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CIFE Seed Proposal Summary Page
2007-2008 Projects

Proposal Title: *4D-Checker:* Analyzing Renovation Schedules for Requirements Compliance

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Abstract (up to 150 words):

Renovation planners have the greatest opportunity to achieve breakthrough schedule performance during the development of the renovation phasing schedule. Planners must balance the execution of renovation work with the ongoing operational requirements of the building occupants. The success of the schedule depends upon whether it satisfies project-specific requirements throughout the renovation. We propose to define a representation of renovation planning elements and to develop a method to analyze schedules automatically in 4D. The practical implication of this research will be a method to enable planners to check schedules more quickly and comprehensively by explicitly considering occupant requirements. This proposal extends prior CIFE work on 4D modeling from new construction to building renovation. It adds an automated analysis component to 4D modeling and considers occupant requirements explicitly in the automated assessment of the quality of a renovation schedule in its spatial and temporal context.

Meeting the Challenges of Renovation Scheduling

> *"Occupant X has threatened to sue us if they do not move to the 16th floor of the building."*
>
> *"In revising the schedule, I know there are parts of the schedule I can re-use, but I'm not sure how…"*
>
> *~ Various GSA Renovation Planners*

Schedule performance is a 2015 breakthrough business objective for CIFE members (CIFE 2007). With respect to scheduling, renovation projects have several unique considerations that make it different from planning and scheduling new construction. For example, coordination constraints (i.e., coordination with occupants) and physical constraints (i.e., the existing building) must be considered when planning renovation projects (Whiteman and Irwig 1988). Phase planning typically occurs during the design stage of a renovation project. Its purpose is to develop a high-level project phasing schedule that describes the relationships between occupants and construction work. Typically, it only shows high-level construction activities and dates of occupant moves.

Breakthrough schedule performance on renovation projects is difficult because planners need to keep track of multiple stakeholders with multiple requirements and evaluate the impacts of changes in the schedule. During design, multiple stakeholders are often involved in the design process (Haymaker et al. 2005); this is no different with respect to phase planning. Planners must analyze the schedule from multiple perspectives because multiple stakeholders with differing requirements are involved. Planners must work with occupants to understand not only requirements for the final design, but also the occupant requirements during renovation (e.g., the best and worst times to move). The problem is further exacerbated because unforeseen changes in requirements, scope, or design affect the phasing schedule, causing planners to re-plan the project. The absence of a formal model to represent the requirements of a renovation schedule and the lack of a consistent set of metrics makes these changes difficult to understand and are not easily observable.

To achieve breakthrough schedule performance on renovation projects, planners must check the phasing schedule against project-specific requirements and metrics to determine the feasibility and quality of the schedule. Phase planning is the process of developing a feasible renovation plan which balances construction and occupant requirements. This inherently requires planners to check requirements against a phasing plan. Planners need four fundamental elements to check the schedule: occupant requirements, construction requirements, representation of the building configuration, and a phase schedule.

We propose to develop a "4D Checker," which allows planners to automatically check the phasing schedule quickly and comprehensively, enabling breakthrough schedule performance. The checking process can be automated because the common denominators for the four fundamental elements are spatial and temporal attributes. Spatial and temporal attributes provide the necessary link between requirements and phasing, which will allow planners to evaluate a phasing schedule against a set of requirements. The schedule should also be evaluated with a comprehensive set of project-independent global metrics (e.g., move costs, renovation costs, duration, number of occupants with secondary moves). This process would allow planners to manage requirements to comprehensively evaluate and compare phasing schedules.

Observations from current renovation projects

Observed Project A (Figure 1) underscores the difficulty in managing multiple stakeholders and multiple requirements. This project involved the renovation of a courthouse/office building, which included both court-related and non-court-related occupants. The project required some courtrooms to remain operational throughout the renovation. The project team was so focused on the court-related occupant requirements that they failed to take into account several non-court occupant requirements. The result was insufficient space allocated for non-court occupants, a major flaw resulting in the need for two extra floors on the terrace of the building.

Picture Removed.

Figure 1. On Observed Project A, failure to take into account all of the occupants resulted in the need to build two extra floors on the building to fit everyone in the building.

