

A Visual Process for Planning Trade Flow on Construction Projects

by

Bo Tan

Technical Report No. 48
© Copyright
May 2005



*Computer Integrated Construction
Research Program*



Computer Integrated Construction Research Program
Department of Architectural Engineering
The Pennsylvania State University
University Park, PA 16802

ABSTRACT

The characteristics of congested construction sites and simultaneous multi-contractor working environments require the general contractor (GC) or construction manager (CM) to coordinate and manage many trades to accomplish a project safely, on time, with the desired quality and within budget. To provide a conceptual framework for construction activity modeling, an innovative production flow concept in construction was proposed and elaborated in the early 1990's. In contrast to the traditional understanding of construction as activities, the production flow model treats construction as composed of flow processes. The benefit of using this concept of production flow to manage construction includes providing alternatives to a sequential model of project realization, improved construction quality and better coordination among trade contractors. However, the understanding of this theory is limited by not only the abstractness of the concept itself, but also the lack of a visual representation of planning and evaluating techniques for implementing the production flow concepts.

The goal of this research was to develop a visual production flow planning methodology, at the trade level, that integrates building elements, construction methods, and trade space occupation requirements for coordinating and sequencing construction trades on a project. The visual trade flow space planning methodology is presented to provide a formal method for planning the flow of trades. This method includes a trade flow space model, flow occupation patterns and a trade flow planning process model.

Two detailed case studies were performed to validate the methodology. Based on the methodology, visual trade flow plans were developed and evaluated for each case study project. The case study results indicated the effectiveness of the methodology in representing major trade flow characteristics, e.g. flow occupations, flow directions, and flow continuity. The visual trade flow plan helped the communication between contractors regarding the building design, construction schedule and space plans by allowing them to better visualize the space requirements for trade flow.

TABLE OF CONTENTS

	ABSTRACT	iii
	LIST OF FIGURES	x
	LIST OF FIGURES	xi
	CHAPTER 1 INTRODUCTION	
1.1	Research Introduction	1
1.2	Description of research study	4
	1.2.1 Goal	4
	1.2.2 Objectives	4
	1.2.3 Relevance	5
	1.2.4 Research Approach	5
	1.2.5 Research Steps	6
	1.2.6 Scope	7
1.3	Reader’s Guide	7
	CHAPTER 2 RESEARCH METHODOLOGY	
2.1	Research Method Selection	9
2.2	Research Processes	10
	2.2.1 Literature Review	10
	2.2.2. Initial Case study	11
	2.2.3 Develop a Visual Trade Flow Planning Methodology	11
	2.2.4 Methodology evaluation with case study projects	12
	2.2.4.1 SALA Building project	12

2.2.4.2 National Air and Space Museum project	13
2.3 Research Summary	15

CHAPTER 3 LITERATURE REVIEW

3.1 Trade Flow Concept	16
3.1.1 Trade Flow in Construction	17
3.1.2 Characteristics of flow	18
3.2 Construction Work Space Planning	19
3.2.1 Space modeling	20
3.2.1.1 Construction Space Planning Model	20
3.2.1.2 SCaRC System	22
3.2.1.3 Summary	23
3.2.2 Graphical representation	23
3.2.2.1 Defining working zones	23
3.2.2.2 Space Position Patterns	25
3.2.2.3 Occupation factors	25
3.2.3 Space analysis	23
3.3 Summary	27

CHAPTER 4 INITIAL CASE STUDY

4.1 Case Study Introduction	29
4.2 Experiment Steps	32
4.3 Results & Discussion	32
4.3.1 Space conflicts	33
4.3.2 Inappropriate direction	33

4.3.3	Disruption of flow	33
4.4	Summary	34

CHAPTER 5 VISUAL TRADE FLOW PLANNING

METHODOLOGY

5.1	Methodology overview and structure	35
5.2	The Trade Flow Space model	36
5.2.1.	Representing Trade Flow Occupation	36
5.2.2	Space position patterns	37
5.2.3	Defining Working zones	40
5.3	Flow Occupation Patterns	40
5.3.1	Flow occupation patterns	41
5.3.2	Flow Conflict Taxonomy	42
5.4	Visual Trade Flow Planning process model	43
5.4.1	Level 0: Visual Trade Flow Planning	44
5.4.1.1	Planning Input	45
5.4.1.2	Planning Output	46
5.4.1.3	Plan control	47
5.4.1.4	Mechanism	49
5.4.2	Level 1: Visual Trade Flow Planning Process	50
5.4.2.1	Level 1 Define space availability (D)	52
5.4.2.1.1	Level 2: Decompose design into building elements (D.1.)	52
5.4.2.1.2	Level 2: Evaluate available space on site (D.2.)	54
5.4.2.1.3	Level 2: Define construction method (D.3.)	54
5.4.2.2	Level 1: Generate work zones (G)	54

5.4.2.2.1	Level 2: Identify room/work-unit level working zones (G.1.)	56
5.4.2.2.2	Level 2: Identify floor level working zones (G.2.)	56
5.4.2.2.3	Level 2: Identify Building level working zones (G.3.)	56
5.4.2.2.4	Level 2: Integrate work zones into 3D model (G.4.)	57
5.4.2.3	Level 1: Plan trade space (P)	57
5.4.2.3.1	Level 2: Identify trade activities (P.1.)	58
5.4.2.3.2	Level 2 Identify trade spatial needs (P.2.)	58
5.4.2.3.3	Level 2: Identify flow occupation level (P.3.)	60
5.4.2.3.4	Level 2: Generate trade flow plan (P.4.)	62
5.4.2.4	Level 1 Evaluate trade flow (E)	62
5.4.2.4.1	Level 2 Identify flow conflicts (E.1.)	62
5.4.2.4.2	Level 2 Identify conflicts cause (E.2.)	64
5.4.2.4.3	Level 2: Resolve conflicts (E.3.)	64
5.5	Summary	64

CHAPTER 6 ILLUSTRATIVE CASE STUDY: SALA BUILDING PROJECT

6.1	Case Study Project Background	65
6.2	Developing the Visual Trade Flow Planning Model	66
6.2.1	Input	66
6.2.2	Define space availability	68
6.2.2.1	Recognize building elements (D.1.)	68
6.2.2.2	Evaluate the available space on site (D.2.)	70
6.2.2.3	Define construction methods (D.3.)	72
6.2.3	Generate work zone (G)	73

6.2.4	Plan trade space (P)	73
6.2.4.1	Recognize trade activities (P1)	73
6.2.4.2	Identify trade spatial needs (P2)	74
6.2.4.3	Identify trade occupation level (P3)	74
6.2.4.4	Generate trade plan (P4)	74
6.2.5	Evaluate trade flow	76
6.3	Evaluate the visual production flow planning methodology	81
6.4	Summary	82

CHAPTER 7 CASE STUDY: NASM PROJECT

EXPERIMENT PROCEDURES AND RESULTS

7.1	Case Project Background	83
7.2	Visual Trade Flow Plan Development	85
7.3	Experiment I: Graduate Production Management Course	92
7.3.1	Experiment Procedures	92
7.3.1.1	Results	93
7.3.1.2	Discussion	94
7.4	Experiment II : Architectural Engineering Graduate Students	95
7.4.1	Experiment Steps	95
7.4.2	Results	96

CHAPTER 8 CONCLUSIONS

8.1	Research Summaries	100
8.2	Research Contributions	101
8.3	Research Limitation	102

8.4	Future Research	103
	8.4.1 Comprehensive Flow Modelling	103
	8.4.2 Interactive Work Zones Generator	103
8.5	Concluding Remarks	104
	BIBLIOGRAPHY	105
	APPENDIX A: Human Subject Consent Form	107
	APPENDIX B: IDEF0 Process Modeling Methodology	109
	APPENDIX C: Survey Form for Graduate Production Management Course	115
	APPENDIX D: Survey Form for Architectural Engineering Graduate Students	120

LIST OF TABLES

Table 3.1: Flows in car production and site construction	17
Table 5.1: Space Position Patterns and the corresponding visual representations, descriptions and examples.	39
Table 5.2: Flow Occupation Patterns	42
Table 5.3: Taxonomy of flow conflict types	44
Table 6.1: Building element availability and the corresponding modeling solution	69
Table 6.2: Space Position Patterns examples	75
Table 6.3: Flow Occupation Patterns examples at roof area	76
Table 6.4: Identified Conflict Types	77
Table 6.5: The conflict cost breakdown of carpentry contractor	80

LIST OF FIGURES

Figure 1.1: Construction trade occupations in different models	3
Figure 2.1: The Visual Trade Flow Planning Methodology	12
Figure 2.2: The SALA virtual building prototype	13
Figure 2.3: The National Air &Space Museum portrait and drawing.	14
Figure 3.1: Riley’s (1994) space planning model structure	20
Figure 4.1: Space conflict between roof truss crew and roof decking crew	30
Figure 4.2: Direction conflict in work flow	31
Figure 4.3: Disruption in work flow	31
Figure 4.4: Errors identified with CPM and 4D CAD	32
Figure 5.1: Structure of Visual Trade Flow Planning Model	35
Figure 5.2: Working zone of floor finishing trade	40
Figure 5.3: Visual Trade Planning Process Model	45
Figure 5.4: Factors in plan control	49
Figure 5.5: Process decomposition for the Visual Trade Flow Planning Process	50
Figure 5.6: Visual Trade Flow planning (Level 1)	51
Figure 5.7 Define the space availability	52
Figure 5.8: Level 2 Define space availability	53
Figure 5.9: Level 2: Generate work zones	55
Figure 5.10: Plan trade space process	57
Figure 5.11: Level 2: Plan trade space	59
Figure 5.12: Identify trade spatial needs	60
Figure 5.13: Level 3: Identify trade spatial needs	61
Figure 5.14: Evaluate the trade flow	62
Figure 5.15: Level 2: Evaluate trade flow	63
Figure 6.1: 3D CAD model of the SALA Building in ArchiCAD	66
Figure 6.2: Site condition: the movement of the crane is limited by the site fence	67
Figure 6.3: Site space condition: material storage inside the building	71
Figure 6.4: Site space condition: Accessibility issue outside of the building	71

