (Staub-French 2002). Simulated data allows researchers to test specific input variables to understand their impact on the method's performance. In some cases, using real project data is impossible because the development of the method is not sophisticated enough to handle complex project data or there are data access and confidentiality issues. Using real data, however, provides stronger evidence than using simulated data.

Un-controlled or controlled environment – The validation can either be performed in a controlled (i.e., laboratory) or un-controlled (i.e., field) environment. Another barrier to adoption of VDC methods is that they are often validated in a controlled environment, which may not take into account real project conditions (i.e., time constraints, uncertainty in the input data, politics) (Haymaker et al. 2008). Therefore, a method that is validated during a real project provides stronger evidence than if the method were validated after the project is completed.

Practitioners or researchers – The new method can be used by the practitioner or the researchers during validation. While use by practitioners provides much stronger evidence of power, there are instances where the new method should be used by researchers (e.g., if researchers want to test the new method against practitioners using existing methods). This decision also has impacts on the development of the computer prototype that implements the new method, since the user interface and instructions for the prototype must be much more sophisticated if practitioners are using it (Clayton et al. 1998).

2.3. Criterion related to supporting business objectives

Alignment with project decisions – If the new method is tested in parallel to the existing method, researchers can either choose to validate predictions from the new method against the predictions of the practitioners at the time, or later, against the actual outcome of the project. If researchers choose to compare the predictions of the new method against the predictions of the practitioners, the researchers can reveal the results to the practitioners in a timeframe that can affect future project decisions. Since an intervention has an impact on actual project performance, the disadvantage of revealing these results is that the predictions from the new method can no longer be compared to the actual results. Researchers would have to re-test the method taking the intervention into account.

In summary, the six-criterion framework relates the objectives of VDC methods (i.e., predict project performance, use on design-construction projects, and support business objectives) to specific parameters that can demonstrate this power. These criteria can be mapped to six basic questions that researchers should ask themselves regarding the purpose and constraints of the validation:

- ***How do I want to compare the new method against an existing method?***
- ***Do I want to compare the outputs of the method against actual data?***

- ***Can I / Do I want to use real project data?***
- ***Can I / Do I want to see if the method works in an un-controlled environment?***
- ***Can I / Do I want practitioners to use the new method?***
- ***Can I / Do I want to perform the analysis within a timeframe to affect business (project) decisions?***

3. Evaluating validation methods

Based on this framework, this section examines different validation methods used in VDC research. A literature review of prior VDC research revealed four common types of validation methods: charrette testing, indirect comparison, retrospective testing, and contemporaneous validation. An analysis of these four common validation methods in addition to prospective validation allows researchers to understand in what situations prospective validation should be used. We describe and define key terms for each validation method to clarify discrepancies because literature in other domains revealed different terms and meanings for different validation methods. Finally, an evaluation matrix is used to compare each of these validation methods to the criteria established in the framework.

3.1. Five types of VDC validation methods

***Charrette testing* –** The charrette test method is designed to evaluate "whether a process performed using one set of tools is superior to a process performed using another set of tools (Clayton et al. 1998)." Charrette testing is performed in a controlled environment using simulated data. This allows the direct comparison of two groups utilizing different processes (i.e., the new method and an existing method) to perform the same task. Examples of the application of charrette testing include Mourgues (2009) and Dawood and Sikka (2008).

***Indirect Comparison* –** Indirect comparison is used when practitioners implement a new method on a real project, but there is no direct comparison to how the method performs against an existing method. Instead, the method is evaluated based on the practitioners past experience performing the task using traditional methods on similar projects. Examples of indirect comparison include Collier and Fischer (1996), Manning and Messner (2008), and Torrent and Caldas (2009).

***Retrospective validation* –** Retrospective validation occurs when researchers validate a method against the actual outcomes of a real project. The analysis occurs after the task or project is completed. Within the pharmaceutical industry, retrospective validation refers to tests made after a new product is in commercial production to ensure that it still meets the pre-defined specifications of the product (Nash and Wachter 2003). Examples of retrospective validation in the VDC domain include Koo and Fischer (2000) and Akinci et al. (2000).

***Contemporaneous validation* –** Contemporaneous validation (Thomsen et al. 1999) occurs when researchers validate a new method in parallel with an existing method. Once the predictions are made, the researchers wait until the outcomes of the existing method are known and compare the new method's predictions with the actual data. Examples of contemporaneous validation include Thomsen et al. (1999) and Shah et al. (2008).

***Prospective validation* –** Prospective validation occurs when researchers validate a method in parallel with an existing method. It is similar to contemporaneous validation, but the results of the method are compared to existing predictive results. These results are then presented to practitioners within a timeframe that allows practitioners to make business decisions with insights from the new method (if they choose to do so). Prospective validation is a term that is used within many other domains. Within the medical community, the term prospective validation equates to contemporaneous validation in the terms defined in this paper (Kidwell et al. 2000). Within the pharmaceutical industry, prospective validation refers to tests made before a new product is approved for commercial production to ensure it meets the pre-defined specifications of the product (Nash and Wachter 2003). Thomsen et al. (1999) provide a similar description of prospective validation as the one defined in this paper, where researchers implement a method within a timeframe to affect business decisions, but the description does not explicitly compare an existing method with a new method. Han et al. (2000) influence the design of an office building using an automated design analysis method, but do not explicitly compare an existing method with the new method. Ho et al. (2009) provide an example of prospective validation according to the definition above, where the performance of an automated method to identify occupant interactions in renovation projects was compared directly to the performance of an existing method, and resulted in planned and actual changes to projects.

Charrette testing is differentiated from the other validation methods because it is not used on a real project. Figure 2 compares the differences between the four project-based validation methods: indirect comparison, retrospective validation, contemporaneous validation, and prospective validation. These methods are differentiated based on when the analysis with the new method is done relative to the project timeline, when the results of the new method are compared, and what type of data is compared (i.e., past performance, existing predictions, actual performance).

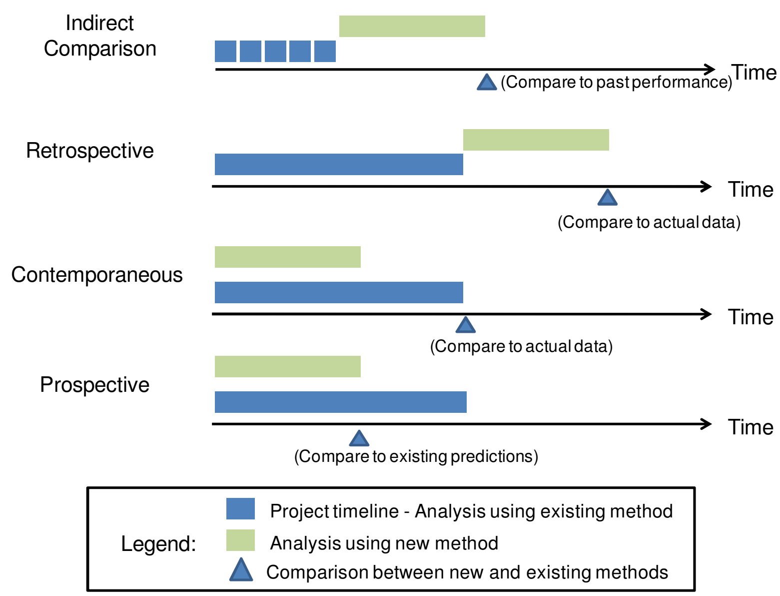


Figure 2. Indirect comparison, retrospective, contemporaneous, and prospective validation methods differ based on when the new method is tested relative to the project timeline, when the results are compared, and what type of data is used for the comparison.

3.2. Comparison of validation methods against criteria for a good validation method

Table 1 shows an evaluation matrix which compares each validation method against the six criteria for validating VDC methods. This chart enables researchers to understand the merits of each validation method, compare different methods, and select the appropriate method for the purpose of a validation. The next section demonstrates how the evaluation matrix can be applied to determine the appropriate validation method.

Table 1. Evaluation matrix of the five validation methods using the six-criterion framework to select an appropriate validation method for a new VDC method.

	Validation methods				
Criteria for selecting a validation method	Charrette testing	Indirect comparison	Retrospective validation	Contemporaneous validation	Prospective validation
Data for comparison with new method outputs					
How do I want to compare the new method against an existing method?					
Direct comparison of data	X		X	X	X
Indirect comparison		X			
Do I want to compare actual or predicted data?					
Use actual data	X	X	X	X	
Use predicted data	X				X
Test case characteristics					
Can I / Do I want to use real project data?					
Method utilizes real project data		X	X	X	X
Method utilizes simulated data	X				
Can I / Do I want to perform the analysis within a timeframe to affect business decisions?					
New method has potential to change future decisions during validation		X			X
New method cannot change future project decisions during validation	X		X	X	
Can I / Do I want see if my method works in an un-controlled environment?					
Field-based (un-controlled environment)		X		X	X
Laboratory-based (controlled environment)	X		X		
User					
Can I / Do I want practitioners to use the new method?					
New method is used by researcher			X	X	X
New method is used by practitioner	X	X			

4. Prospective validation of a VDC method on three test cases

This section describes the prospective validation of a new VDC method. The new VDC method is an automated method to identify occupant interactions (IOI method) in renovation schedules for office buildings. First, we describe the challenges associated with identifying occupant interactions and development of the IOI method and computer prototype system (4DRenCheck). Then, we demonstrate how prospective validation can be selected, using the six-criterion framework, as the most appropriate validation method based on the purpose of the validation. Next, we describe the steps taken to prepare, execute, and analyze the test. Three test cases were selected, each of which is presented to demonstrate that prospective validation provides strong evidence of the power of the IOI method.

