www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

PROSPECTIVE VALIDATION OF VIRTUAL DESIGN AND CONSTRUCTION METHODS

SUBMITTED: December 2010
PUBLISHED: June 2013
EDITOR: Robert Amor

Peggy Yee, Researcher
Stanford University
peggy.yee@gsa.gov

Martin Fischer, Professor
Stanford University
fischer@stanford.edu

Calvin Kam, Consulting Assistant Professor
Stanford University
calvin.kam@stanford.edu

SUMMARY: *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.

KEYWORDS: *4D, renovation, validation, prototype, implementation guidelines*

REFERENCE: *P. Yee, M. Fischer, C. Kam, Prospective validation of virtual design and construction methods. Journal of Information Technology in Construction (ITcon), Vol. 18, pg. 214 - 239, http://www.itcon.org/2013/11*

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. Fig. 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

FIG 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 withan 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. Fig. 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).

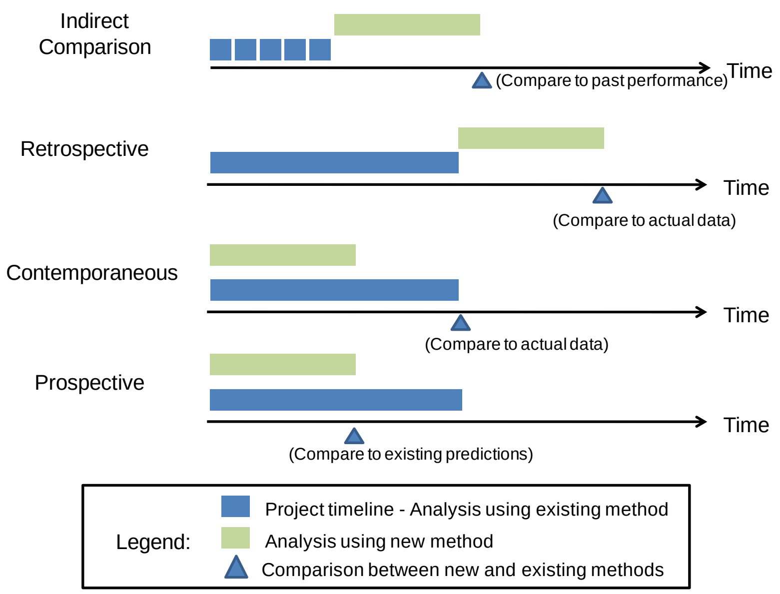


FIG 2: Indirect comparison, retrospective, contemporaneous, and prospective validation methods differ based on when the new method is tested relative to the project timeline, when the results are compared, and what type of data is used for the comparison.

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. Section 4 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.

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	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. Fig. 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.

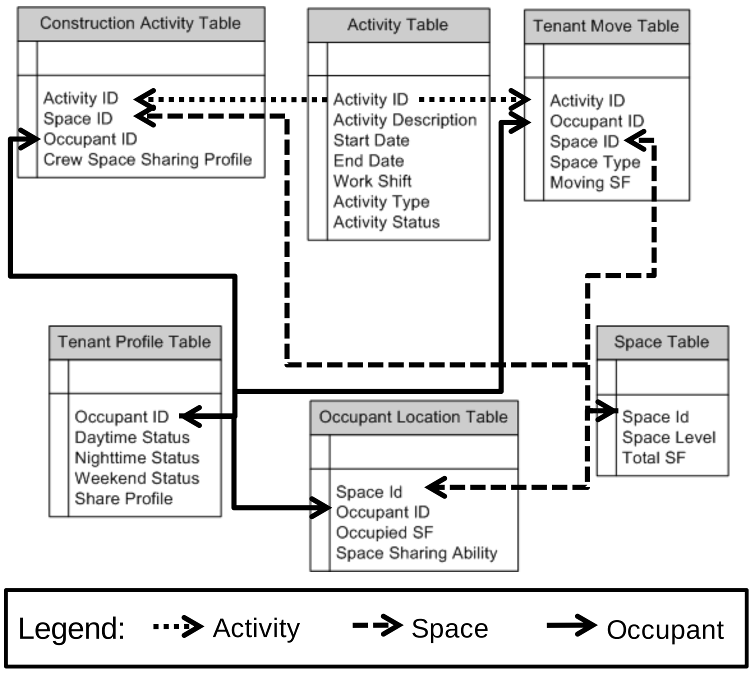


FIG 3: Tables and properties in 4DRenCheck prototype allow the integration of activity, space, and occupant information

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 Section 4.3.