Figure 6.5: Steel trade uses light mobile crane to install tube steel due to the congested site	72
Figure 6.6: Masonry trade uses scaffolding for brick piers along B line	73
Figure 6.7: Conflicts between masonry trade and concrete trade	78
Figure 6.8: Medium Conflict between carpentry trade and steel Trade	79
Figure 6.9: Mild Conflicts between mechanical trade and carpentry trade at the roof area	80
Figure 7.1: NASM project drawings	84
Figure 7.2: The flow conflict between the decking trade and the truss trade	87
Figure 7.3 Component 4D model with clipping – Inappropriate flow direction	88
Figure 7.4: Visual Trade Flow 4D model – Inappropriate flow direction	89
Figure 7.5 Component 4D model: Disrupted flow	90
Figure 7.6 Visual Trade Flow 4D model: Disrupted flow	91
Figure 7.7 Survey results of the Experiment I	94
Figure 7.8: The add-on effect of Trade Flow 4D	97
Figure 7.9: Multiple trades occupation conflict in original schedule	98

CHAPTER 1

INTRODUCTION

1.1 Research Introduction

Building construction often involves a large number of trades working simultaneously on a single construction site. Each trade has its own crews, equipment and materials. Each trade also performs its own construction work activities on site to fulfill their contract with the owner, construction manager or general contractor. These trades also work interdependently to share construction space and other resources. These trades may require the same space or other resources on site at the same time. Typically, a construction manager (CM) or a general contractor (GC) coordinates and manages these trades to accomplish projects safely, on time, with desired quality, and within budget.

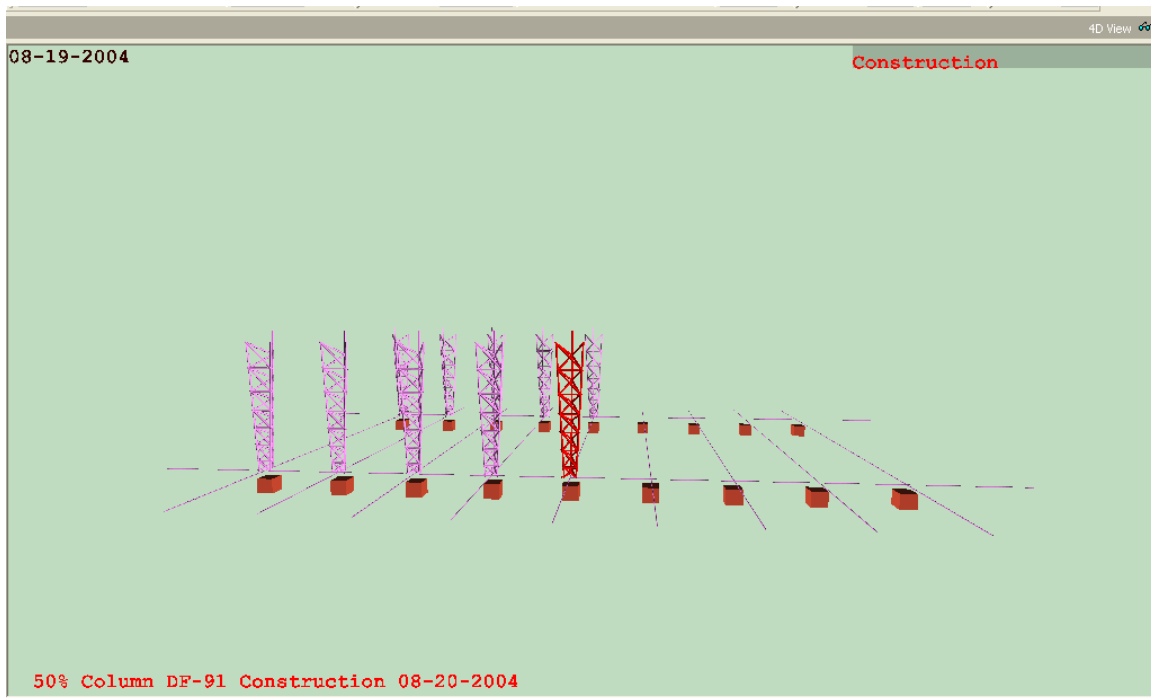
From a theoretical perspective, the conceptual framework for construction project organizational design is far from sufficient (Sanvido et al. 1990). Traditionally, construction activities are treated as the basic unit of construction management principles. The primary concept of this theory is to understand construction as a set of activities aimed at a certain output, i.e., conversions (Koskela 1992). However, the construction conceptual framework based on this conversion model might lead to several problems, including a linear sequential method of project realization instead of concurrent engineering (Dupagne, 1991), lack of quality considerations (Koskela 1992), and segmented control (Oglesby et.al. 1989, Tommelein and Ballard 1998).

Based on the observation of these problems, a production flow concept in construction was proposed and elaborated by Koskela (1992). In contrast to understanding construction as activities, the production flow model treats construction as a series of flow processes. On a construction site, there are three types of flow: material flow, location flow, and assembly flow. The benefits of using the idea of production flow to manage construction includes providing alternatives to a sequential model of project

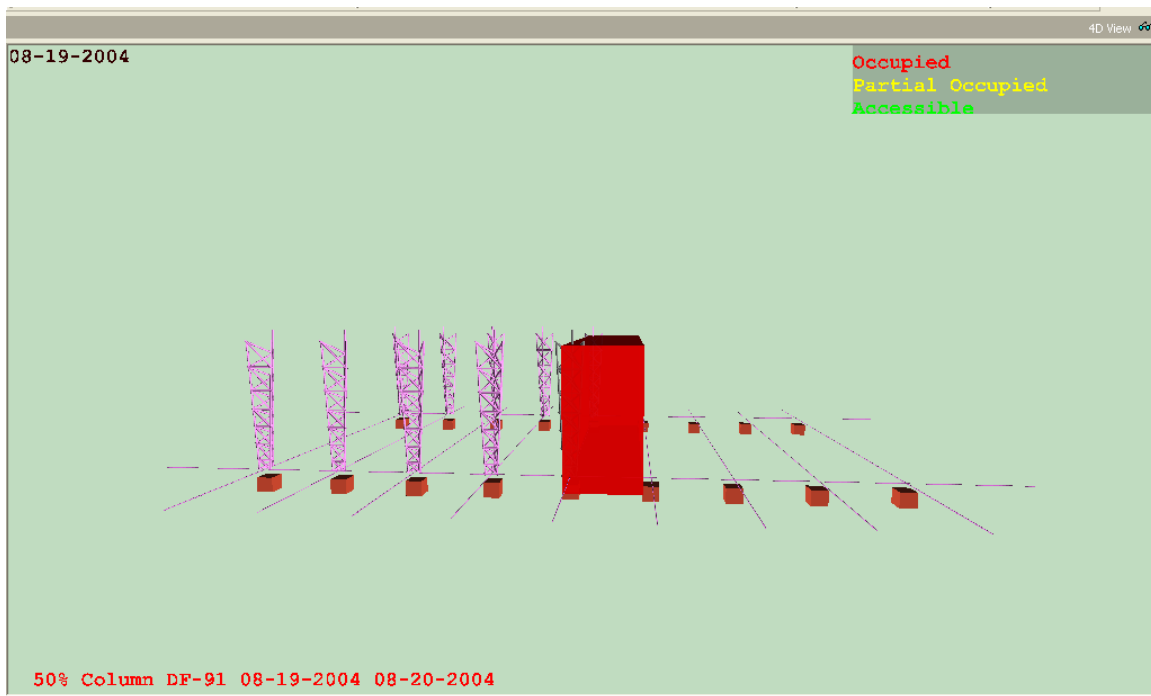
realization, improved construction quality, and better coordination among trade contractors.

Due to a limited formal definition of production flow planning in the construction industry and the lack of tools to support detailed flow planning, it is difficult to plan and evaluate production flow on a construction project. Unlike other traditional concepts in construction, e.g., critical path method (CPM) scheduling, production flow is still a relatively new construction management principle, and has not been emphasized to the same degree as other concepts by schedulers and site managers. Moreover, the current scheduling software application, e.g. Primavera P3 and Microsoft Project, are not able to visually display production flow information. This makes production flow planning more challenging and limits the practical application of the theory into practice.

Advanced visualization technologies, such as 4 dimensional (4D) Computer Aided Design (CAD), which integrate 3 dimensional (3D) CAD models with scheduling information can contribute to solving these issues in production flow planning and further assist managers and foremen in the visualization of the production trade flow on a construction project. This research aims to develop a visual production flow planning methodology, at the trade level, that integrates building elements, construction methods, and trade space occupation requirements for coordinating and sequencing construction trades on a project. First, the preliminary research of using 3D CAD components (building elements) to represent a trade flow plan was performed. Based on this research, a visual modeling methodology was developed to facilitate the planning for trade flow. In this method, the space occupation of each trade during construction process is visually represented (see Figure 1.1). This methodology included (1) a trade flow space model, (2) flow occupation patterns and (3) a trade flow planning process model. The National Air and Space Museum project and the School of Architecture and Landscape Architecture Building were then used as case studies to validate the methodology. With visual models and generated production space plans for each project, this research validates the effectiveness of the Visual Trade Flow Planning methodology in representing the major characteristics of trade flow.