4.1. An automated method to identify occupant interactions (IOI method)

Based on an analysis of seven renovation projects, Ho et al. (2009) found that identifying occupant interactions is a difficult task for renovation project planners because it requires an integrated analysis of spatial, organizational, and temporal renovation planning information. Ho et al. (2009) identified four types of occupant interactions: tenant-tenant, minor tenant-crew, major tenant-crew, and crew-crew interactions. Minor tenant-crew interactions, such as crews working at night in tenant spaces are considered tolerable to occupants. Major tenant-crew interactions, where crews are working at the same time as the tenants, and tenant-tenant interactions, where tenants are scheduled to use the same space at the same time, are considered disruptive. These disruptive occupant interactions can result in schedule delays and tenant dissatisfaction if missed during the planning process.

To identify interactions, planners must first determine where tenants are located. This is difficult because renovations of occupied buildings involve tenants moving and crews working in different spaces throughout the renovation. This creates many unique building configurations (i.e., locations of occupants). If there is more than one occupant in a space, planners must understand how occupants can share spaces at the workshift level to determine if the interaction is tolerable or disruptive. The necessity for thoroughness and detail in such an analysis makes existing, manual methods using distributed information inaccurate in identifying interactions.

To address these challenges, Ho et al. (2009) developed a method to identify interactions that integrates renovation planning information and automates the identification process. The method is a discrete event simulation where the users (i.e., in the test cases, the researchers) input spatial, organizational, and temporal renovation planning information. The method first updates detailed occupant location and space sharing data automatically. This allows dynamic tracking of changing building configurations over the entire renovation schedule. Then, the method analyzes the building configurations and identifies occupant interactions automatically. Ho et al (2009) detail the reasoning methods to automate these steps.

The method was implemented in a computer prototype, 4DRenCheck. 4DRenCheck was implemented in Microsoft Access 2007 (Microsoft 2007) and consists of several database tables which integrate spatial, organizational, and temporal renovation planning information. Figure 3 highlights these relationships among spaces, organizations, and activities in each of the tables. These tables enable the user to input renovation planning information once, eliminating redundant and inconsistent project information found in traditional project documents. The user interface of the prototype was minimally developed since, at this stage of the research, only the researchers are using the prototype.

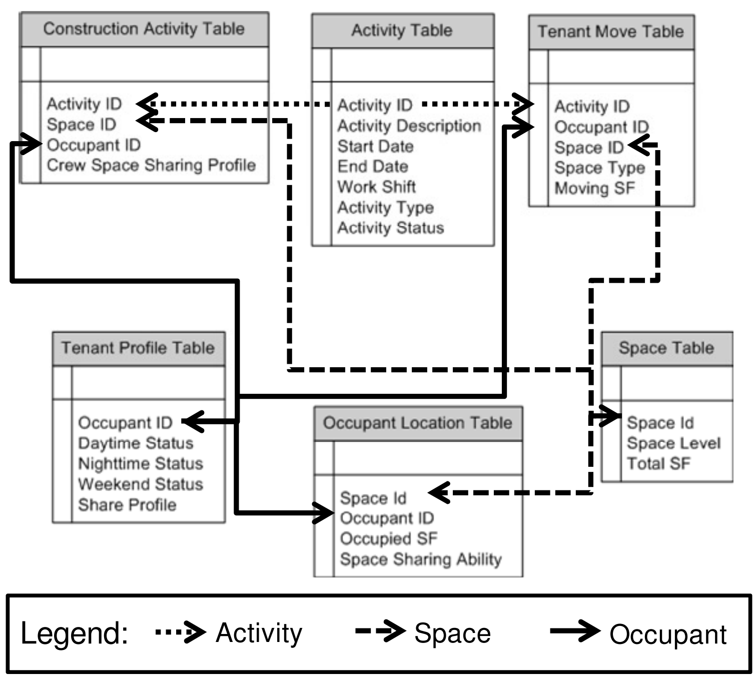


Figure 3. Tables and properties in 4DRenCheck prototype allow the integration of activity, space, and occupant information

4.2. Application of the six-criterion framework to select the validation method

The purpose of the validation is to test whether or not the IOI method can perform better than expert project planners using traditional (i.e., existing) methods on real projects. The researchers also wanted to test whether the method could be applied in a reasonable timeframe to impact future project decisions. We apply the six-criterion framework to determine the appropriate validation method by addressing the following questions listed in Table 1. These questions also have implications on the characteristics of projects (i.e., test cases) that are selected (e.g., on-going or completed project, timeframe of decision making). The requirements for test cases utilizing prospective validation are discussed in the following section.

- ***How do I want to compare the new method against an existing method?*** The researchers wanted to compare directly the performance of the IOI method against traditional planning methods used by project planners for the same situation.
- ***Do I want to compare the outputs of the method against actual data?*** No, obtaining actual data on the number of interactions found during renovation would take too long, so the researchers decided to compare the predictions from the IOI method against existing predictions (i.e., predictions based on traditional planning methods used by project planners).
- ***Can I / Do I want to use real project data?*** Yes, Ho et al. (2009) found that identifying interactions using traditional methods was infeasible to perform manually because of the amount of renovation planning information required, so the researchers wanted to test the method using real data (i.e., test whether the method allows the researchers to work with the large sets of information used on the projects in a timely manner). Anticipating this goal, 4DRenCheck was developed to handle real project data.
- ***Can I / Do I want to see if the method works in an un-controlled environment?*** Yes, the researchers wanted to understand the broader context of identifying interactions and how it related to other business objectives.

- ***Can I / Do I want practitioners to use the new method?*** No, the researchers wanted to see how the planners use the existing methods. Therefore, the researchers used 4DRenCheck themselves.
- ***Can I / Do I want to perform the analysis within a timeframe to affect business decisions?*** Yes, the researchers wanted to see if the method could be performed in a timeframe to affect business decisions and if the results of the new method were useful to the planners.

Table 2 shows the evaluation matrix for the validation of the IOI method. Prospective validation met all six criteria. Based on the intended purpose for the validation, prospective validation is the best method to use.

Table 2. Application of framework to determine validation method for IOI method

Criteria for selecting a validation method	Charrette testing	Indirect comparison	Retrospective validation	Contemporaneous validation	Prospective validation
	Validation Methods				
Data for comparison with new method outputs					
How do I want to compare the new method against an existing method?					
Direct comparison of data	**√**		**√**	**√**	**√**
Indirect comparison		X			
Do I want to compare actual or predicted data?					
Use actual data	X	X	X	X	
Use predicted data	**√**				**√**
Test case characteristics					
Can I / Do I want to use real project data?					
Method utilizes real project data		**√**	**√**	**√**	**√**
Method utilizes simulated data	X				
Can I / Do I want to perform the analysis within a timeframe to affect business decisions?					
New method has potential to change future decisions during validation		**√**			**√**
New method cannot change future project decisions during validation	X		X	X	
Can I / Do I want see if my method works in an un-controlled environment?					
Field-based (un-controlled environment)		**√**		**√**	**√**
Laboratory-based (controlled environment)	X		X		
User					
Can I / Do I want practitioners to use the new method?					
New method is used by researcher			**√**	**√**	**√**
New method is used by practitioner	X	X			
Number of criteria that meet requirements for validating the IOI Method (Number of "√" highlighted in each column)	**2**	**3**	**3**	**4**	**6**

4.3. Selection of projects

To utilize prospective validation, the test cases must demonstrate that the IOI method can:

- Be utilized in an un-controlled environment
- Utilize real project data
- Be compared directly against project planners using their existing methods
- Result in changes to project decisions

Furthermore, in selecting the test cases, we kept in mind the goal to validate the generality of the new method also.

The three test cases, therefore, consist of real renovation projects which were in the planning stages during our validation study. The actual renovations were planned to occur from late 2009 through 2015. This timeframe allowed the researchers to directly compare the predictions from the IOI method against planners' predictions that were based on utilizing their existing methods because the planners were actively analyzing the renovation schedule during this time. The analysis also occurred early enough in the planning process such that any insights provided by 4DRenCheck could be incorporated in future revisions of the schedule. Table 3 provides an overview of the three test cases. Project data were gathered regarding the scope, size, schedule characteristics and analysis needs of each project. These three projects, selected from a large portfolio of renovation projects of the U.S. General Services Administration, are representative of the types of renovation projects of a large owner. The researchers analyzed summary data from 78 GSA renovation projects and found that approximately 70% of these projects had a renovation scope which contained multiple systems upgrades and the average size of a renovation project was approximately 560,000 sf (U.S. General Services Administration 2009). Therefore, these three test cases are representative of the size and complexity of renovation projects.