Observed Project B (Figure 2) emphasizes the uncertain nature of requirements during phase planning and difficulty in understanding the impact on the schedule. The schedule was changed based upon changing construction requirements (due to a design change in the curtain wall to the building façade). Project requirements and phasing schedule, however, were linked in a static document. This method did not show how a change in requirements would affect the phasing schedule. Instead, the planner had to manually check the impact on the schedule. Although the project manager had several ideas on how to change the schedule, it was not immediately apparent how to revise the existing schedule to accommodate this change.

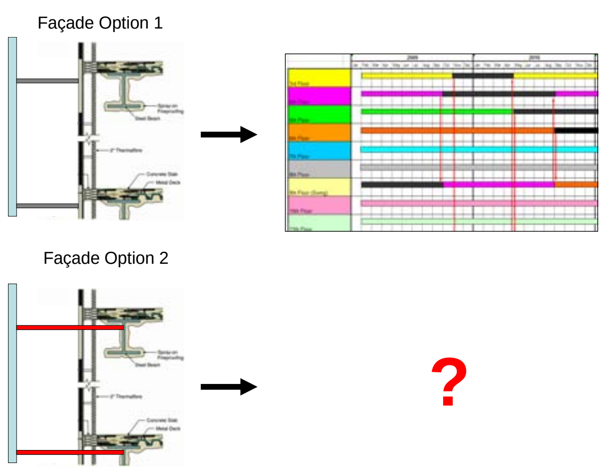


Figure 2. On Observed Project B, Changes in design options affect the schedule. It was not immediately clear to planners which parts of the original schedule could be re-used.

Points of Departure: Building on prior CIFE research

Based upon our motivating examples, we propose to develop a "4D Checker" to address these renovation challenges. A 4D checking system would enable planners to explicitly manage requirements (i.e., the challenge from Observed Project A) and would enable planners to understand the impact of changing requirements on the schedule (i.e., the challenge from Observed Project B). To develop this system, however, we will need to represent four renovation planning elements that were found in our observed projects: 1) building space configuration, 2) occupant requirements, 3) construction requirements, and 4) phasing schedule. We will also need a method to analyze these elements in order to check the schedule.

CIFE's rich tradition in virtual design and construction (VDC) research provide the three main points of departure: 4D activity representation, requirements management models, and 4D/BIM model-based analysis methods.

- **4D activity representation:** Current 4D representations of activities (Aalami 1998; Darwiche et al. 1989) provide a useful starting point for modeling phasing activities, but are unable to track occupant specific requirements (e.g., the number of courtrooms available during renovation) and are unable to track occupant movement throughout renovation.
- **Requirements management models:** Current requirements management models separate the requirements from the product model (Kiviniemi 2005). This does not address occupant requirements during renovation, nor does it show how changes in requirements affect the schedule.
- **4D/BIM model-based analysis:** Current 4D analysis methods enable planners to use 4D models to detect geometric conflicts (Akinci et al. 2002), but are unable to check for project-specific requirements (e.g., number of courtrooms, number of occupant moves).

4D Process modeling and 4D/BIM model-based analysis methods have focused only on construction activities (and not the occupant), while requirements management models have typically only focused on the occupant (and not construction). Both occupant and construction processes must be integrated in renovation planning. The proposed research will extend these points of departures to address these limitations.

Synergies with POP, Narratives, and Decision Dashboard

Although not direct points of departure, POP, Narratives and Decision Dashboard (Fischer et al. 2005; Haymaker et al. 2005; Kam 2005) are closely related to this research. We believe these VDC methods can inform the inputs to our 4D checker. In return, this research can provide the schedule analysis capabilities that can inform the use of POP, Narratives, and Decision Dashboard. As part of our research tasks, we propose to conduct a charrette to experiment on how these technologies can interface with each other.

4D Checker: Our Proposed System

We propose to build on these points of departure by developing a system that separates requirements from the phasing schedule. We first define a representation for the fundamental renovation elements: 1) building space configuration, 2) occupant requirements, 3) construction requirements, and 4) phasing schedule. Based upon these representations, we then define a method to analyze the phasing schedule with respect to the requirements and metrics. Finally, we define a representation for visualizing conflicts and unsatisfied requirements in 4D. Figure 3 diagrams the process. The bold, continuous lines indicate user-entered information, while the dotted lines indicate the automated analysis method.