(a) Component 4D CAD model (the column in red is under construction)



(b) Trade Flow 4D plan model (the column in red is under construction and the red box indicate the trade space occupation)

Figure 1.1: Construction trade occupations in different models

1.2 Description of research study

This section provides an overview of the research study, including the research goal, objectives, relevance, approach, methodology, steps and scope. Chapter Two provides a more detailed description of the research methodologies and reasons for their selection.

1.2.1 Goal

The goal of this research is to develop and evaluate a formal trade level space planning methodology which allows a planner to visually plan the trade flow and trade space occupation levels to improve the coordination and sequencing of trade flow on a construction project.

1.2.2 Objectives

To accomplish this goal, the following objectives for this research were developed:

1. **Develop a visual trade flow space model:** This model will define spatial representations of construction trade flow and identify typical representation patterns that define the relationship between space and trade flow. The model will evaluate the effect of building elements, construction methods, and construction work space requirements on the representation patterns.
2. **Define flow occupation patterns:** These patterns will identify typical flow occupation levels based on the characteristics of the flow, the related construction activities, and the construction methods. For each flow occupation level, the accessibility for other trade flow will be defined.
3. **Develop a trade flow planning process model:** Develop a detailed planning process that includes the sequence of the major steps to develop a trade flow plan; a detailed breakdown of each step; and the input and expected outcome of each process in the model.

4. **Evaluate the methodology:** The Visual Trade Flow Planning methodology will be evaluated through the detailed analysis of and evaluation of two case study projects.

1.2.3 Relevance

This research can benefit two types of organizations in the construction industry. One is the general contractor, construction manager, and trade contractors. They can apply the Visual Trade Flow Planning methodology to improve their planning process, compare different project execution scenarios, communicate the plan and solicit feedback on the plan from trades. The method could also be used in weekly schedule progress meetings or sub-contractor coordination meetings to help them visually coordinate and sequence construction trades on site. The second group is researchers focused in trade flow management or virtual facility prototyping. This methodology provides a process for planning trade flow visually, which covers major aspects of trade flow, e.g. flow occupation coordination, flow direction, and pace of flow. Based on this methodology, future research can be performed in visually analyzing other characteristics of trade flow, e.g., stabilizing work flow and improving downstream flow performance.

1.2.4 Research Approach

Before developing the visual methodology to plan trade flow, preliminary research was performed to investigate the effectiveness of using the current visual representation methods, e.g. 3D CAD components (building elements), to describe trade flow plans. Based on this preliminary research, a Visual Trade Flow Planning methodology was developed to assist construction managers, general contractors, and researchers to plan and evaluate trade flow visually. To develop such a model, the following questions were proposed:

- What characteristics of Trade Flow need to be visualized in a trade flow planning process?
- How should trade flow be graphically displayed?

- How can the flow visualization representations be integrated into flow planning and evaluating processes?

1.2.5 Research Steps

This research aims to develop an approach to improve the visual planning and analysis of trade flow. The primary research steps are as follows:

1. *Literature Review*: An analysis of the literature in trade flow and construction space planning was performed, including the concept of trade flow, the characteristics of production trade flow, and space planning methodologies. The detailed literature analysis is presented in Chapter 3.
2. *Initial Component 4D CAD case study experiment*: In this initial case study, the 3D CAD component (building element) and a construction schedule were used to present trade flow occupation in a project. The effectiveness of this method was evaluated through an experiment and a questionnaire.
3. *Develop a Visual Trade Flow Planning Methodology*: A Visual Trade Flow Planning methodology was developed to address deficiencies identified in the initial case study. This method includes trade flow space modeling, flow occupation patterns and a trade flow planning process.
4. *Methodology Evaluation with Case Study I*: This case study used the School of Architecture and Landscape Architecture Building project. The focus of this case study was to demonstrate the Visual Trade Flow Planning methodology step by step and evaluate the trade flow planning methodology based on the visual plan and the feedback from site crew.
5. *Methodology Evaluation with Case Study II*: Two visual trade flow plans for the National Air and Space Museum project were developed in this case study. One used traditional component 4D CAD modeling methods as in the initial case study. The other model followed the proposed Visual Trade Flow Planning methodology

to develop a trade flow visual space 4D CAD model. Both visual trade flow plans were compared and evaluated through an experiment conducted in a graduate class at The Pennsylvania State University to test the effectiveness of both approaches in representing the characteristics of production trade flow.

1.2.6 Scope

The Visual Trade Flow Planning methodology was developed for building projects with typical floors (such as offices, residential buildings, or hospitals) with multiple construction trades working in the building. This research is focused on the flow of production, or construction trades, and the associated materials and equipment needed by each trade. The planning process is performed at a trade-level, and focused on flow occupation patterns and flow occupation levels. The projects selected for case studies had a general contractor or construction manager who planned trade flow sequences and coordinated flow occupations. Although the methodology is believed to encompass all primary trade flow patterns required in the planning process, it is necessary to identify that the method has only been tested through the detailed analysis of the two presented case study projects.

1.3 Reader's Guide

This chapter described the research goal, objectives, major steps and scope of the research. Chapter 2 introduces the detailed research methodologies and the basis for research method selection. Chapter 3 includes background literature including a review of current trade flow research and space planning research. Chapter 4 is a description of the initial case study with a component 4D model for communication. The main purpose of this charter is to justify the effectiveness of using 4D CAD component (building element) to represent trade flow plan. Based on the literature review and this case study, a Visual Trade Flow Planning methodology is proposed in Chapter 5. A detail description of this methodology is provided, including a trade flow space model, flow occupation patterns and a trade flow planning process model. Two case studies are performed and

documented in Chapter 6 and Chapter 7. In Chapter 6, the School of Architecture and Landscape Architecture (SALA) Building is used to demonstrate and evaluate the Visual Trade Flow Planning methodology. Chapter 7 presents a trade flow planning case based on the National Air and Space Museum project. The visual trade flow plan is compared with a Component 4D model with building elements to evaluate the effectiveness of using Visual Trade Flow Planning to analyze the characteristics of trade flow. Finally, Chapter 8 summarizes the research and concludes with the primary contributions and limitations of this Visual Trade Flow Planning methodology.

CHAPTER 2

RESEARCH METHODOLOGY

This chapter describes the methods used for conducting this research and discusses the basis for the selection of the research methods. Four research methods are used in this study including: (1) literature review and analysis; (2) investigative case study; (3) model building; and (4) model validation through case studies and surveys.

2.1 Research Method Selection

The primary purpose of this research is to develop a Visual Trade Flow Planning methodology. Limited documentation on methods for Visual Trade Flow Planning is available. The literature review was performed in related areas, e.g. trade flow concepts and space planning, to provide the background information for this research.

An initial component 4D CAD case study was conducted to evaluate the ability of an existing method (component 4D CAD) for representing trade flow concepts. A comparative research method was used in this case study. In this case study, a comparative experiment was performed in using traditional schedules (paper schedules) and 2D drawings against advanced visualization technology (Component 4D CAD model) to evaluate trade flow. The participants in this experiment were equally divided into two groups, and each was provided either a paper schedule and 2D drawings or a Component 4D model to evaluate the characteristics of trade flow. The evaluation results of both groups were compared and conclusions were developed at the end the experiment. This experiment illustrated several deficiencies in the use of typical component 4D CAD models for analyzing trade flow.

Based on the literature and the experience gained in the initial case study, a Visual Trade Flow Planning methodology was developed. In the first two parts of the Visual Trade Flow Planning Methodology, the Trade Flow Space Model and the Flow

Occupation Patterns (a 3D graphical model format) are used to visually represent the flow occupations and to facilitate the communication of the trade space plans. The third part of the methodology, the Trade Flow Planning Process Model, is an IDEF₀ model of the process to visually plan and analyze the trade flow. This IDEF₀ model organizes the information for each process into inputs, outputs, constraints, and mechanisms.

Finally, two case studies were employed to validate the methodology. Surveys were used to gather feedback from students and professionals in the construction industry. Yin (1984) summarized that a case study research method is used to examine contemporary real-life situations. The validation of research is examined by applying the research ideas or techniques to case studies. For this research, two case studies were conducted to test the proposed Visual Trade Flow Planning Methodology. The model validation was based on the feedback from the participants of each case study. Surveys were performed among the participants after each case study. The participants for each case study were either graduate students majoring in construction management or professionals in the construction industry. The results of the surveys and other feedback were analyzed and summarized.

2.2 Research Processes

The major research processes of this study are introduced in the following sections.