Table 3. Characteristics of renovation projects

Test Case	1	2	3
Project size (in thousand sf)	335	1,300	419
Number of tenants	114	8	10
Number of crews	0	6	3
Number of spaces	1098	59	102
Scope of renovation	Historic preservation, building systems upgrades	Building systems upgrade, tenant build out	Seismic upgrades, asbestos abatement, tenant build out
Renovation Schedule Characteristics			
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
% occupied spaces at start of project	71%	93%	86%
% tenants impacted by renovation	54%	88%	90%
% of spaces impacted throughout renovation	62%	93%	54%

The experience and knowledge of the project planners provide a solid benchmark for direct comparison. The projects were large, complex projects, which are typically managed by senior project managers. The project planners on the selected renovation projects each had 15+ years of experience on design and construction projects and came from public and private industry. The planners from private industry came from internationally recognized construction management firms. Most importantly, the project planners had worked on the selected renovation project for over two years and were intimately familiar with the project context and information. For example, on TC#3, the planner's main duty was to manage the tenant moves in the building.

4.4. Execution of the validation study

First, the researchers identified a specific task in the project (e.g., analysis of the renovation schedule at 75% design) that included identifying interactions. The researchers gathered all of the project documentation that the project planners used to identify interactions. From the planner's perspective, the analysis of the schedule and identification of interactions was a regular part of their duties.

Then, utilizing the same project information, the researchers entered the spatial, organization, and schedule information from project documents (e.g., CPM schedules, Excel files, 2D CAD files with occupant locations annotated) into 4DRenCheck. Since there was no explicit organization information documented, information about each tenant's space sharing abilities came from the knowledge of the project planners. The 4DRenCheck analysis and the traditional analysis were performed concurrently. This was done to ensure that there was no "learning effect" from knowledge of the outcomes from the other method.

The researchers then compared the outcomes of the existing method and 4DRenCheck. The methods were compared based on accuracy, thoroughness, and detail. A summary of the results for each test case is given in the next section. Ho et al. (2009) provide a detailed review of the results for each test case. The results were then presented to the project planners. One of the planners changed the start and end locations of tenants, another planned to detail the renovation schedule further, and the third planner anticipated changing the sequencing of the renovation. The results demonstrate that the method was powerful in predicting project performance, was able to be used on real projects, and supported business objectives.

5. Test cases

First, we describe the background of each test case to demonstrate that validation on real test cases allow researchers to understand additional factors and implications of the new method in a project context. Second, we describe the performance of traditional methods and 4DRenCheck to demonstrate how direct comparison of performance metrics (i.e., accuracy, thoroughness, and detail) between the two methods can be accomplished. We also describe additional uses of the detailed occupant location and space sharing data to support other schedule analysis needs. Finally, we discuss how prospective validation enables researchers to demonstrate strong evidence of the power of the IOI method. Power is demonstrated through better performance of the new method as compared to traditional methods, that it can be used on real projects in the sense that the method can be implemented with real data within a reasonable time frame, and that the method supports business objectives by influencing project decisions. No other validation method discussed in this paper tests both whether a new VDC method can be implemented within a useful timeframe and whether it can influence project decisions.

5.1. Test case #1

TC #1 involved the renovation of a six-story, 355,000 square foot office building with 144 different tenant groups. The scope of the renovation included major upgrades to the electrical and communication systems and the renovation of historic interior building finishes. The renovation occurred in three phases and involved 97 tenant moves, ranging from a simple one-to-one space move to moving from multiple start spaces to multiple end spaces.

There were two main project challenges in scheduling the tenant move activities:

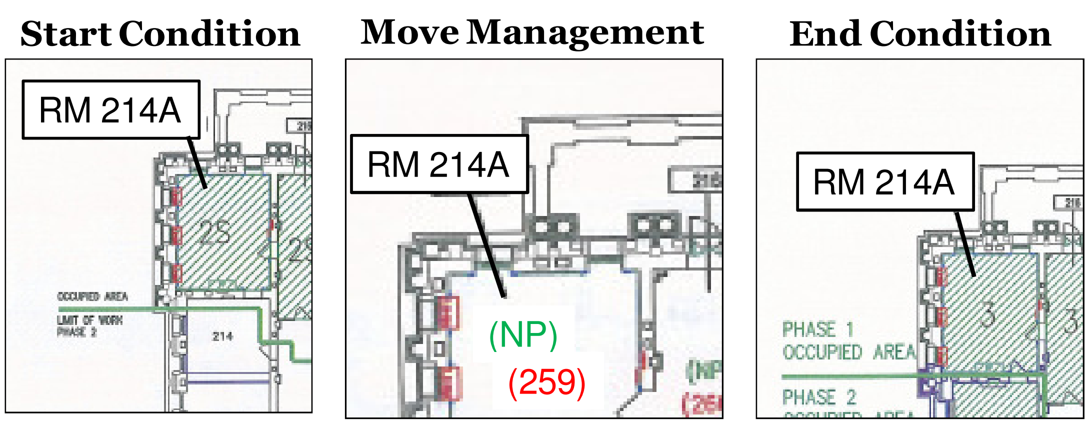
Difficult tenants with changing requirements – The tenants were head strong and temperamental at times. Sometimes, tenants argued over occupying the same space. Higher levels of the organization had to intervene to make a decision on who would ultimately occupy the space. These decisions, however, could change at a moment's notice, requiring the project planner to revise the renovation schedule weekly based on the changing decisions of the tenants. Additionally, tenants did not want to share spaces with other tenants making it even more important for the analysis to be accurate. For example, if a tenant suddenly required additional space, the project planner had to identify which spaces were vacant.

Coordination with Phase 2 construction – The tenants were going to be moved into parts of the building where renovations were close to completion. The project planner, therefore, had to understand when building spaces would be available for tenants to occupy. There was, however, uncertainty from the construction manager regarding when these spaces would be turned over, making it difficult for the project planner to sequence the tenant moves. This uncertainty inhibited the project planner from finalizing the tenant move schedule.

To manage these challenges, the project planner needed to track where tenants and empty spaces were throughout the renovation to identify double-booked spaces, to communicate the move locations to tenants and to react quickly to the dynamic tenant space requirements.

5.1.1. Traditional management methods

Figure 4 depicts the renovation planning documents used to track and communicate the tenant moves. The documents included: 2D CAD drawings of start and end tenant locations only (Figure 4-a,c) and 2D CAD drawings indicating move to and from locations for each space (Figure 4-b). For example, Figure 4 shows tenant group 2S starting in space 214A, then moving to space NP. Tenant group 3 moves from space 259 into space 214A.



4-a. 4-b. 4-c.

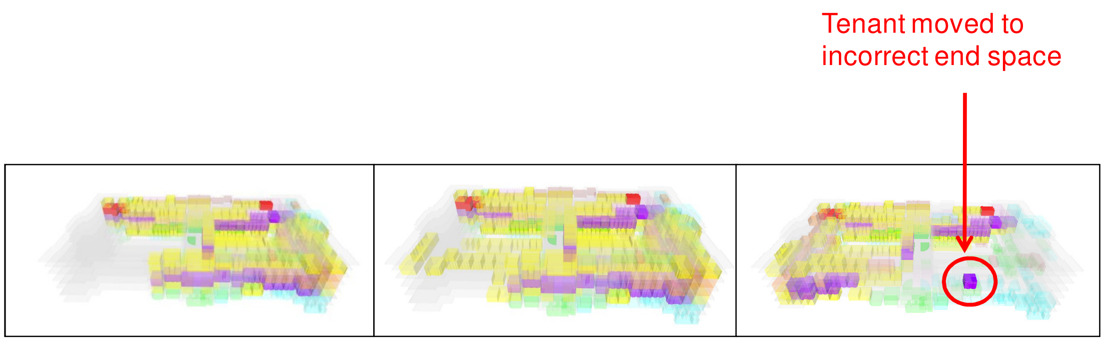
Figure 4a-c. Traditional move management documents. Start locations of tenants (4-a), move activities (4-b), and end locations (4-c) are managed in three separate sets of 2D CAD drawings. For each space in the move management drawing, one label (e.g., NP) indicates to which space a tenant will be moving, and another label (e.g., 259) indicates from which space a tenant will be moving.

The move documents contained enough detail to determine which tenants were moving from/to which spaces, but the documents were not integrated, forcing the project planner to manually coordinate the drawings. This involved synthesizing tenant, schedule, and spatial information over three sets of drawings to ensure that the correct tenant was depicted on the end drawings. With 97 moves to manage, the manual coordination of the documents became difficult to maintain. The project planner indicated that she had “gotten lazy” in updating all of the information as changes occurred and was not sure if she had double-booked any rooms.