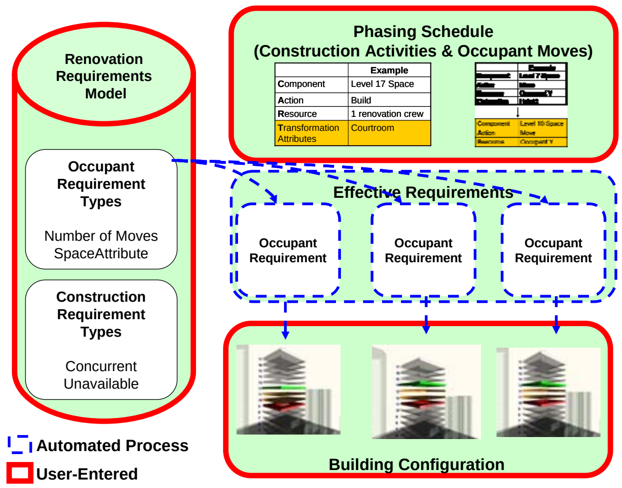


Figure 3. The proposed system allows users to enter occupant and construction requirements, phasing schedule, and building configuration (bold, continuous line). Based upon these inputs, the computer automatically analyzes the phasing schedule for requirements compliance (dotted line).

Example Problem

A fictitious, but realistic, example of a renovation planning problem and its proposed solution is provided in the following sections. In this example, the planner must evaluate the phasing schedule against a specific set of requirements. Each renovation element (i.e., existing and final building configurations, the occupant and construction requirements, and the phasing schedule) are described as well as the proposed reasoning method and visualization output.

Step 1. Planners enter four renovation planning elements (RPE 1-4)

The planners (e.g., architect, occupants, construction manager, scheduler) work together to enter information on four renovation planning elements (RPE): the building configuration, occupant requirements, construction requirements, and phasing schedule. Each element is described in detail.

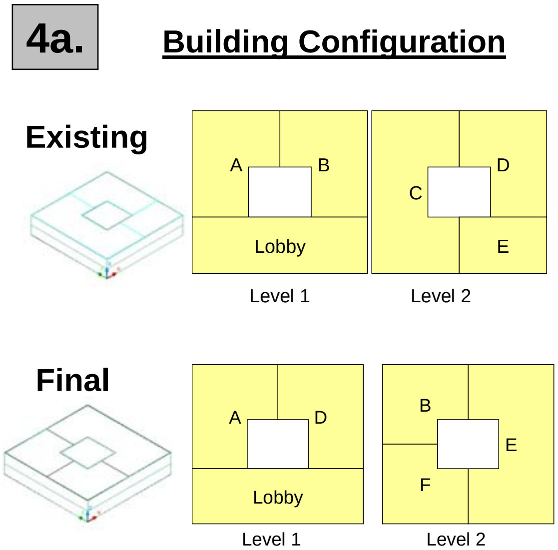
RPE 1: Building Configuration

Planners define the characteristics of the existing and final building configuration (Figure 4a). Unique space IDs allow for automated tracking of spaces during the checking process. Each space must have the following attributes: an occupant, a function, and a square footage. The building spaces and its attributes can be tracked throughout the renovation.

RPE 2 & 3: Occupant and Construction Requirements

Each occupant (e.g., a department) has different space and time requirements based upon its business functions. For example, an office that has many people coming in and out should be located near the lobby or an office with very specialized equipment and space functions should be moved only once. We define Occupant Requirement Templates (ORT) to store information about occupant requirements (Figure 4b).

Construction requirements define the scope of the specific project (e.g., Space 2-3 is required to be a courtroom) and project-independent processes (e.g., asbestos removal requires full-floor work zones). We define Construction Requirement Templates (CRT) to store information about construction requirements (Figure 4c).