2.3 Literature Review

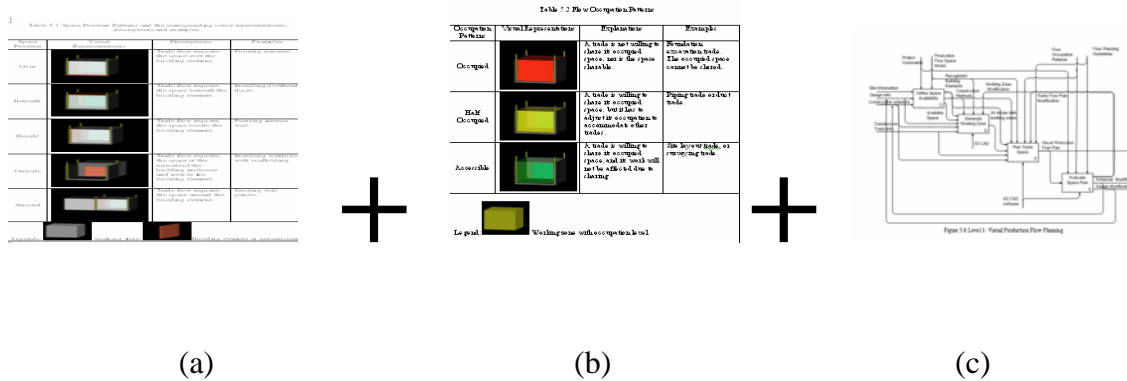
An analysis of the literature in production trade flow and construction space planning was performed. Both the concept of the trade flow and characteristics of the construction flow were reviewed. The research in construction space planning was introduced and reviewed as three categories based on the different stages of their focus: space modeling, graphical representation, and space analysis. Finally, the literature was summarized from the three major aspects of Visual Trade Flow Planning, including (1) trade-level space modeling, (2) flow occupation level, and (3) dynamic characteristics of flow.

2.4 Initial Case Study

In the initial study, an experiment was designed and performed to investigate the possibility to use current component 4D CAD to representing trade flow in construction. 4D CAD refers to 3D CAD linking to construction schedules. In Component 4D, 3D CAD components (building elements) were used by planning to visualize the trade occupation. In this approach, the space occupation of 3D CAD components was treated as the space occupation of the trade flow. Although the result of using 3D CAD components to represent the dynamic issue of production work flow was valuable for identifying some space conflicts, some flow issues were not easily identified, e.g. direction of the flow and disruption of the flow. Therefore, it is desirable to develop a more effective approach to illustrate the dynamic issues and occupation levels of trade flow.

2.4.1 Develop a Visual Trade Flow Planning Methodology

A Visual Trade Flow Planning methodology was developed by integrating building components, construction methods, and trade space requirements. This methodology consists of three parts: (1) the Trade Flow Space Model, (2) the Flow Occupation Patterns, and (3) the Trade Flow Planning Process Model (see Figure 2.1). The first two parts use a graphical model to represent the trade flow occupations. The Trade Flow Space Model places emphasis on how to position the trade flow occupation based on the associated building elements; while, the Flow Occupation Patterns visually defines the accessibility of each flow occupation. The Trade Flow Planning Process model provides a formal process definition for the planning process with the integrated graphical representations of trade flow with construction project information, e.g. design information and schedule information.



(a) (b) (c)

Figure 2.1: The Visual Trade Flow Planning Methodology includes (a) the Trade Flow Space Model descriptions, (b) the Flow Occupation Patterns description, and (c) the Level 1 diagram of the Trade Flow Planning Process Model.

2.4.2 Methodology Evaluation with Case Study Projects

Two case studies, the National Air and Space Museum project and the SALA Building project were used to illustrate the methodology. The visual trade flow models for each project were built and trade flow plans were generated. The generated trade flow plans of both case studies were evaluated by the students in a construction management class and industry practitioners from construction companies. The surveys were designed to focus on the validation of the trade flow plan, the feasibility of the proposed trade flow planning methodology and other related issues for both projects

2.2.4.1 SALA Building Project

The new School of Architecture and Landscape Architecture (SALA) Building was the first case study project. The SALA Building started construction at Penn State in the fall of 2003. The faculty and students from the Architectural Engineering, Architecture, and Landscape Architecture Departments worked together to develop a virtual building prototype of this project. The virtual building prototype included information on the building product, the construction process, and the surrounding project environment. As part of this project, this research investigated the trade flow planning and trade sequencing.

This case study focused on the detailed steps of developing a visual trade flow plan based on the Visual Trade Flow Planning Methodology. Step by step process decomposition was performed in this case study. Since this project was still under construction during this research, the interaction between the researcher and the construction management staff was an essential part of this case study. The general contractor and subcontractors contributed in generating the visual trade flow plan. Valuable feedback was provided by the professionals. This case study aimed at presenting the procedure for developing a trade flow plan and examining the application of the methodology by the professionals in the construction industry.

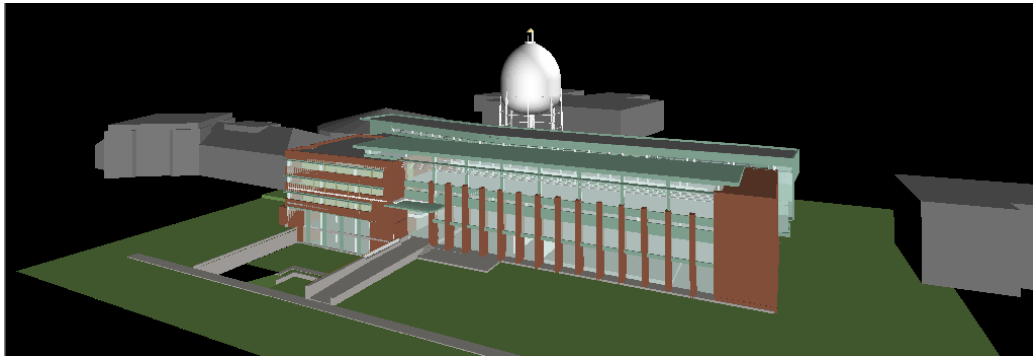


Figure 2.2: The SALA virtual building prototype

2.2.4.2 National Air and Space Museum Project

The National Air & Space Museum is a \$150 million project in Dulles, VA that houses examples and artifacts of aviation (see Figure 2.3). This case study aimed at developing a trade flow plan using this visual Trade Flow Space Planning Methodology. The generated plan evaluation focused on the effectiveness of visualizing trade flow characteristics, e.g. continuity of the flow and direction of the flow. The results of this evaluation were compared with those of the initial research to identify potential benefits and shortcomings of the proposed methodology.

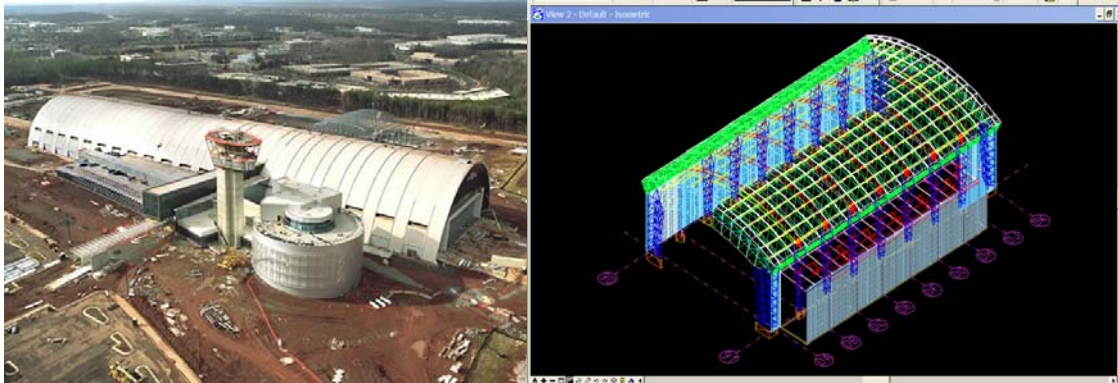


Figure 2.3: The National Air &Space Museum portrait and drawing. The Space Hangar is shown in the photograph at the rear of the Main Hangar (erected but unroofed).

Two trade flow plan models of the construction sequence of the museum, from the subbase to the roofing, were developed. The first model is a Component 4D CAD model, in which 3D CAD components (physical building elements) were used to represent the trade flow occupation. The second model was developed followed the visual Trade Flow Planning Methodology. To test the effectiveness of the proposed methodology, trade flow flaws, e.g., space conflicts and direction of the flow, were intentionally embedded into both the traditional component 4D model and visual trade flow 4D model.

A comparative experiment was designed and performed in an Architectural Engineering (AE) graduate course (AE 597A) at Penn State to evaluate the effectiveness of the proposed methodology. The participants of this experiment were divided into two groups, and each group was provided with one of the 4D CAD models. The students tried to identify the embedded flaws from one of the two different representations (Component 4D model or Trade Flow 4D model).

Based on this experiment, a more controlled experiment was performed with 4 selected graduate students. For this experiment, no time limitation was set. Furthermore, two experiment organizers were present during the experiment period to help four participants answer all the questions.

The participants in this case study were provided with a questionnaire survey after the experiment and were instructed to complete the questionnaire. To avoid any potential bias and to protect the participants' privacy, an anonymous survey was designed. According to the Pennsylvania State University's policy, an Application for the Use of Human Participants was filed for this research. The application was approved by the Office for Research Protections and filed with serial number IRB # 18806 (see Appendix A).

2.5 Research Summary

This chapter described the methods used for this study, including (1) literature review and analysis, (2) initial case study, (3) model building, and (4) model validation through case studies and surveys. The basis of selection was discussed and the details of each method were provided. The next chapter provides a summary and analysis of related research performed in trade flow and construction space planning.

CHAPTER 3

LITERATURE REVIEW

This chapter presents previous research related to production trade flow and construction work space planning. The production trade flow concept is introduced and the previous work in space modeling, graphical representation of space on construction sites and space analysis is then discussed.