5.1.2. Results of 4DRenCheck

4DRenCheck identified thirteen double-booked rooms that the project planner had missed using the traditional method. The project planner confirmed that eleven of these were undesirable/intolerable 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.

4DRenCheck also tracked the locations of tenants thoroughly and automatically based on the renovation schedule. Figure 5 shows the progression of tenants from their start locations (Figure 5-a), through the moves (Figure 5-b), to their end locations (Figure 5-c). It also shows which spaces are vacant during renovation. From the visualization of occupant location data, the researchers identified that one tenant 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 and the identification of the incorrectly moved tenant were accurate. As a result, the project planner changed the end location of the tenant. The project planner also indicated that visualizing the locations of every tenant was useful to determine vacant spaces during renovation.



5-a. ***5-b.*** ***5-c.***

Figure 5a-c. Snapshots of tenant locations throughout the renovation show the starting locations of tenants (5-a), mid-move locations (5-b), and final tenant locations (5-c). On this project, 4DRenCheck automatically tracked the locations of 114 occupants.

5.1.3. Evidence for the power of the IOI method

Prospective validation allowed researchers to demonstrate the power of the IOI method because the VDC method:

Predicts project performance – The IOI method identified 11 double-booked rooms that the project planner could not identify with traditional methods. The method was also more thorough and detailed than existing, manual methods because it can track tenant locations throughout the renovation.

Can be used on design-construction projects – The method successfully analyzed 97 tenant moves and tracked 114 tenants. The results were presented to the planner such that changes to the tenant move locations could still be made.

Supports business objectives – Based on insights from the analysis with 4DRenCheck, the project planner moved tenants to different end locations and updated her 2D CAD drawings to eliminate the eleven double-booked rooms. After the researchers showed the project planner the analysis, she stated "Well, you certainly found all of my mistakes." Validation on real projects also allowed researchers to understand the relationship between identification of interactions and tenant satisfaction (i.e., in trying to meet tenant space requirements).

5.2. Test case #2

TC#2 involved the renovation of a thirty-story, 1.3 million square foot office building. The main scope of the renovation was the upgrade of the HVAC system, including the replacement of condensate piping on all floors, which affected seven of the eight tenants in the building. The project scope included the build out of vacant space on the 8th, 9th, and 10th floors, with the 10th floor serving as the swing space floor. Only tenants on the upper floors (i.e., Floors 17-23, 25) were scheduled to move into swing space on the 10th floor. Condensate piping work was scheduled throughout the entire building during daytime and nighttime shifts, depending on the floor. For example, on the 16th floor, construction crews planned to replace the condensate piping at night because the tenant kept occupying the floor but could share the space at night. On the 19th floor, construction crews planned to replace the condensate piping during the daytime because the tenants moved into swing space. For each floor, the installation of the condensate piping required crews to occupy support spaces in the floor above to access the pipes.

There were two main project challenges in analyzing the schedule:

Changing scope and schedule – As the project progressed there were several changes in the scope of the project (e.g., installation of additional variable air volume (VAV) boxes), which required adjustments to the schedule. A third party review of the schedule also changed some of the activity relationships, thus altering the sequence and the start and finish dates of activities. It was difficult for the project planners (i.e., owner's representatives, construction manager, and schedule reviewer) to understand how these changes impacted the move dates of the tenants.

Communication with tenants **–** The project planners were very cautious in discussing the renovation schedule with the tenants because they did not want to change the information provided (and be held accountable for any tenant-initiated activities related to out-of-date information). For example, the project team originally told the upper-floor tenants that they would need to relocate to swing space for twelve weeks. With the changes in scope and schedule, the project planners wanted to ensure that there was no impact to the tenants with respect to the time they had to spend in swing space so that they could avoid changing any information previously given to the tenants.

To understand the impact of the renovation on the tenants, the project planners needed to understand who was in each space over time and how many times they needed to notify the tenants that there would be work happening in their space. The focus of the analysis was to determine the impact of condensate piping work on the tenants since the installation of the piping required crews to access the pipes from the floor above.

5.2.1. Traditional management methods

Figure 6 shows the traditional planning methods that were employed on the project. The project planners primarily used a CPM schedule to create and update the renovation schedule. They also developed a day/night/weekend activity matrix to manage the workshifts for each activity on each floor. The activity matrix and the CPM schedule, however, were not integrated and contained inconsistent information. The documents were also at two different levels of detail. The matrix only detailed each activity to each floor, whereas the CPM schedule detailed the activities based on their north or south location on each floor. In addition to the application of 4DRenCheck, the researchers also created a 4D model using Autodesk Navisworks to communicate the renovation schedule to project stakeholders and describe the construction activities to potential subcontractor bidders. The project planners used the model to verify the constructability of the schedule. While the 4D model integrated the activity matrix and the CPM schedule information, the project planners still had to go through the 4D model to identify if there would be more than one occupant in a space and if so, what type of occupant interaction would occur.

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

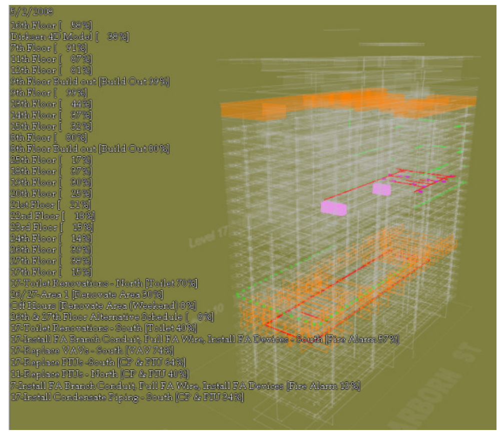


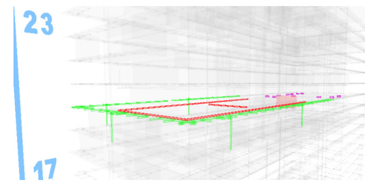
Figure 6. The traditional planning methods used on TC#2 included a CPM schedule, day/night/weekend activities matrix, and 4D Model.

There were two problems with using the traditional methods to identify occupant interactions. First, multiple sources of the same information created inconsistencies between the CPM schedule and the day/night/weekend activities matrix. For example, the matrix indicated nighttime work to demolish columns on certain floors, whereas the CPM schedule indicated daytime work.

Second, the lack of explicit documentation of organizational information (i.e., occupant work schedules and their ability to share spaces) misled the planners to assume that only minor tenant-crew interactions occurred on the project. In Figure 7, 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.

Daytime Installation of Condensate Piping on 19th Floor

19th Floor	**320 days**	**Wed 12/19/07**	**Mon 3/9/09**
19-Install FA Risers & Panels	3 days	Wed 12/19/07	Fri 12/21/07
19-Move 19th Floor Tenants to Swing Space - Start	6 days	Mon 12/22/08	Mon 12/29/08
19-Move 19th Floor Tenants to Swing Space - End	6 days	Mon 12/22/08	Mon 12/29/08
19-Demo & Abatement - North	16 days	Fri 12/26/08	Fri 1/16/09
19-Install FA Branch Conduit, Pull FA Wire, Install FA Devices - I	14 days	Mon 1/19/09	Thu 2/5/09
19-Replace VAVs - North	11 days	Mon 1/19/09	Mon 2/2/09
19-Toilet Renovations - North	24 days	Mon 1/19/09	Thu 2/19/09
19-Install Condensate Piping - North	10 days	Mon 1/19/09	Fri 1/30/09
19-Patch & Paint Columns - North	5 days	Mon 2/2/09	Fri 2/6/09
19-Replace PIUs - North	12 days	Mon 1/19/09	Tue 2/3/09



Nighttime Installation of Condensate Piping on 16th Floor

16th Floor	**570 days**	**Wed 1/31/07**	**Tue 3/17/09**
16-Install FA Risers & Panels	3 days	Thu 12/6/07	Mon 12/10/07
16-Install FA Branch Conduit, Pull FA Wire, Install FA Devices	22 days	Wed 1/31/07	Thu 3/1/07
16-Demolition of Columns - North	1 day	Sat 10/6/07	Sun 10/7/07
16-Install Condensate Piping Risers - North	11 days	Mon 10/8/07	Fri 10/19/07
16-Replace PIUs - North	12 days	Thu 2/12/09	Fri 2/27/09
16-Demolition of Columns - South	1 day	Sat 10/13/07	Sun 10/14/07
16-Install Condensate Piping Risers - South	10 days	Mon 10/22/07	Fri 11/2/07
16-Replace PIUs - South	12 days	Mon 3/2/09	Tue 3/17/09

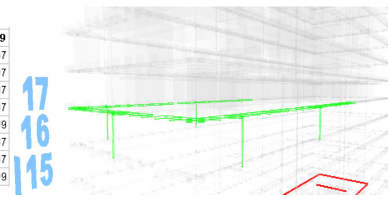


Figure 7. The current representation of the project schedule and 4D model of the condensate piping activity does not allow project managers to distinguish the impact of construction workshifts on tenants.