4b. Occupant Requirement

	Field	Example
User-Entered	Occupant	E
	Requirement Type	Space Attribute
	Required Value	Secure
	Effective Period	Total Duration
	Requirement Status	Hard

4c. Construction Requirement

	Field	Example
User-defined	Requirement Type	Concurrent
	Requirement Status	Hard
	Component	SP 2-1,2-2,2-3,2-4
	Action	RemoveAsbestos
	Affected Space	
	Space Attributes	
	Effective Period	Total Duration

Each requirement has the following attributes: a required value, an analysis algorithm to measure the requirement, and an effective period. The effective period indicates when the requirement should be checked in the phasing schedule. Different requirements have different effective periods. For example, requirements may only be required for a few months (e.g., the worst months to move), while other requirements must be met throughout the entire renovation process (e.g., security). ***These requirement templates extend from Kiviniemi's (2005) requirements model and enable planners to dynamically understand the impact of requirement changes on the phasing schedule.***

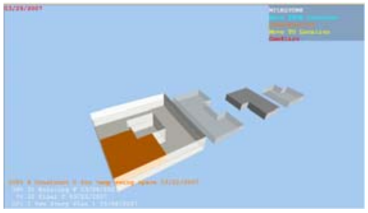
Each requirement also has a status, which prioritizes all requirements in the analysis. The status of each requirement can be: hard, soft, or tentative. Hard requirements are those that must be satisfied in order for the schedule to be feasible, while established soft requirements are requests which do not absolutely need to be satisfied. Tentative requirements have the lowest priority; they are pending requirements that the planner would like to investigate. Planners may indicate the status of requirements to help determine tradeoffs between schedules.

Figure 4. In this example, in the existing building, Occupant E is in a secure space, while Occupant C is not (4a). Occupant E requires secure space throughout the entire renovation process (4b). Asbestos removal is required to occur on the entire second floor concurrently (4c).

RPE 4: Phasing Schedule

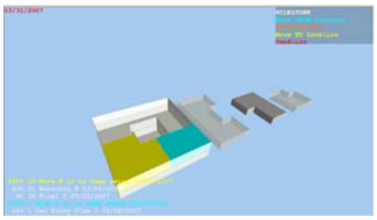
Planners must also specify the phasing schedule to analyze. All phasing activities are based upon the Component, Action, and Resource (<CAR>) activity representation (Aalami 1998; Darwiche et al. 1989). Construction activities also track the end attributes of a space (e.g., secure, courtroom) (Figure 5a). Occupant move activities track the occupant's name, start space, and end space (Figure 5b). ***Our representation of the phasing schedule enables planners to track both occupant locations and space attributes over time, which are critical to renovation planning, but do not exist in current 4D process representations.***

5a. <u>Construction Activity</u>



		Field	Example (Construction Activity)
User-defined	For all activities	Component	Space 2-4
		Action	TempConstruct
		Resources	1 renovation crew
		Start Date	3/22/2007
		End Date	3/28/2007
		Duration	5 days
	Construction	End Space Attribute(s)	Office
	Occupant Move	End Space	
		Occupant	
Computer-based		Unique ID	ACT-6

5b. <u>Occupant Move</u>

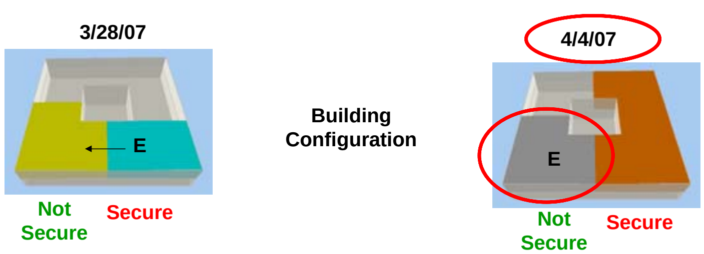


		Field	Example (Occupant Move)
User-defined	For all activities	Component	Space 2-3
		Action	Move
		Resources	
		Start Date	3/29/2007
		End Date	3/30/2007
		Duration	2 days
	Construction	End Space Attribute(s)	
	Occupant Move	End Space	Space 2-4
		Occupant	E
Computer-based		Unique ID	ACT-7

Figure 5. This representation shows that Space 2-4 is being constructed for swing space (5a), and that Occupant E will move into that space temporarily (5b).