3.1 Production Trade Flow Concept

One of the significant works in understanding construction as production was presented by Koskela (1992), who suggested how to integrate the Transformation, Flow and Value (TFV) model into construction. Contrary to the popular conceptualization of production in terms of transformation of inputs to outputs, the TFV model uses the conception of production as consisting of flows of material and information through networks of specialists, and the conception of production in terms of generation of customer value (Koskela and Ballard 2003).

In contrast to the traditional conceptualization of construction as activities, the TFV model views construction as composed of flow processes. There are three types of flow on a construction site: material flow, location flow, and assembly flow, in contrast to two types in the factory (material flow and assembly flow). Material flows in car production and site construction are compared in Table 3.1. As can be seen, both the location flow and the assembly flow are highly related to the sequence and the moving direction of the specific construction trade. The location flow can be described as the movement of the specific trade through the building, while the assembly flow can be described as the moving sequence of these trades.

Among flows mentioned above, material flow and assembly flow have been the focus a much flow concept research in factory manufacturing, and even have been

integrated into many Enterprise Resource Planning (ERP) systems, such as SAP, PeopleSoft, Baan, Oracle, and so on (Wamelink 2001). However, as far as location flow is concerned, limited research has focused on either the theoretical or practical nature of this flow including the research in trade flow in construction (Riley and Sanvido 1997).

Table 3.1: Flows in car production and site construction (Koskela 2000)

	Car production	Site construction
Material flow (Supply Chain)	A seat is assembled in the seat factory, transported to the car assembly factory, transferred to the workstation and installed.	A window is assembled in the window factory, transported to the site, transferred to the place of the installation and installed.
Location flow	The seats of one car are installed as one task at one workstation.	All window openings proceed through the installation workstation (in practice, the team moves throughout the building).
Assembly flow	The car body moves through all workstations of the assembly line.	The building proceeds through all assembly phases (e.g. window installation, partition wall construction, etc.).

3.1.1 Trade flow in construction

Building construction involves a large number of construction teams or construction trades. These trades generally work closely and interdependently, and may be responsible for the building's foundation, steel erection, decking, formwork, concrete reinforcing bars, concrete, drywall, mechanical, electrical, plumbing, roofing, glazing, vertical transportation systems, fire and sprinkler systems, and environmental controls. These trades can be categorized as follows (Riley and Sanvido 1997):

- *Structural Trades:* e.g., erecting structural steel (steel erector); placing and securing decking as well as welding shear studs (decking contractor); and placing rebar, then pouring and finishing concrete (concrete contractor);
- *Overhead Work Trades:* e.g., installing HVAC system (mechanical contractor), sprinkler system (fire protection contractor), emergency lighting (electrical contractor), and pipe (plumbing contractor);

- *Interior Finishes Trades*: e.g., installing wall studs, routing electrical conduit, placing insulation material, hanging drywall, and painting; and
- *Perimeter Enclosure Trades*: e.g., building perimeter walls, placing windows, installing flashing, and applying sealants.

3.1.2 Characteristics of flow

Trade Flow is an essential concept in construction production management. Good flow refers to trade flow with characteristics of work continuity (Ballard 2000; Tommelein et al. 1999), avoidance of space conflicts with other contractors or activities (Akinci and Levitt 2002), and consistent work direction (Tan et al. 2003).

Flow continuity is one of the main characteristics for measuring trade flow. The unexpected variability in pace or a pause of the trade flow normally causes delay to site crews, induces double handling of material, promotes the unnecessary build up of site inventory, and impedes the start of successive trades. It is essential to understand the importance of shielding trade flow from unexpected variability and to keep movement continuous (Ballard 2000).

Several researchers have analyzed the impact of flow variance on productivity. Ballard and Howell (1998) address shielding production from variability. Concerning work flow, variability could refer to changes in pace or pauses in the flow of work. A computer simulation of a parade game is used to illustrate that workflow variability has impact on the performance of construction trades and their successors (Tommelein et al. 1999). Simulation can be very useful for understanding the nature of workflows. As concluded in previous research, variance of the trade flow has a strong impact on productivity (Ballard and Howell 1998; Tommelein et. at. 1999). With the increase of variability of the production rate of construction trades, the intermediate buffers (work in process) grow larger, and the variance of the project completion date increases leading to a greater probability that the project deadlines will not be achieved. However, little research has focused on using visualization technology to provide project managers and

superintendents with a methodology for planning and evaluating trade flow visually on a construction project.

Avoidance of space conflicts is another essential criterion to evaluate good flow. Labor, equipment, material and temporary structures from different construction trades require their own adequate work space to maximize a productive rate and minimize possible safety problems. It is desirable to coordinate the flow of these trades and manage the work space effectively to avoid potential space conflicts (Akinici and Levitt 2002).

The proper direction of the trade flow is another distinct criterion. There are several alternatives for site managers to execute construction. Different construction flow directions lead to various effects on the flow of other trades. For example, a masonry contractor can build a masonry wall either face-by-face, or construct multiple faces at the same time, or even construct the entire perimeter all at once by floor. The face-by-face sequence may reduce the movement of the site crew and reduce the amount of scaffolding; however, the flow of interior finish trades may be seriously impacted and disrupted. This method may be a better choice for the masonry trade; however, it may disrupt other perimeter enclosure trades.

3.2 Construction Work Space Planning

Among characteristics of flow, there have been many attempts to define and describe the work space conflicts on construction sites (Koo and Fischer 2000; Dawood et al. 2002; Akinici et al. 2003; Akinici and Fischer 2000; Guo 2002). These construction work space planning research can be categorized in three areas based on the different stages of their focus: space modeling, graphical representation, and space analysis.

First, space modeling focuses on space representation modeling methodologies, which model the spatial needs of corresponding construction work. This step provides a language to communicate special issues and construction activities, and bridges the gap between the actual construction and the modeling system on paper.

Second, research in graphical representation describes visual representation methods of spatial issues. These methodologies translate space modeling systems on paper into computer visual software and system, e.g., 3D CAD or 4D CAD. 4D CAD refers to 3D CAD linked to construction schedules (Koo and Fischer 2000).

Third, with computer modeling, space analysis can be effectively performed; including space constrained scheduling systems, space-time conflict analysis, construction schedule flaw identification, and 4D project case studies.

3.2.1 Space modeling

Space modeling is the first step in work space planning research, and can be treated as the foundation of graphical representation and space analysis research. The purpose of this stage of research is to provide an approach to describe the space types, characteristics, and representations. The major research work in this part includes Riley's Construction Space Planning Model (Riley, 1994) and Thabet's SCaRC System (Thabet 1992).

3.2.1.1 Construction space planning model

Riley (1994) developed a Space Planning Model, which included a Construction Space Model and a Planning Process Model, illustrated in Figure 3.1.

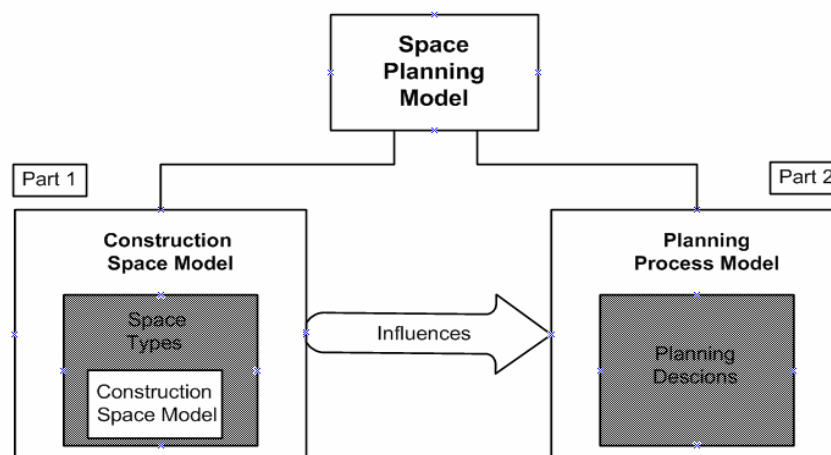


Figure 3.1: Space Planning Model Structure (Riley 1994)

In Part 1, Construction Space Model, Riley identified Space Types and Space Behavior Patterns from the perspective of construction activities. Corresponding to construction activity work elements, the spatial needs were defined into two categories: areas and paths. Areas are the spaces occupied by activity work elements for a period of time, while paths are the spaces required for the movement of materials, people, and other resources. Based on these two categories, the following 12 process space types are defined:

1. *Layout area*: The space required to determine the position of a material to be placed by an activity;
2. *Unloading area*: The space occupied or required by material-handing resources to place materials onto floors at access points;
3. *Material path*: The space required to move a particular material from unloading areas to storage areas and work areas;
4. *Staging area*: The space required to temporarily arrange material near work areas for short intervals of time;
5. *Personnel path*: The path required for workers to travel between access points, material storage areas, and work areas;
6. *Storage area*: The space required to keep material or tools from the time delivered to site to the time of use;
7. *Prefabrication area*: the space used to prepare, shape, prefabricate, or assemble materials;
8. *Work area*: The space required for crews to install materials;
9. *Tool and equipment area*: Space occupied by a resource or temporary facility, which is used to support other activity work elements;
10. *Debris path*: The space needed for the disposal of scrap material and packaging;
11. *Hazard area*: Space that is unusable due to health hazards or other dangers created by construction activities; and
12. *Protected area*: Space that is used to protect material in place.

The Space Behavior Pattern is another essential part of the Construction Space Model. To define team workers' special needs over time for performing each construction work, a set of patterns has been identified for each Space Type. Normally, a pattern of generic space needs for each type of detail construction work is defined the Construction Space Model.