5.2.2. Results of 4DRenCheck

Figure 8 shows the impact of daytime versus nighttime installation of condensate piping that was found using 4DRenCheck. Since the condensate pipe required access from the floor above, the installation of condensate piping during the daytime caused major occupant interactions in the support spaces above (on the 20th floor), because tenants were working during the daytime and did not want to share spaces with crews (Figure 8-a).

In contrast, on the 16th floor, if the installation of condensate piping occurred at night, the activity would only cause a minor disruption on the 17th floor. Since the tenant allowed their space to be shared at night, the planners only needed to notify tenants that there would be construction work happening in their space at night (Figure 8-b).

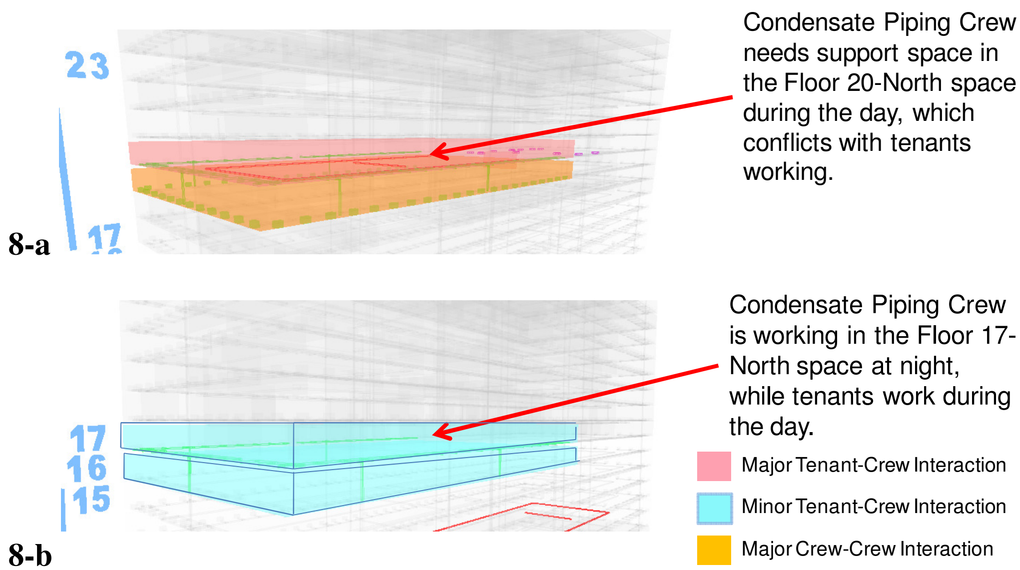
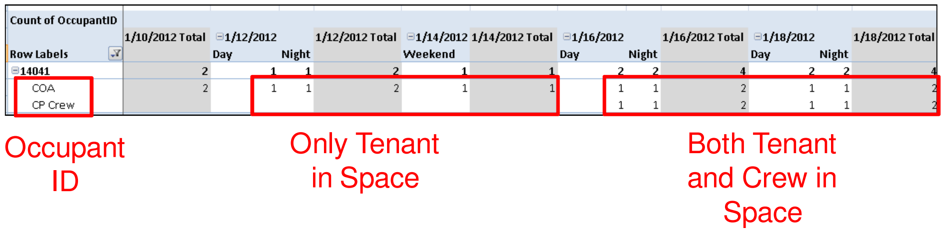


Figure 8a-b. Impact of daytime (8-a) and nighttime (8-b) installation of condensate piping

The planners identified a majority of the minor occupant interactions, but misidentified all the major occupant interactions associated with the support space needs in the installation of the condensate pipes. The project planners mistakenly identified them as minor tenant-crew interactions.

The additional detail of occupant space sharing abilities and identification of interactions in 4DRenCheck enabled project planners to understand the types of interactions between crews and tenants at the workshift level. A pivot table (Figure 9) allowed project planners to see which occupants were in each space over time and what their space sharing abilities are. The detail of this information allows project planners to drill down to any specific date and workshift to identify what types of occupant interactions occur and to determine which underlying renovation activities cause the interactions.



Count of OccupantID Row Labels	1/10/2012 Total	1/12/2012 Day	1/12/2012 Night	1/12/2012 Total	1/14/2012 Weekend	1/14/2012 Total	1/16/2012 Day	1/16/2012 Night	1/16/2012 Total	1/18/2012 Day	1/18/2012 Night	1/18/2012 Total
14041	2	1	1	2	1	1	2	2	4	2	2	4
COA	2	1	1	2	1	1	1	1	2	1	1	2
CP Crew							1	1	2	1	1	2

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

5.2.3. Evidence for the power of the IOI method

Prospective validation allowed researchers to demonstrate the power of the IOI method because the VDC method:

Predicts project performance – The method was able to identify the major tenant-crew interactions that were missed by the project planners. The data generated automatically in the pivot table shows that the IOI method is more detailed and thorough than existing methods.

Can be used on design-construction projects – The method was able to analyze 292 activities and track 628 building configurations. The results were presented to the planner such that changes to the detail of the schedule could be made to address the major tenant-crew interactions.

Supports business objectives – Based on insights from the analysis with 4DRenCheck, the project planners realized that they needed to update the day/night/weekend matrix to reflect a greater level of detail in the renovation schedule. Validation on real projects also allowed researchers to understand the relationship between identification of interactions and tenant satisfaction (i.e., communicating consistent information to tenants).

5.3. Test case #3

The building in TC#3 is a 419,000 square foot building constructed in the 1960's. The scope of the renovation included asbestos abatement and build out of eight floors, and non-structural seismic upgrades to all sixteen floors. The building was scheduled to be occupied during renovation, with each of the eight floors moving into swing space on the second floor. The renovation impacted nine of the ten tenants in the building.

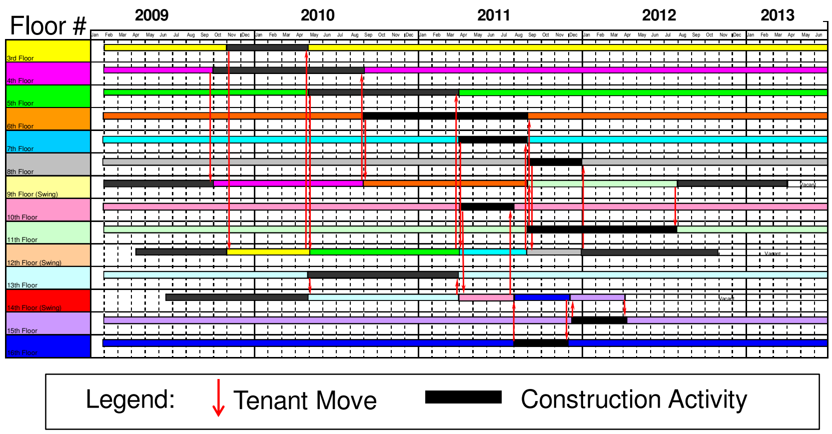
The main project challenge faced by the project planner was:

***Determining swing space needs* –** The project planner was unsure whether the building contained enough swing space or if additional swing space would be necessary throughout the renovation. Un-utilized swing space is calculated by the amount of vacant square footage in the building at any given time, which is derived from knowing the locations of all occupants at all times. If additional swing space was necessary, the project planner needed to know during which dates there was insufficient swing space so that she could lease space outside the building.

The focus of the analysis was to track the locations of occupants over time to determine the amount of swing space required for the renovation. Since the project planner did not indicate any problems with the locations of occupants in the schedule, it was a secondary objective to determine if occupant interactions occurred.

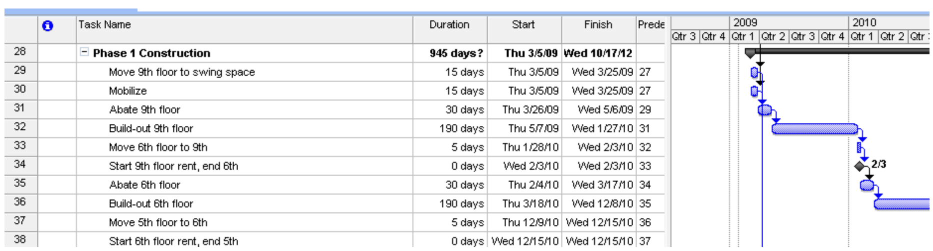
5.3.1. Traditional management methods

The project planner used Excel diagrams (Figure 10-a) and Gantt charts (Figure 10-b) to plan and communicate the moves. The Excel diagrams display when each tenant moves (using the arrows) and on which floors construction occurs (indicated by black bars), but do not list the specific tenants or locations on the floor. The Gantt chart describes to which floors tenants move, but do not indicate the specific tenants or start and end locations. Furthermore, the Excel diagrams and Gantt charts are not integrated, requiring the project planner to ensure consistency between the documents.



10-a.

10-b.