Step 2. The computer "checks" the phasing schedule automatically

Figure 6 shows the proposed method to check the phasing schedule. At each user-specified date (e.g., Figure 6 – 3/28/07 and 4/4/07), our system first determines the state of all spaces in the model during each specified time interval. Our system then checks which requirements are in effect and measures whether or not they have been satisfied. If a requirement is not satisfied, the date and space of the unsatisfied requirement is shown in the results. ***Our method of analysis enables planners check project-specific requirements against the phasing schedule.***



	Field	Example
User-Entered	Occupant	E
	Requirement Type	Space Attribute
	Required Value	Secure
	Effective Period	Total Duration
	Requirement Status	Hard
Computer-based calculations	Unique ID	OR-7
	Initial Value	
	Calculation Value	SATISFIED
	Unit of Measurement	Yes, Satisfied / No, Not Satisfied
	Analysis Algorithm	Check to see if Occupant E space is "Secure"

YES

	Field	Example
User-Entered	Occupant	E
	Requirement Type	Space Attribute
	Required Value	Secure
	Effective Period	Total Duration
	Requirement Status	Hard
Computer-based calculations	Unique ID	OR-7
	Initial Value	
	Calculation Value	NOT SATISFIED
	Unit of Measurement	Yes, Satisfied / No, Not Satisfied
	Analysis Algorithm	Check to see if Occupant E space is "Secure"

YES

Figure 6. In this example, our system correctly identified that Occupant E's security requirement was not satisfied on 4/4/07. The date and space (circled, upper right) are shown in the 4D model of the results.

Step 3. The computer presents the results visually and comprehensively

Figure 7 shows a mock-up of a user-interface (UI). This user-interface is based upon the UI in Solibri Model Checker (Solibri Inc 2007), a BIM-based requirements checking software. On the left hand side of the interface, planners can see the requirements entered. On the right side of the interface, planners can visualize the 4D model, which will also highlight activities that do not comply with the requirements (i.e., conflict activities). On the bottom of the interface, planners can see exactly which requirements (and dates) are not being met. ***This interface enables planners to understand what, how, and when requirements are not being satisfied.***

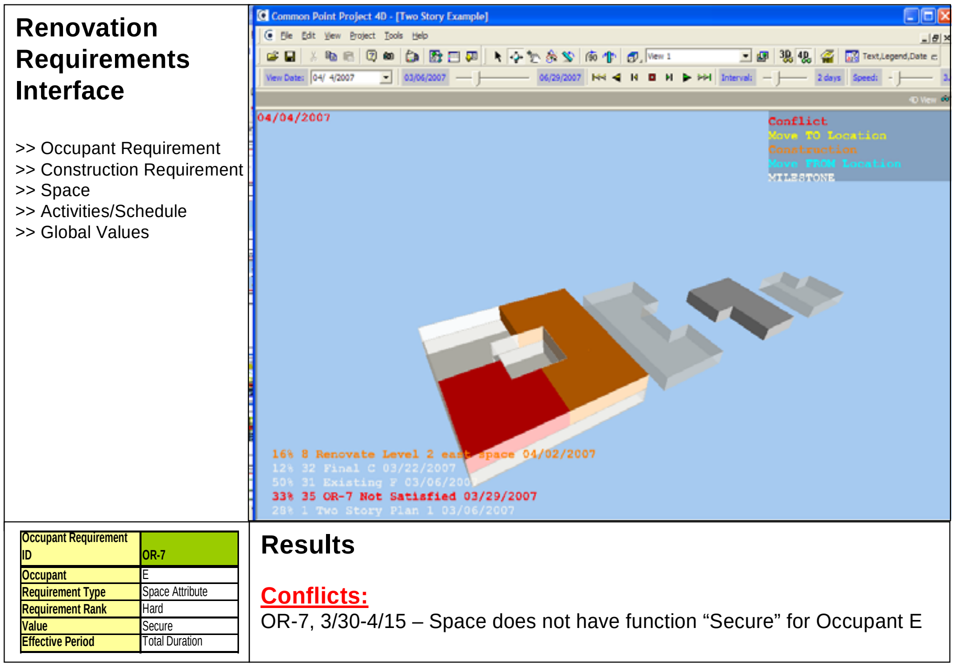


Figure 7. This mock-up of a user interface shows how this system will enable planners to understand what, how, and when requirements are non-compliant.