Taking construction material storage as an example, different materials may require different storage methods. For example, it is ideal to distribute bulky materials in appropriate quantities to storage locations near the points of use. The protection from weather or theft might be necessary for other materials. These materials are ideally stored in bulk at one location and distributed in small quantities as needed. The usage of space based on the selected method of work is also considered in the pattern representations.

Based on this model, construction space can be decomposed to building level, floor level and room level according to the required modeling detail level. In their succeeding work (Riley and Tommelein 1996; Riley 1997), several case studies of multistory buildings present the effectiveness and capability of the model.

3.2.1.2 SCaRC system

To quantify work space as a constraint in the generation of construction schedules, Thabet (1992) defined two primary parameters of construction space: work space demand and work space availability. Work Space Demand defines the space needed to accommodate any activity in a work area. While, Work Space Availability refers to the amount of space available at any specify time when scheduling, which was defined by total available space of work area and the work space usage consumed by other concurrent activities.

Based on the space allocation level, space demand and its related activity were grouped into different categories. Assuming that the level of space demand is constant during the process of an activity, activities were grouped into three classes. An activity in Class A requires an entire work area, and the work area is solely assigned to the crew of

the activity. The space demand level for this class is constant during the activity duration. An activity in Class B requires space for the workforce and equipment, but only requires a small amount of space for material storage. The space demand level for this class is also constant, but the work area can be shared by other concurrent activities. While, an activity in Class C requires a large space for construction material storage in the work area, and as work progresses, the space demand will decrease over time since material storage space is converted into available space.

In addition to these three space demand levels, Thabet's space model classified the space demand for each activity into two types: manpower and equipment space demand; and material space demand. With these two space demand types, an activity's spatial needs in each space demand level class can be quantitatively presented as a constraint in Thabet's scheduling methodology.

3.2.1.3 Summary

Both approaches in space modeling focused on developing a methodology to describe the special needs of a construction activity. Riley's work aimed at presenting a qualitative method to define a set of space occupation patterns based on the occupation purpose of the space, while Thabet's model aims to quantify spatial needs for each construction activity based on the space demand level and type.

3.2.2 Graphical representation

There are several approaches to visually represent the spatial needs of construction activities. The graphical representation normally consists of three parts: defined working zones, space position patterns, and the occupation factor (Akinici 2000).

3.2.2.1 Defining working zones

Riley (1994) defined twelve different space patterns based on different work element types. To visually present these Space Behavior Patterns, Riley (1994) employed a set of 2D and 3D drawings to illustrate the planning method. As an extension to the construction space model, Riley (2000) discussed the usage of 4D modeling for detailed

trade sequencing and production planning for construction. After presenting conceptual methodologies for modeling construction work spaces, Riley presented the four major aspects to adjust visual space planning as follows:

- *Planning interval*: A time frame that is planned and evaluated individually, e.g. hours, days, weeks;
- *Space usage*: Spaces that should be modeled, e.g. work, storage, prefabrication, etc.;
- *Activity type*: Crew level operations that warrant planning; and
- *Work zone*: Specific areas of a facility that are likely candidates for congestion.

Dawood (Dawood and Mallasi 2002; Dawood et al. 2002) integrated the space graphical representation into research on construction design and scheduling tools, and developed a comprehensive and integrated virtual schedule and space analysis tool; Virtual Construction Site (VIRCON). In VIRCON, a simple approach was employed in the tool to describe the space demand of a construction activity. The outside area of the building component is treated as the construction space.

Another significant research effort was performed by Akinci (2002) in work space auto generation. A 4D WorkPlanner Space Generator (4D SpaceGen) was developed, which automates the generation of work space requirements for activities based on the user-defined space requirements and project-specific production model. In this model, Akinci quantified spatial needs for each activity based on the related resources, e.g. crew, equipments and materials.

To define the size of the space on site, Riley (1994) defined the classification of work element space into building, floor and room levels. A conceptual space occupation is indicted in the example instead of a quantitative definition. In Thabet's (1992) quantitative space modeling method, a typical floor was divided into three work blocks based on characteristics of construction activities. Akinci (2000) used 3D mathematical data to define spatial needs of a specific construction activity.

3.2.2.2 Space position patterns

Several research projects were performed in both computer science and construction space planning to describe the orientation of space with respect to its reference object.

In computer science research, the Mukerjee (1998) defined the spatial relationship between two objects by constraining the position of the *primary object* (the one located) with respect to the *reference frame*. The *reference frame* refers to the *orientation* determining the direction of the primary object in relation to the *reference object*.

In construction space modeling, Riley (1994) defined a general collection of space behavior patterns to describe generic space needed for each type of defined work element. An example is shown as in Figure 3.2.

Akinci (2000) summarized three common attributes of a generic representation of different types of work spaces:

1. *Reference object*: the object to which the space is located;
2. *Orientation*: the orientation of the space with respect to its reference object; and
3. *Volumetric parameters*: the size of the space (e.g., length, width, and height).

Akinci also positioned spatial needs of an activity to the related building product. A set of orientation descriptions was provided in Akinci (2000), e.g. above, below, inside, outside, around, and around the connected side.

3.2.2.3 Occupation factors

The last part of the graphical representation is focused on definition of an occupation factor for a space. Riley (2000) introduced a density index scaled from 1.0 to 0.1 to measure the ability to share. In this index, a density of a space exceeding 1.0 indicates a potential conflict. This density index is similar to the Space Capacity Factor by Thabet (1992). This factor refers to the ratio of space demand required by the activity compared to the current space availability. This rate was used to access the degree of congestion in an area and to define the corresponding productivity impacts of that congestion. Another

similar index is the conflict ratio proposed by Akinci (2000). The conflict ratio for each type of space required by the conflicting activities by using the following equation:

$$ConflictRatio = \frac{\sum Conflicting_Volume}{\sum VolumnofSpace_REQUIRED} \times 100\%$$

With this factor, congestion situations were grouped into three different levels: 1) mild congestion, 2) medium congestion; and 3) severe congestion. Akinci (2000) explained an example where 40% of the labor crew space conflicts with 15% of the scaffolding space resulting in medium congestion. From a project manager or general contractor's perspective, the severity of the congestion is measured by the degree of the problem that will be caused by the congestion. For example, congestion will be severe if a labor crew is pouring a concrete slab and scaffolding cannot be placed on the slab since the concrete slab is not set. In another example, the situation will be mild if a labor crew is performing site layout in an area while another crew is working without disruption. The difference between these two situations is the amount of effort that the supervisors of both trades will be required to expend to resolve the conflict or modify sequence. The first one is almost beyond remedy; in which scaffolding cannot be placed on the wet concrete. For the second example, the supervisors or crews for both trades may agree to share the space without any revisions to the original schedule.

3.2.3 Space analysis

A large amount of research has focused on construction space analysis. 4D CAD and virtual reality feasibility analysis were performed with an emphasis on the cost-benefit analysis of using visualization technology in construction (Fischer et al. 2003; Fischer and Kunz 2003; Koo and Fischer 2000; Messner et al. 2002). Other significant research efforts in space analysis include heavy equipment representation and modeling (Akinci et al., 2003); case studies of construction space conflicts (Akinci and Fischer 2000; Guo 2002); and construction schedule review and generation (Songer et al. 2001a; Songer et al. 2001b; Yerrapathruni 2003).

3.3 Summary

In summary, construction trade production flow and space planning literature provides many useful models for space planning, but detailed methods to represent the dynamic production trade flow in construction planning has not been fully explored. Future improvements could be developed in the following three areas of trade flow planning:

- **Trade-level/flow-level space modeling:** Trade-level / flow-level space modeling defines spatial needs over time at the production trade flow level. Current space modeling relates spatial needs to construction activities (Thabet 1992), or work-units (Riley 1994). To facilitate Visual Trade Flow Planning, it is desirable to develop a space model at a trade flow level which can bridge the gap between the production-flow-oriented approach and the activities-based space models.
- **Flow occupation level:** Flow occupation level can be defined as the accessibility of each flow space occupation for other Trade Flow. Thabet (1992) introduced a mathematical way to define the space occupation by grouping space demands of worker and equipment space demand and material space demand. However, this model did not describe the method of visually integrating the occupation level with building drawings or a 3D model. Riley (2000) mentioned using a Density index scaled from 1.0 to 0.1 to measure space's ability to share, in which a density of a space exceeding 1.0 indicates a potential conflict. However, this type of accurate description of scale might lead to the argument of what is the difference between two adjacent density indexes, e.g., 0.6 and 0.7. Furthermore, considering the complexity related to the space utilization on construction projects, it is challenging to provide a complete methodology to accurately represent the density for each space.
- **Dynamic characteristics of flow:** Among the characteristics of flow, little research had investigated visual methods to present flow continuity and flow direction: the dynamic characteristics of flow. It is desirable to develop a

methodology to use space planning techniques to describe the dynamic characteristics of flow.

CHAPTER 4

INITIAL CASE STUDY

An initial case study performed to illustrate the effectiveness of using a commercial 4D CAD application for visualizing the elements of trade flow planning. This chapter presents the preliminary case study by illustrating the methodology for using 3D CAD components to visualize work space and trade flow in a building project.

4.1 Case Study Introduction

This case study presents the comparative analysis of the use of Critical Path Method (CPM) schedules against the use of advanced visualization technology (4D CAD model) to evaluate trade flow. An experiment was performed with nine students in a graduate construction management class in the Architectural Engineering Department at The Pennsylvania State University to determine the potential value of using 4D CAD to visualize trade flow. The National Air and Space Museum was used for this initial study. This project was also used in the detailed study contained in Chapter 7.