		Task Name	Duration	Start	Finish	Prede
28		**Phase 1 Construction**	**945 days?**	**Thu 3/5/09**	**Wed 10/17/12**	
29		Move 9th floor to swing space	15 days	Thu 3/5/09	Wed 3/25/09	27
30		Mobilize	15 days	Thu 3/5/09	Wed 3/25/09	27
31		Abate 9th floor	30 days	Thu 3/26/09	Wed 5/6/09	29
32		Build-out 9th floor	190 days	Thu 5/7/09	Wed 1/27/10	31
33		Move 6th floor to 9th	5 days	Thu 1/28/10	Wed 2/3/10	32
34		Start 9th floor rent, end 6th	0 days	Wed 2/3/10	Wed 2/3/10	33
35		Abate 6th floor	30 days	Thu 2/4/10	Wed 3/17/10	34
36		Build-out 6th floor	190 days	Thu 3/18/10	Wed 12/8/10	35
37		Move 5th floor to 6th	5 days	Thu 12/9/10	Wed 12/15/10	36
38		Start 6th floor rent, end 5th	0 days	Wed 12/15/10	Wed 12/15/10	37

Figure 10a-b. Excel diagrams (10-a) and Gantt charts (10-b) used to manage the renovation of TC#3 are not at the space level of detail to track occupant locations.

Identifying occupant interactions and tracking vacant space was difficult using traditional methods because the tenant move activities did not detail the name of the tenant or their start and end locations. The activities indicated that all tenants on each floor would move, but in some situations only certain tenants on the floor moved. There was also no explicit documentation of organization information.

5.3.2. Results of 4DRenCheck

This resulted in the schedule containing four double-booked spaces (i.e., tenant-tenant interactions) and thirteen major tenant-crew interactions. All of these interactions were missed by the project planner. After the results of the 4DRenCheck analysis were shown, she agreed that all interactions found were valid and that there were no additional interactions missed by 4DRenCheck. Table 4 contains some of the interactions in the baseline schedule of TC#3 that were automatically identified from the analysis.

Table 4. Major issues found in baseline schedule

NotificationID	StartDate	EndDate	Work Shift	NotificationType	Space ID
N-SHB6AB	09-Mar-09	09-Mar-09	Night	Major - More than 1 tenant is sharing this space	B6AB
N-SHB4CF	27-Mar-09	27-Mar-09	Day	Minor - Tenant-Crew Interaction	B4CF
N-SHB3FE	27-Mar-09	27-Mar-09	Night	Minor - Tenant-Crew Interaction	B3FE
N-SHB463	27-Mar-09	27-Mar-09	Night	Minor - Tenant-Crew Interaction	B463
N-SHB4DC	27-Mar-09	27-Mar-09	Night	Minor - Tenant-Crew Interaction	B4DC
N-SHB523	27-Mar-09	27-Mar-09	Night	Minor - Tenant-Crew Interaction	B523
N-SHB495	08-Feb-10	08-Feb-10	Night	Minor - Tenant-Crew Interaction	B495
N-SHB43E	16-Feb-10	16-Feb-10	Night	Minor - Tenant-Crew Interaction	B43E
N-SHB703	16-Feb-10	16-Feb-10	Night	Minor - Tenant-Crew Interaction	B703
N-SHB4A5	17-Dec-10	17-Dec-10	Day	Minor - Tenant-Crew Interaction	B4A5
N-SHB412	27-Dec-10	27-Dec-10	Day	Minor - Tenant-Crew Interaction	B412
N-SHB4FE	27-Dec-10	27-Dec-10	Night	Minor - Tenant-Crew Interaction	B4FE
N-SHB603	31-Oct-11	31-Oct-11	Day	Major - More than 1 tenant is sharing this space	B603

4DRenCheck also updated building configurations automatically. A pivot table with thorough and detailed occupant location data was utilized to determine the amount of un-utilized swing space (i.e., vacant square footage) in the building and to compare its utilization between two alternative renovation schedules. An analysis of the baseline vacant space (Figure 11, dotted line) highlighted two issues in the schedule. First, a significant increase in vacant space in the building revealed an error in the sequencing of activities. Second, there was approximately 5,000 sf of vacant swing space available during the majority of the project. This indicated that more occupants could be moved into the swing space to enable the renovation crews to work faster. Since the project planner was unsure about the amount of swing space needed, they overcompensated by having more swing space available than was necessary. Based on these two insights, the researchers developed a new renovation schedule which involved re-sequencing the renovation activities and moving a greater number of occupants into swing space. As a result, the space utilization was higher since the amount of vacant space during the renovation (Figure 11, solid line) was reduced significantly.

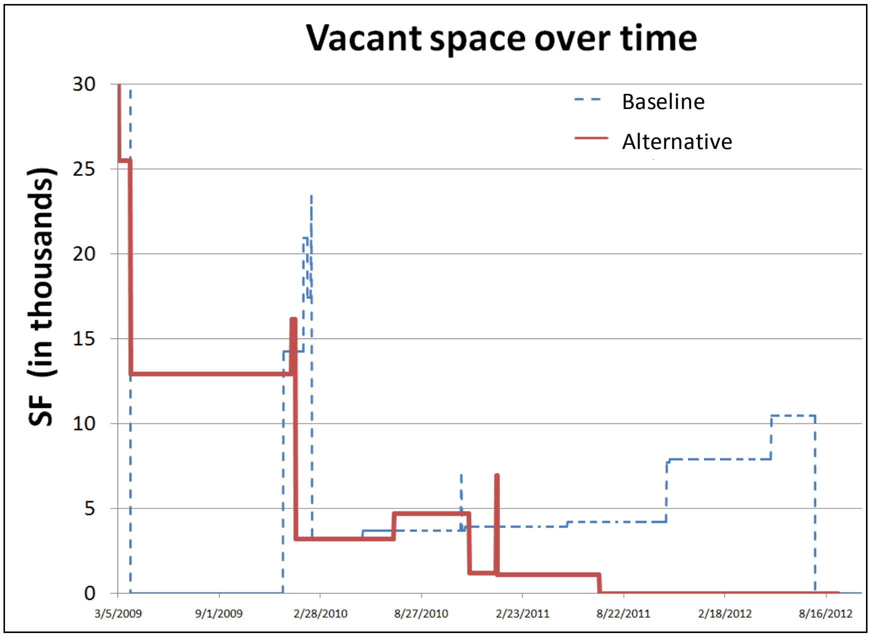


Figure 11. Comparison of vacant space usage in baseline and alternative renovation schedules

5.3.3. Evidence for the power of the IOI method

Prospective validation allowed researchers to demonstrate the power of the IOI method because the VDC method:

Predicts project performance – The method was able to identify tenant-tenant and major tenant-crew interactions that were missed by the project planner. The data generated to analyze the vacant square footage shows that the IOI method is more detailed and thorough than existing methods.

Can be used on design-construction projects – The method was able to analyze 23 tenant moves and 23 construction activities and track 92 building configurations. The results were presented to the planner within a timeframe that she could investigate alternative sequences.

Supports business objectives – Based on the analysis of the vacant space in the building, the project planner decided to consider the alternative sequencing strategy that the researchers proposed. The planner commented, "The suggestion of a new sequence was a welcome surprise." Automatically tracking vacant square footage informed the planner that there was enough vacant space in the building to swing tenants, thus eliminating the cost and effort to find and lease space outside the building.

5.4. Discussion

For the purposes of our validation, prospective validation was an ideal way to test the power of the method. It enabled researchers to demonstrate strong evidence that the IOI method can predict project performance better than planners using existing methods, can be used on real projects, and can support business objectives. The six-criterion framework also provides a way to understand what additional validation tests should be employed in the future. For example, future tests where practitioners use 4DRenCheck would strengthen the external validity of the method. Comparison against actual data on the number of interactions found during renovation should also be tested.

The use of prospective validation also gave the researchers an opportunity to receive feedback, identify barriers to implementation, and identify other uses for the IOI method. In the interviews with the project planners of TC#1 and TC#2, the researchers asked the project planners what the general usefulness of the data (i.e., the locations of occupants and their space sharing abilities at frequent, regular intervals) is on a scale of 0-10, where 0 means that they would not use the data at all to 10, where they would regularly use the data as part of their planning process. Each project planner indicated the usefulness of these data approximately as 8.5 on a scale of 10. Both felt that entering and updating the data in the six tables could be time-consuming, and therefore rated the overall usefulness of the system as 6.5 to 7.0, indicating that other project factors can influence the implementation of new VDC methods.

After seeing the use of the prototype system, the project planners also suggested several additional types of related analyses, which require detailed or thorough occupant location and space sharing data. These analyses also support additional stakeholder business objectives (e.g., workforce tracking for security purposes, analyzing rent billing, and scheduling building maintenance), indicating the usefulness of the data beyond identifying occupant interactions. Without the use of real projects to understand the broader context, the researchers would not be able to understand that the occupant location data could be used for many other types of analysis.