- ***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 Section 5. 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:

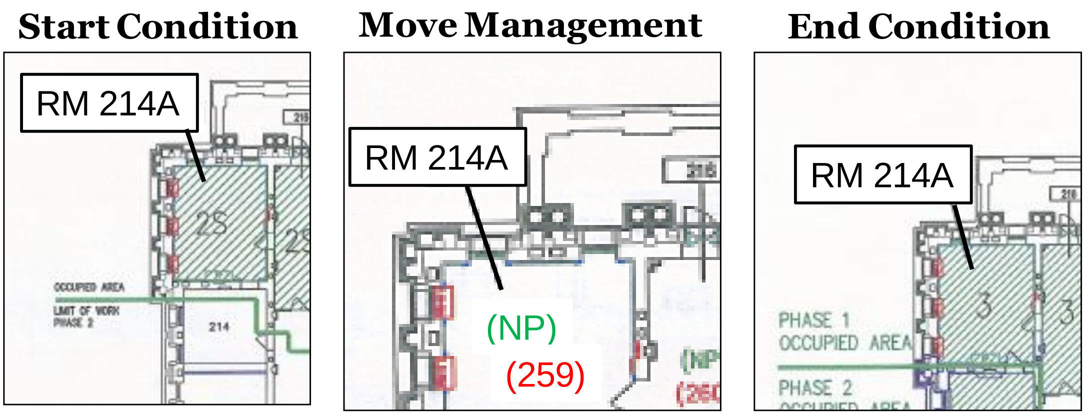
Difficult tenants with changing requirements – The tenants were head strong and temperamental at times. Sometimes, tenants argued over occupying the same space. Higher levels of the organization had to intervene to make a decision on who would ultimately occupy the space. These decisions, however, could 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

Fig. 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 (Fig. 4-a,c) and 2D CAD drawings indicating move to and from locations for each space (Fig. 4-b). For example, Fig. 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.*

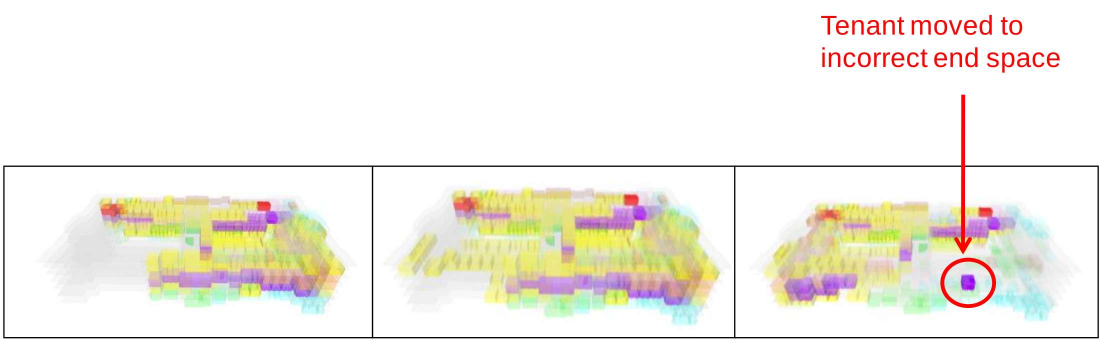
FIG 4a-c: Traditional move management documents. Start locations of tenants (4-a), move activities (4-b), and end locations (4-c) are managed in three separate sets of 2D CAD drawings. For each space in the move management drawing, one label (e.g., NP) indicates to which space a tenant will be moving, 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 and 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. Fig. 5 shows the progression of tenants from their start locations (Fig. 5-a), through the moves (Fig. 5-b), to their end locations (Fig. 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.*

FIG 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 8^{th}, 9^{th}, and 10^{th} floors, with the 10^{th} 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 10^{th} floor. Condensate piping work was scheduled throughout the entire building during daytime and nighttime shifts, depending on the floor. For example, on the 16^{th} 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 19^{th} 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

Fig. 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

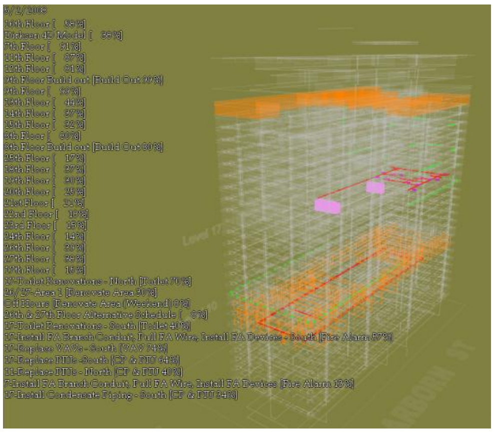


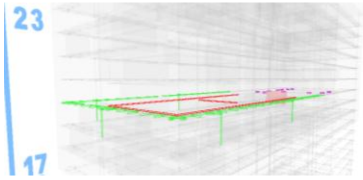
FIG 6: The traditional planning methods used on TC#2 included a CPM schedule, day/night/weekend activities matrix, and 4D Model.