A Critical Path Method (CPM) schedule and a 4D CAD model of the Space Hangar of the National Air & Space Museum Project were used for this experiment. The National Air & Space Museum is a \$150 million project in Dulles, VA that will house examples and artifacts of aviation. The main hangar of the building consists of 21 arch trusses each spanning 220 feet and weighing 200 tons. This experiment focuses specifically on the Space Hangar. The space hanger was an addition to the project that will house the space shuttle and related artifacts. Its structure is a steel space frame with a membrane roofing system.

Based on the characteristics of good flow, three flaws were intentionally placed within both the CPM schedule and the corresponding 4D CAD model. These flaws include a space conflict, inappropriate flow direction, and disrupted flow (see Figure 4.1,

Figure 4.2 and Figure 4.3 respectively). This was performed to test if the participants could identify these errors with the tools provided to them. In the 4D CAD model, the user had to visualize the construction space needs in construction processes for physical building elements based on the CAD components.

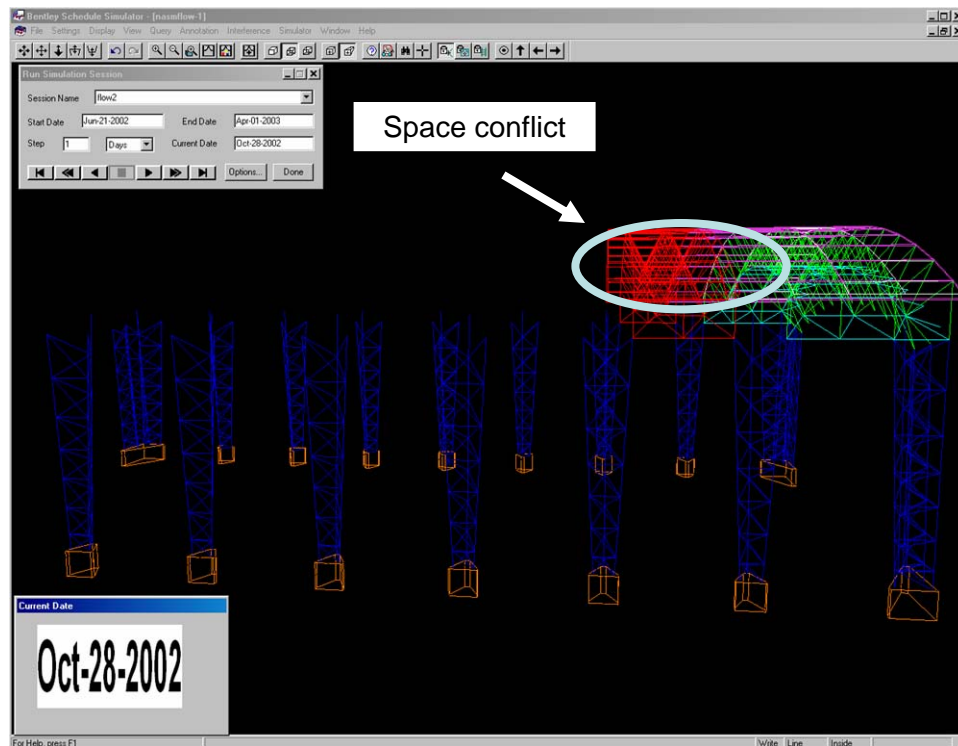


Figure 4.1: Space conflict between roof truss crew and roof decking crew

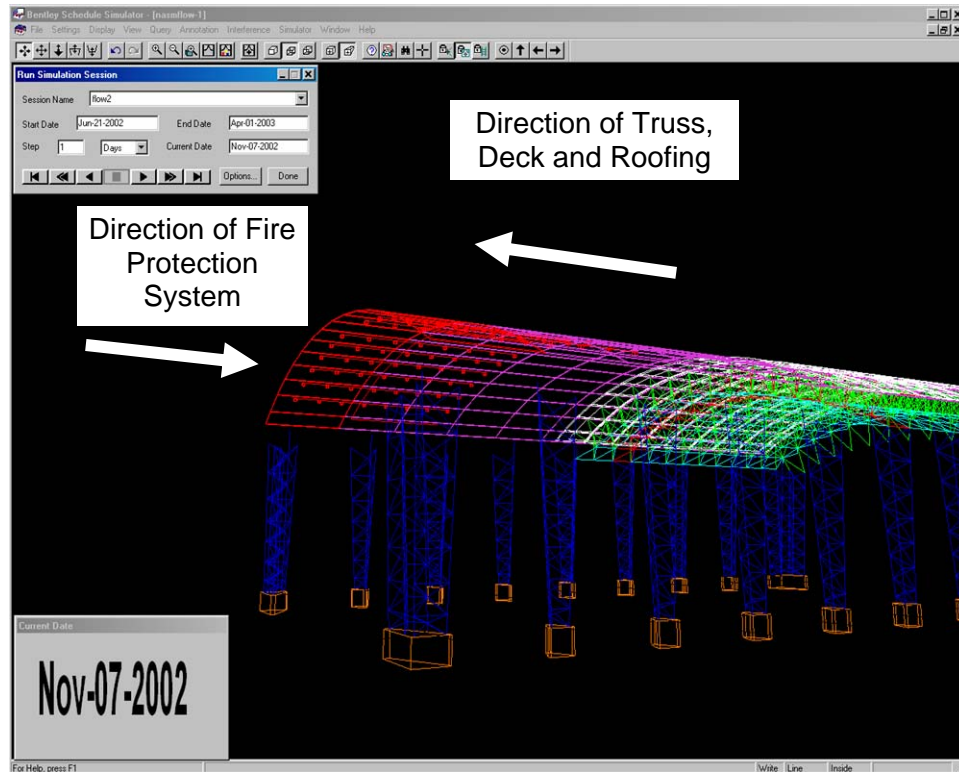


Figure 4.2: Direction conflict in work flow

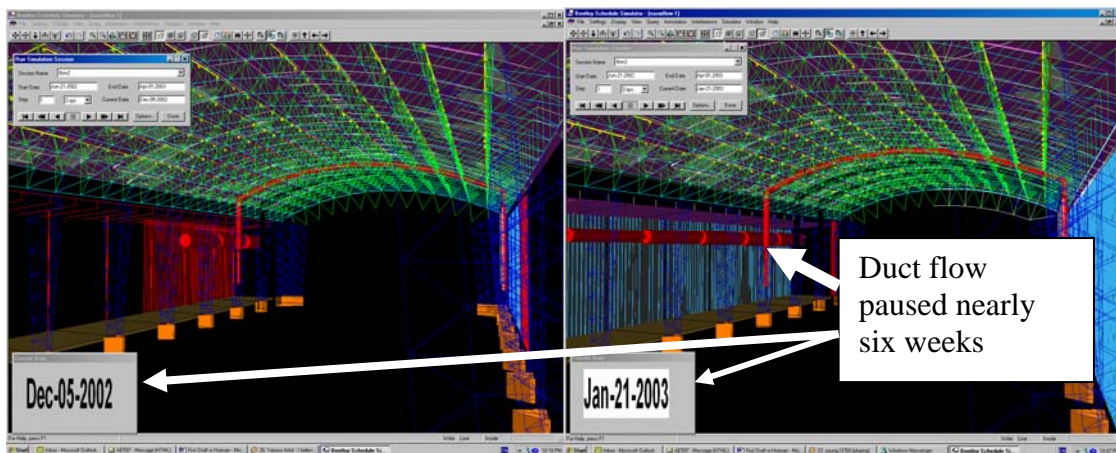


Figure 4.3: Disruption in work flow

4.2 Experiment Steps

The experiment involved two steps: 1) examine the flow in construction using 2D drawings and the CPM schedule; and 2) examine the flow using the 4D CAD model. First, all students in the class reviewed and evaluated an electronic copy of the construction schedule and a series of 2D plan drawings. There were approximately 150 activities in the schedule.

The second part of the experiment requested the participants to review the construction process with the 4D model of the project. A detailed demonstration of the 4D simulation software (*Bentley Schedule SimulatorTM*) was provided. The participants were asked to run the model, review the model, and evaluate the construction workflow.

4.3 Results & Discussion

The results of both phases of the experiment are shown in Figure 4.4. It was postulated that if students found more flaws with the 4D CAD model, this would indicate that the 4D CAD model could contribute to the evaluation of construction flow.

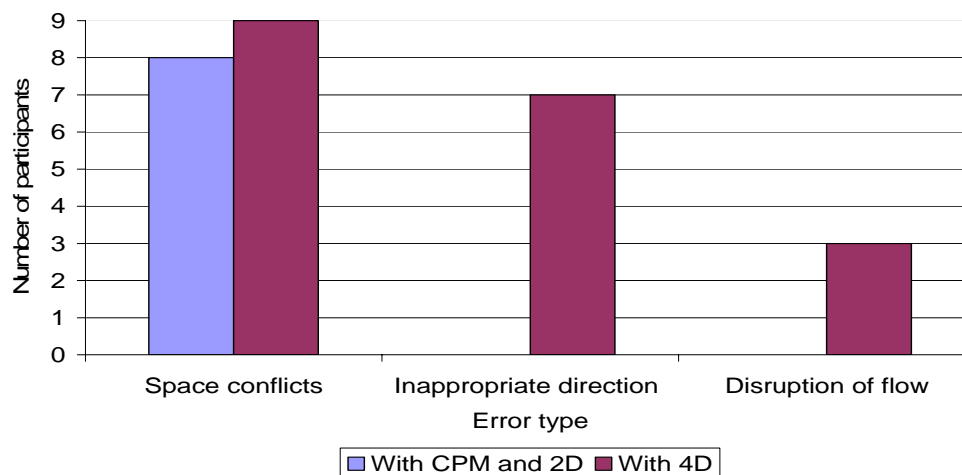


Figure 4.4: Errors identified with CPM and 4D CAD

4.3.1 Space conflicts

Construction trades need adequate space to perform work efficiently (Riley 1998). Space conflicts may occur either between the different work in the same trade or between the work of different trades. It is comparatively easier for the planner to pay attention to potential conflicts within the same trade than between different trades. As shown in Figure 4, eight out of nine participants in the experiment identified the potential flow space conflict between the roof truss crew and the roof decking crew using the CPM schedule, and the remaining student identified the problem after reviewing the 4D CAD model.