6. Guidelines for implementing prospective validation

Based on the lessons learned from the prospective validation tests and a review of prior implementation guidelines in validation methods, we present guidelines for implementing prospective validation. The planning, execution, and analysis of a prospective validation test is challenging because it involves real projects and requires a testing strategy that ensures direct comparison between the new and existing methods. There are, however, no guidelines on performing prospective validation. Therefore, the remainder of this paper first reviews related implementation guidelines. From these prior guidelines and lessons learned, we present a guideline for performing prospective validation.

6.1. Prior literature in implementation guidelines

A review of literature did not reveal any guidelines for performing prospective validation. Research in mechanical engineering, computational modeling, and consumer research provides general principles regarding validation (Calder et al. 1981; Nash and Wachter 2003; Pedersen et al. 2000), but there are few implementation guidelines. Implementation guidelines in medical research (Friedman et al. 1998; Good 2006) do not apply to VDC validation because the purposes for validation are different. For example, in medical clinical trials, most of the implementation guidelines relate to ensuring statistical significance in the results. This, however, is not applicable to the types of prospective validation tests VDC researchers will perform since the sample sizes in VDC research are not typically statistically significant. Within the VDC domain, there are many examples of implementation guidelines for practitioners to implement new VDC methods, which are not applicable in prospective validation (Khanzode et al. 2008; Mourgues 2009).

We found three implementation guidelines that are directly applicable to the challenges of prospective validation: charrette testing, case study research, and field-based construction research. We focus on these three areas because they provide guidelines for the challenges expected in prospective validation. Charrette testing (Clayton et al. 1998) provides guidelines related to evaluating the performance of VDC methods compared to existing methods. Case study research (Yin 2003) provides guidelines on testing on real projects. Field-based construction research (El-Diraby and O'Connor 2004) provides guidelines related to the challenges of working with design-construction projects. Based on these guidelines and the lessons learned from the application of prospective validation of the IOI method, the next section presents implementation guidelines for performing prospective validation. We reference the prior implementation guidelines when applicable.

6.2. Implementation guidelines for prospective validation of VDC methods

The guidelines are divided into three stages: preparation, execution, and analysis.

Phase 1: Preparation

Develop specific scope and adhere to it – All of the related guidelines emphasize the importance of proper preparation before executing a validation study. Yin recommends developing a protocol for the study which includes specifying the goals of the validation, the procedures for data collection, the questions that will be asked during validation, and the procedures for analyzing the data. This ensures that all aspects of the validation have been thought through.

Define task and metrics – Developing a specific scope requires the researchers to define the task and metrics of the test. Clayton et al. recommend that researchers "devise two or more processes for performing the same task, one to be designated the innovative process [new method] and one to be designated the conventional process [existing method]." The metrics of the task should also be clearly defined. All of the guidelines recommended selecting reliable and quantitative data sources. El-Diraby and O'Connor also recommend that researchers analyze the barriers to data collection to ensure that the data can be collected on real projects. Yin recommends that researchers develop "shell tables" to ensure that all of the quantitative data are collected during each test case. For example, to test the IOI method, the researchers defined identifying occupant interactions as the specific task and measured the performance of the traditional and IOI methods based on the metrics of accuracy, thoroughness, and detail. Ho et al. (2009) provide examples of shell tables to gather metrics for accuracy and thoroughness.

Develop Technology – Researchers should develop a prototype that is robust enough to handle real project data (i.e., large data sets, complex relationships). The researchers should anticipate the type of data that will be encountered. Since the prototype is used by the researchers, not practitioners, the user interface does not need to be sophisticated. For example, 4DRenCheck was developed to handle large project data, but did not have a sophisticated user interface.

Select projects – Projects should meet the following minimum criteria:

- The project must be in the correct stage where practitioners are performing the task using existing methods as part of their regular duties.

- The project must have a timeline where the researchers are confident that they can perform the task with the new method in a timeframe such that interventions could be made.

- Practitioners are willing to share data and are open to consider ideas that could result from the analysis.

Section 4.3 describes how projects were selected to validate the IOI method.

Phase 2: Execution

Document as many project performance metrics and project data as possible – Yin indicates that there is no clear cut-off point for gathering data. While the minimum amount of data gathered should be the quantitative metrics defined in the planning stage, additional data regarding project characteristics or processes should be gathered as well (Table 3). Since the analysis of the data may reveal unanticipated results, gathering as much data at this stage is recommended. For example, the researchers wished they had gathered additional metrics on the frequency and amount of time project planners took to identify occupant interactions. This could have provided further insights on the impact of the IOI method.

Ensure that the traditional method is documented before results from the new method are revealed to the practitioners – To ensure no learning effects from practitioners knowing the results of the new method, the traditional method must be completed and documented before the results from the new method are revealed (Clayton et al. 1998). No further comparison data can be utilized after the results are revealed to the practitioners. Researchers should utilize the study protocol and shell tables prepared in the first phase to ensure all data are collected. If possible, two separate interviews with practitioners should be scheduled: the first to discuss and gather metrics of the traditional method and another to review and discuss the results of the new method. This allows time for the researchers to review and ensure that all of the data from the traditional method are collected before discussing the results of the new method with the practitioner.

Traditional method is carried out without knowledge of automated method results – Practitioners using the traditional method should perform the task as part of the project. Therefore, researchers must choose the timing of the validation to coincide with the project schedule. For example, in TC#2, the project planners analyzed the renovation schedule regularly to identify occupant interactions during monthly project meetings.

Automated method is carried out without knowledge of traditional method results **–** Once the practitioner has given the researchers the input documents, the researchers can begin to implement the new method. Since the automated and traditional methods are done in parallel, the researchers should not know the results of the existing method beforehand. Once the results from the new method are determine and measured, the researcher should then gather the results from the traditional method from the practitioners.

Present results and gather feedback from practitioners **–** Once the results of the traditional and new method are completed, researchers can then determine whether the results of the new method could result in project interventions. If so, the results and suggested interventions should be presented to the project planner. Yin recommends that researchers be as "naïve" as possible in order to allow the practitioners to explain rival theories or refute the interventions. El-Diraby and O'Connor indicate that feedback from experts is one of the most important aspects of field-based construction research and that one-on-one interviews allow researchers to better understand the scope of the problem. Researchers again should utilize the study protocol to ensure all aspects of the problem are discussed with the practitioner.

Phase 3: Analysis

***Analyze quantitative data* –** The quantitative data from the shell tables should be examined to determine how the new method performed relative to the existing method. Ho et al. (2009) provide a detailed comparison between the traditional and IOI methods, based on accuracy, thoroughness, and detail. While practitioners would be interested mainly in finding better methods, researchers are interested in any result, regardless of whether the new method performs better, the same, or worse.

***Analyze broader context* -** Researchers should also examine the broader context of the problem to understand additional uses or benefits from implementing the new method. Yin recommends explanation building as a possible method to examine broader consequences. In explanation building, the researcher develops a hypothesis based on one test case and examines the other test cases to see if the hypothesis holds true. For example, the researchers saw that the data from the IOI method was useful for other analysis needs in one test case, which prompted further examination of this hypothesis in the other test cases.

Refine test protocol - Finally, based on the results of the analysis, the researchers should ask themselves if additional metrics or data should be collected and understand what the lessons learned from the study are. This ensures that any future validation studies can incorporate the insights based on the current study. For example, the researchers would like to gather additional metrics on the frequency of identifying interactions, the amount of time the analysis takes for each method, and to further examine what additional uses the occupant location and space sharing data have.

7. Limitations and Extensions

7.1. Limitations and future extensions of the six-criterion framework

Incorporate additional VDC research methods – The framework is limited to VDC research which involves the development of a new method that can be implemented in a computer prototype. There are additional types of VDC research, such as observational studies of VDC implementation (Hartmann and Levitt 2009). The framework could be expanded to incorporate these research methods.

Incorporate additional criteria for power – This framework developed a six-criterion approach based on Kunz and Fischer's definition of VDC. There may be additional definitions of power which could create additional criteria and parameters for selecting a validation method.

Validate the framework – The framework itself should also be validated. Future work could include analyzing the power of different types of validation in past VDC research according to the framework and comparing the results to what practitioners and other researchers think about the power of the different VDC methods.

7.2. Limitations and future extensions of the implementation guidelines

Additional guidelines on metrics – Prior VDC research shows that many VDC methods are validated based the same metrics (e.g., speed, consistency, accuracy) (Akinci et al. 2002; Haymaker et al. 2003). Additional guidelines could be developed with respect to identifying which metrics to measure and how to measure each metric.

Development of a project characteristics and data shell table – One challenge identified in the implementation guidelines is determining what data to gather. As more researchers utilize prospective validation, a shell table of project characteristics and data could be developed to help future researchers gather a comprehensive set of data.

Guidelines on reporting prospective validation tests – The implementation guidelines do not discuss how the results of prospective validation tests should be reported. The combination of both quantitative information (i.e., project characteristics and data, validation metrics) and qualitative information (i.e., project context, feedback from practitioners) creates various ways to report these results. Other implementation guidelines on reporting case studies (Yin 2003) or quantitative information (Tufte 2001) could be examined to determine how to best report prospective validation results.