Figure 8 shows a mock-up of an executive dashboard module which would allow project managers to comprehensively understand the benefits and disadvantages of a phasing schedule and enables comparison with other alternatives. The global metrics in the dashboard based upon our observed projects and are automatically calculated. The planner is also able to visualize the percentage of requirements satisfied for the schedule. On the upper right of the dashboard, previous schedule evaluations can be stored, which allow the planner to compare different schedules. ***This dashboard enables planners to comprehensively evaluate the schedule, and determine the impact of changing requirements.***

Executive Dashboard			
Global Data		**Process Metrics**	
Global Variables		% of Tentative Occupant Requirements	**0.09%**
Cost/sf move to temp off-site swing space	$15	Previous Phasing Schedule Evaluations	Date
Cost/sf move in building	$10	Schedule v1	2/10/2007
Construction Cost/sf	$40	Schedule v2	2/14/2007
		Schedule v3	3/1/2007
Global Metrics			
Global Metrics		**Satisfaction of Requirements**	0% 100%
Total SF-Days (not including Building Common)	532,800 sf-days	**Occupant Requirements**	
Total Vacant SF-Days	37,800 sf-days	% Hard Requirements Met	**83%**
Swing space utilization: sf-vacant days/totalsf-days	93%	% Soft Requirements Met	**N/A**
Max renovation crew required	1 crew	% Tentative Requirements Met	**100%**
Total Duration	74 days		
Construction Cost	$324,000	**Construction Requirements**	
Move Cost	$87,750	% Hard Requirements Met	**100%**
% Occupants with Primary Move	50%	% Soft Requirements Met	**50%**
% Occupants with Secondary Move	50%	% Tentative Requirements Met	**N/A**

Figure 8. An executive dashboard shows the metrics for evaluation.

Methodology and Schedule

Our methodology integrates the development of our system with industry interactions. CIFE members will have many opportunities to participate throughout the year. We also plan to disseminate our findings through publications (journal and conference papers) that will be available to CIFE members.

<u>Conduct retrospective case studies (April 2007 – September 2007)</u>

Prior to the CIFE seed funding year, we will conduct retrospective case studies to understand the types of occupant and construction requirements and schedule evaluation metrics considered during renovation planning. The objective of this task is to gather specific metrics and requirements used by planners to develop, manage, and evaluate renovation plans.

> ***Opportunity for industry involvement:*** The research is currently supported by GSA. We would welcome any other CIFE industry members who have renovation projects that could benefit from this research (e.g., airport facilities, hospitals, highways).

<u>Develop the representation and reasoning methods (April 2007 – March 2008)</u>

We will continue to develop representation and reasoning methods that best capture the information gathered during the retrospective case studies. The initial representation and reasoning methods were presented in this proposal. The definition of the representation and development of the reasoning methods are closely linked and will require constant iterative cycles between the two tasks.

<u>Develop prototype system to test and refine method (April 2007 – March 2008)</u>

Based upon the method developed in the previous task, I will build a prototype system to test and refine the proposed method. ***We plan to use the CIFE seed funding primarily to help with the programming of the prototype system. Funding for the other tasks has already been secured from GSA, the National Science Foundation, and Stanford Graduate Fellowships.***

<u>Validate method and prototype system (January 2008 – August 2008)</u>

We plan to perform three prospective case studies to test our prototype system. The metrics and measurement methods for validation are speed and comprehensiveness. We hope to show that our prototype system enables a faster, more comprehensive evaluation (i.e., more stakeholders considered, more metrics considered) than traditional planning methods.

> ***Opportunity for industry involvement:*** During this stage, CIFE members can be involved in the prospective case studies to test the prototype system.