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 Fig. 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

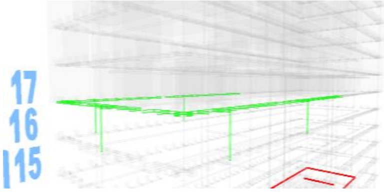


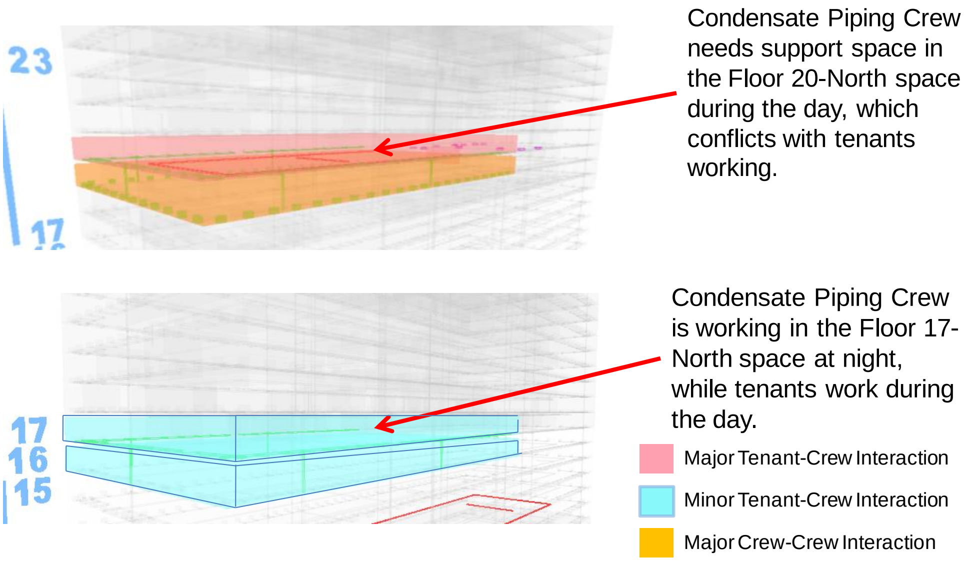
FIG 7: The current representation of the project schedule and 4D model of the condensate piping activity does not allow project managers to distinguish the impact of construction workshifts on tenants.

5.2.2 Results of 4DRenCheck

Fig. 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 (Fig. 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 (Fig. 8-b).

8-a



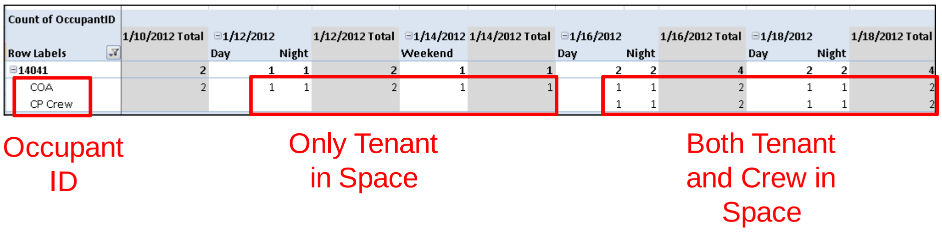
8-b

FIG 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 (Fig. 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.



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

FIG 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.

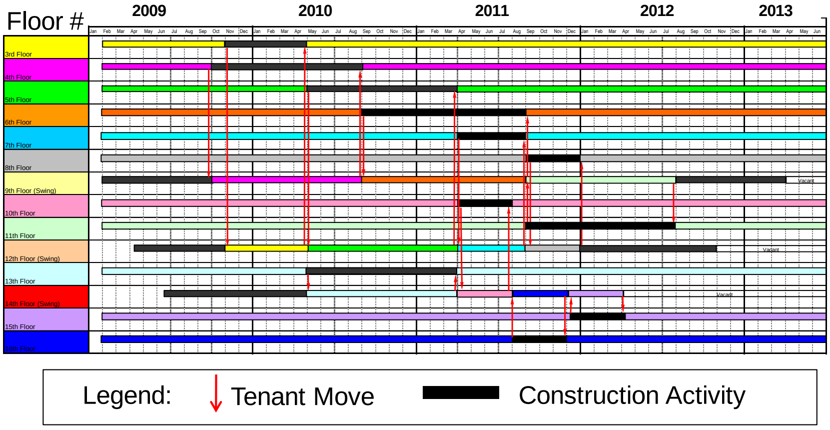
The main project challenge faced by the project planner was:

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.