8. Conclusions

External validation is an important step to determine the power of new VDC methods and to translating these methods from theory to application on real projects. This paper provides a six-criterion framework which relates the objectives of VDC methods (i.e., predict project performance, use on design-construction projects, and support business objectives) to specific parameters that can demonstrate this power. Researchers can utilize this framework to develop a trajectory for validating new VDC methods, evaluate different validation methods, and select the best validation method to meet the purpose of the validation. It provides a way to evaluate and determine when emerging validation methods, such as prospective validation, should be used.

Through the application of prospective validation in testing the IOI method, this paper also demonstrates that prospective validation provides strong evidence of the power of new VDC methods through a direct comparison between new and existing methods on real projects, within a timeframe to affect future project decisions, and providing results that are believable by expert practitioners. However, the limitations of prospective validation are that the new method is not implemented by practitioners or compared against actual performance data (since showing the results of the new method to practitioners alters the project trajectory). Researchers will need to utilize different validation methods to meet these other purposes. The implementation guidelines provide a process for researchers to plan, execute, and analyze a prospective validation study. Ultimately, prospective validation not only enables researchers to benchmark and measure advancements in the AEC industry, but can provide practitioners with insights into which VDC methods should be implemented and when and how they can be implemented.

9. References

Abowitz, D., and Toole, M. (2009). "Mixed Method Research: Fundamental issues of design, validity and reliability in construction research." *Journal of Construction Engineering and Management*, in print.

Akinci, B., Fischer, M., and Kunz, J. (2002). "Automated Generation of Work Spaces Required by Construction Activities." *Journal of Construction Engineering and Management*, 128(4), 306-315.

Akinci, B., Fischer, M., Kunz, J., and Levitt, R. (2000). "Formalization and Automation of Time-Space Conflict Analysis." *Working Paper #059*, Center for Integrated Facility Engineering, Stanford University.

Calder, B., Phillips, L., and Tybout, A. (1981). "Designing Research for Application." *Journal of Consumer Research*, 8(2), 197-207.

Carley, K. (1995). "Computational and Mathematical Organization Theory: Perspective and Directions." *Computational and Mathematical Organization Theory*, 1(1), 39-56.

Clayton, M. J., Kunz, J., and Fischer, M. (1998). "The Charrette Test Method." *CIFE Technical Report #120*, Stanford University.

Collier, E., and Fischer, M. "Visual based scheduling: 4D modelling on the San Mateo County Health Centre." *3rd ASCE Congress on Computing in Civil Engineering*, Anaheim, CA, 800-805.

Cook, T. D., and Campbell, D. T. (1979). *Quasi-experimentation: design & analysis issues for field settings*, Houghton Mifflin, Boston.

Dawood, N., and Sikka, S. (2008). "Measuring the effectiveness of 4D planning as a valuable communcation tool." *ItCon*, 13, 620-636.

Eastman, C., Lee, J.-m., Jeong, Y.-s., and Lee, J.-k. (2009). "Automatic rule-based checking of building designs." *Automation in Construction*, 18(8), 1011-1033.

El-Diraby, T., and O'Connor, J. (2004). "Lessons learned in designing research methodology in field-based construction research." *Journal of Construction Engineering and Management*, 130(2), 109-114.

Flood, I., and Issa, R. (2009). "Empirical Modeling Methodologies for Construction." *Journal of Construction Engineering and Management*, in print.

Friedman, L., Furberg, C., and DeMets, D. (1998). *Fundamentals of clinical trials*, Springer-Verlag, New York.

Good, P. I. (2006). *A Manager's Guide to the Design and Conduct of Clinical Trials*, John Wiley & Sons, Inc., Hoboken, New Jersey.

Hagan, S., Ho, P., and Matta, C. (2009). "BIM: The GSA Story." *Journal of Building Information Modeling* (Spring 2009), 28-29.

Han, C. S., Law, K., and Kunz, J. (2000). "Computer Models and Methods for Disabled Access Analysis Design Environment." *Technical Report #123*, Stanford University, Stanford.

Hartmann, T., and Levitt, R. (2009). "Understanding and Managing 3D/4D Model Implementation at the Project Team Level." *Journal of Construction Engineering and Management*, in print.

Haymaker, J., Chachere, J., and Senescu, R. (2008). "Measuring and improving rationale clarity in a unicersity office building design process." *Techincal Report #TR178*, Stanford University, Stanford.

Haymaker, J., and Fischer, M. (2001). "Challenges and benefits of 4D modeling on the Walt Disney Concert Hall project." *CIFE Working Paper 64*, Center for Integrated Facility Engineering, Stanford University, Stanford.

Haymaker, J., Suter, B., Kunz, J., and Fischer, M. (2003). "PERSPECTORS: Automating the Construction and Coordination of Multidisciplinary 3D Design Representations." *Technical Report #145*, Center for Integrated Facility Engineering, Stanford University.

Ho, P., and Fischer, M. (2009). "An examination of current practices in identifying occupant interactions in renovation projects." *CIFE Working Paper #121*, Stanford University, Stanford.

Ho, P., Fischer, M., and Haymaker, J. (2009). "Automated Identification of Occupant Interactions in Renovations of Occupied Buildings." *CIFE Working Paper #122*, Stanford University, Stanford.

Jongeling, R., Kim, J., Fischer, M., Mourgues, C., and Olofsson, T. (2008). "Quantitative analysis of workflow, temporary structure usage, and productivity using 4D models." *Automation in Construction*, 17(6), 780-791.

Khanzode, A. (2007). "Enabling the lean project delivery process through the application of virtual design and construction technologies," Engineer Thesis, Stanford University, Stanford.

Khanzode, A., Fischer, M., and Reed, D. (2008). "Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project." *ITcon*, 13(Special Issue: Case studies of BIM use), 324-342.

Kidwell, C., Starkman, S., Eckstein, M., Weems, K., and Saver, J. (2000). "Prospective Validation of the Los Angeles Prehospital Stroke Screen (LAPSS)." *Stroke*, 31(1), 71-76.

Koo, B., and Fischer, M. (2000). "Feasibility study of 4D CAD in commercial construction." *Journal of Construction Engineering and Management*, 126(4), 251-260.

Kunz, J., and Fischer, M. (2008). "CIFE Research Questions and Methods." CEE 320 Presentation, 17 October 2008, Stanford University, Stanford.

Kunz, J., and Fischer, M. (2009). "Virtual Design and Construction: Themes, Case Studies and Implementation Suggestions." *CIFE Working Paper #097*, Stanford University, Stanford.

Lucko, G., and Rojas, E. (2009). "Research Validation: Challenges and Opportunities in the Construction Domain." *Journal of Construction Engineering and Management*, in print.

Lynch, J. (1982). "On the external validity of experiments in consumer research." *Journal of Consumer Research*, 9(3), 225-239.

Maile, T., Fischer, M., and Bazjanac, V. (2007). "Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective." *CIFE Working Paper #WP107*, Stanford University, Stanford.

Manning, R., and Messner, J. (2008). "Case Studies in BIM implementation for programming of healthcare facilities." *ITcon*, 13(Special Issue: Case Studies of BIM Use), 246-257.

Microsoft. (2007). "Microsoft Office Access 2007." Microsoft Office, Redmond.

Mourgues, C. (2009). "Method to produce field instructions from product and process models," Ph.D., Stanford University, Stanford.

Nash, R., and Wachter, A. (2003). *Pharmaceutical Process Validation*, Marcel Dekker, Inc., New York.

Pedersen, K., Emblemsvag, J., Bailey, R., Allen, J., and Mistree, F. (2000). "Validating design methods and research: The validation square." ASME Design Engineering Technical Conference, ASME, Baltimore, MD.

Persson, B. (2005). *Sustainable City of Tomorrow: B01 - Experiences of a Swedish Housing exposition*, Forskningsrådet Formas, Stockholm.

Shah, R. K., Dawood, N., and Castro, S. (2008). "Automatic Generation of Progress Profiles for Earthwork Operations Using 4D Visualisation Model." *ITcon*, 13, 491-506.

Staub-French, S. (2002). "Feature-Driven Activity-Based Cost Estimating," PhD, Stanford University, Stanford.

Thomsen, J., Levitt, R., Kunz, J., Nass, C., and Fridsma, D. (1999). "A Trajectory for Validating Computational Emulation Models of Organizations." *Journal of Computational & Mathematical Organization Theory*, 5(4), 385-401.

Torrent, D. G., and Caldas, C. (2009). "Methodology for automating the identification and localization of construction components on industrial projects." *Journal of Construction Engineering and Management*, 23(1), 3-13.

Tufte, E. (2001). *Visual display of quantitative information*, Graphics Press, Cheshire.

U.S. General Services Administration. (2009). "GSA Project Information Portal." Internal Website, Accessed 15 September, Washington DC.

Yin, R. K. (2003). *Case Study Research: Design and Methods*, Sage Publications.