<u>Conduct a charrette to integrate POP, Narratives, and Decision Dashboard (August 2008)</u>

The final milestone of this research will be a half-day charrette to combine this research with POP, Narratives, and Decision Dashboard. By this time, we should have a working prototype system for our 4D Checker. This purpose of this charrette would be to identify the benefits of combining an automated phasing analysis with other VDC tools, as well as identify the limitations and future opportunities for research.

> ***Opportunity for industry involvement:*** During this stage, CIFE members again can be involved by providing a project for the charrette.

Figure 9 summarizes the research tasks, schedule and milestones.

Research Task	Start	Finish	2007 Q1	Q2	Q3	Q4	2008 Q1	Q2	Q3	Q4
Finish developing representation of renovation elements	4/1/2007	12/31/2007								
Begin Journal Paper 1: Representation of Renovation Elements	9/1/2007	9/1/2007								
Develop reasoning methods for analysis of phasing schedules	7/1/2007	3/31/2008								
Begin Journal Paper 2: Reasoning Methods for Phasing Schedules	4/1/2008	4/1/2007								
Develop prototype system	4/1/2007	6/30/2008								
Testing and Validation	1/1/2008	8/31/2008								
Begin Journal Paper 3: Automated analysis for renovation planning	9/1/2008	9/1/2008								
Charrette to integrate prototype system with POP, Narratives, DD	9/1/2008	9/1/2008								

Figure 9. Proposed schedule of research tasks and milestones

Towards CIFE 2010 Goals…And Beyond

This research enables CIFE industry members to achieve CIFE's 2010 measurable goals, while also providing a new research direction to support the 2015 breakthrough schedule performance business objective. A "4D Checker" would enable planners to ***explicitly track*** project-specific requirements and ***reduce the latency*** in checking the phasing schedule for requirement compliance. This research ***integrates both occupant and construction processes*** in a 4D environment. This research proposes to ***automate the requirements checking*** for phasing schedules.

This proposed research has a broader impact on the architecture, engineering, and construction (AEC) industry because it directly supports a value-based approach to project delivery. A 4D model-based analysis of requirements promotes scheduling from a customer value-based perspective. By analyzing requirements using our proposed methods, a project manager can answer the question "How much value does this renovation schedule deliver to my customers?" and "How can I maximize the value of this renovation schedule for my customers?" instead of simply "Can I renovate the building with this schedule?"

Major risks

The major risks for this research are two-fold. The first risk is the ability to assess requirements from the occupants. It may be difficult for the occupant to communicate what requirements they have, especially if they are not familiar with the renovation projects. To mitigate this risk, we plan to provide examples of requirements from other projects, where the occupants have similar processes (and, therefore, may have similar requirements). The second risk will be the ability to program the algorithms for the prototype system. This proposal addresses the second risk by asking for CIFE seed funding for programming assistance.

Next steps

After the CIFE seed research year has passed, we hope to continue using the prototype system for prospective interventions. Based upon our charrette, immediate future work includes further developing the interfaces between our prototype system and POP, Narratives, and Decision Dashboard. Long term future research directions include automatically generate a phasing schedule from project-specific requirements, and expanding the domain to new construction.

Future Opportunities for industry involvement: We hope to continue conducting prospective interventions with an ongoing-renovation projects.

References

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

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

CIFE. (2007). "Call for CIFE Seed Research Proposals." Stanford.

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.

Fischer, M., Haymaker, J., and Kam, C. (2005). "An experiment to combine POP, Narratives, and Decision Dashboard modeling for better process communication and integration." Stanford University, Stanford.

Haymaker, J., Suter, B., Fischer, M., and Kunz, J. (2005). "Narratives: Extensible Distributed Multidisciplinary Parametric Models." ASCE International Conference on Computing in Civil Engineering, ASCE, Cancun, Mexico.

Kam, C. (2005). "Decision Breakdown Structure - Ontology, Methodology and Framework for Information Management in Support of Decision-Enabling Tasks in the Building Industry," Stanford University, Stanford.

Kiviniemi, A. (2005). "Requirements Management Interface to Building Product Models," Stanford University, Stanford.

Solibri Inc. (2007). "Solibri Model Checker." Helsinki, BIM Analysis Software.

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