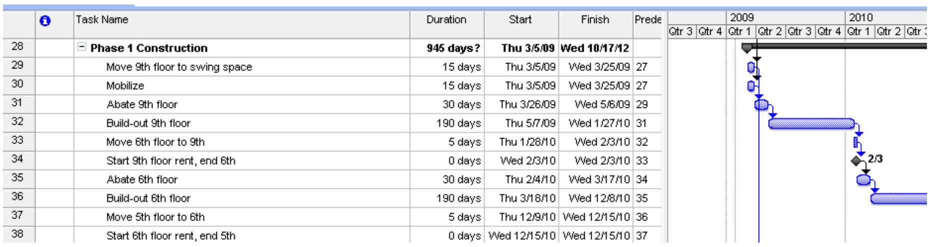
The focus of the analysis was to track the locations of occupants over time to determine the amount of swing space required for the renovation. Since the project planner did not indicate any problems with the locations of occupants in the schedule, it was a secondary objective to determine if occupant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

5.3.1 Traditional management methods

The project planner used Excel diagrams (Fig. 10-a) and Gantt charts (Fig. 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.



		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

10-b.

FIG 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 (Fig. 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 (Fig. 11, solid line) was reduced significantly.

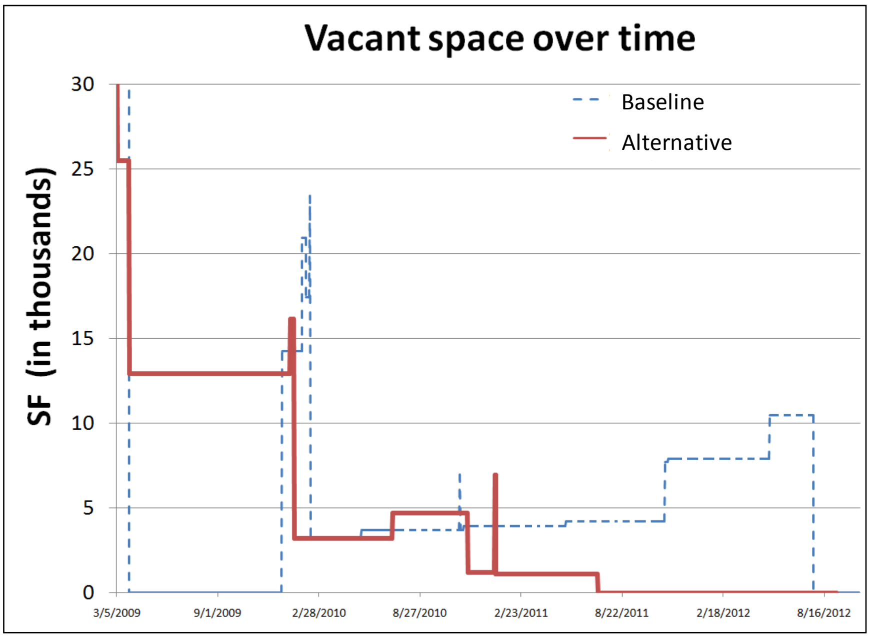


FIG 11: Comparison of vacant space usage in baseline and alternative renovation schedules

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, Section 6. 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 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. ACKNOWLEDGEMENTS

The authors wish to thank Charles Matta and the project teams from the U.S. General Services Administration (GSA) for their support and access to project information. They are also thankful for the support of this research through the Visiting Fellows program of the Center for Integrated Facility Engineering (CIFE) and the Stanford Graduate Fellowship Program at Stanford University. This work is also supported by the National Science Foundation’s Graduate Fellowship Program. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or the U.S. General Services Administration.

10. REFERENCES

Abowitz, D., and Toole, M. (2010). "Mixed Method Research: Fundamental issues of design, validity and reliability in construction research." *Journal of Construction Engineering and Management*, 136, 108-116.

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. (2010). "Empirical Modeling Methodologies for Construction." *Journal of Construction Engineering and Management*, 136, 36-48.

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, CT.

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.