The CPM schedule and 2D drawings allowed a high proportion of participants to identify the space conflict. Both the roof truss work and roof decking work belong to the structural trades and this may have made it easier to identify the conflict as noted by Riley (1998) above.

4.3.2 Inappropriate direction

The direction of the flow is another primary concern in production management in construction projects. Different flow directions may lead to different demands for equipment, material storage, crew sizes, etc. Inappropriate direction of one trade may have a strong effect on the productivity of other trades. As shown in Figure 4.4, none of the participants noticed the inappropriate direction of the fire protection trade in the CPM schedule, while seven out of nine identified the flow issue with the 4D CAD model.

4.3.3 Disruption of flow

Ballard and Howell (1998) discuss the need to shield production from variability during construction. In work flow, variability can refer to changes in pace or pauses in the flow of work. Using a 4D CAD model, three participants identified the pause of mechanical ductwork installation, while none of them identified this issue with the CPM and 2D drawings. The results suggest that 4D CAD models are useful for presenting the dynamic characteristics of flow. The tool allows these characteristics to be visualized and analyzed

with greater efficiency than a CPM schedule. However, only one third of the participants noticed the variances of the pace of the flow.

4.4 Summary

Although the results suggest the effectiveness of using building CAD components to represent the static space of trade flow (e.g. construction space conflicts), the result of using CAD components alone to represent the dynamic issues associated with production work flow (e.g. direction of the flow and disruption of the flow) still require improvements. Therefore, it is desirable to develop a more effective visual approach to illustrate the dynamic nature of trade flow planning so that planner can better visualize the utilization of space and flow of trades on a project.

CHAPTER 5

VISUAL TRADE FLOW PLANNING METHODOLOGY

This chapter presents the Visual Trade Flow Planning (VTFP) Methodology. The methodology describes how to visually plan trade flow in construction. This methodology includes three parts: a Trade Flow Space Model, Flow Occupation Patterns, and a Trade Flow Planning Process Model.

5.1 Methodology Overview and Structure

The VTFP Methodology includes three parts (see Figure 5.1). The Trade Flow Space Model defines the space representation of construction trade flow, in which five typical space position patterns are identified. The second part is the Flow Occupation Patterns which describes three trade flow occupation levels based on a trade's ability to share the occupation with other trades. Based on these two parts, the Trade Flow Planning Process Model presents a visual planning and evaluation process for coordinating and sequencing trade flow. The Trade Flow Space Model and the Flow Occupation Patterns provide a theoretical guideline and visual representation support for the Trade Flow Planning Process Model.

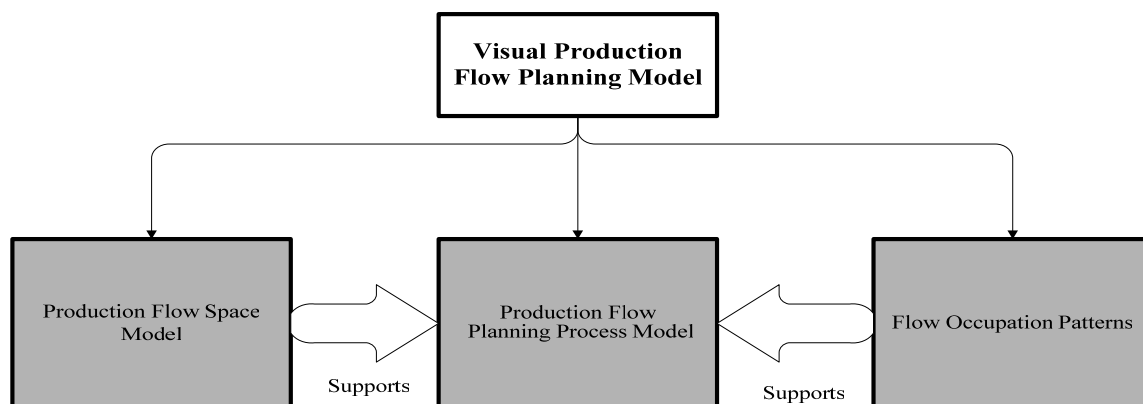


Figure 5.1 Structure of Visual Trade Flow Planning Model

5.2 The Trade Flow Space Model

The Trade Flow Space Model defines the spatial needs of a trade and introduces 3D visual space representation patterns of construction trade usage. With this model, a trade's spatial needs can be visually positioned with the building elements that the trade is required to construct.

5.2.1 Representing trade flow occupation

As discussed in the initial case study of the NASM project, the traditional component 4D method uses 3D components of a building to visualize the trade flow occupation. The deficiency of this method is that the building component cannot explicitly represent the trade occupation for temporary construction activities required for constructing the element. For example, a sheet metal trade performing installation work on site might require space for crew movement, duct storage and installation. The space occupied by the sheet metal trade is much larger than the space represented by the final installed sheet metal in the 3D modeling.

Trade flow on the construction site is impacted when a spatial conflict between associated construction activities arise (Howell and Ballard, 1995; Akinci and Fischer 2000; McKinney and Fischer 1997; Riley 2000). This model focused on qualitative representing spatial needs of trade flow over time. These spatial needs include the space required by work flow (location flow) and associated material flow.

Akinci (2000) summarized three common attributes of a generic representation of different types of work spaces of construction activities:

1. *Reference object*: in relation to which the space is located.
2. *Orientation*: describing the orientation of the space with respect to its reference object.
3. *Volumetric parameters*: representing the size of the space (e.g., length, width, height).

These three attributes were integrated into the construction space modeling approaches reviewed in Chapter 3, including Riley's Construction Space Planning Methodology (Riley 1994), Dawood's Virtual Construction Site (Dawood and Mallasi 2002; Dawood et al. 2002) and Akinci's 4D WorkPlanner Space Generator (Akinci 2000).

The Trade Flow Space model consists of two parts: space position patterns and defined working zones. Space position patterns indicate the orientation attribute and the reference object; while defined working zones represent the attribute volumetric parameters.

5.2.2 Space position patterns

Space Position Patterns describe how to place a working zone in relation to the building elements. Five Space Position Patterns are defined in this part based on the literature review in Chapter 3 and construction site observation. This set of position patterns is intended to cover the possible work zone positions on the site. The work zones associated with a building element may include the spatial needs of a trade's crew, equipment, material storage and movement around the site. The position patterns cover the orientation attribute and the reference object attribute in representing work space.

The five Space Position Patterns are described as follows:

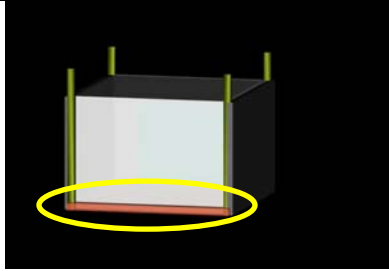
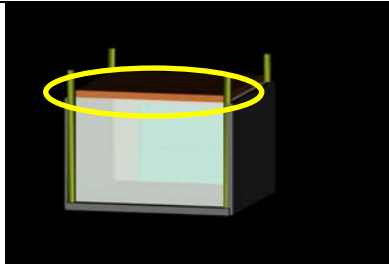
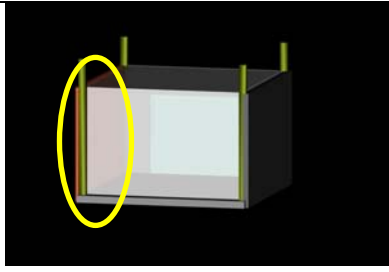
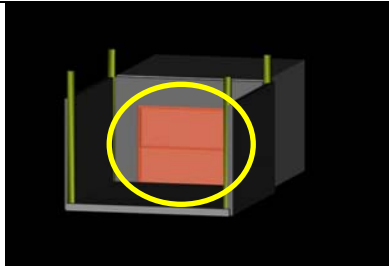
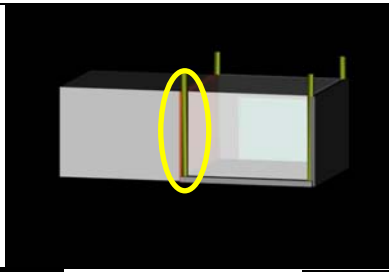


- *Over*: In this space position, trade flow requires the space over the building element. Examples include a concrete trade requiring the space above the concrete they are pouring or an interiors trade requiring the space above the floor while they are installing finished floor material.
- *Beneath*: In this space position, trade flow requires the space beneath the building element. For example, the mechanical trade needs the space beneath the ductwork they are installing for scaffolding and an interior trade needs the space beneath the ceiling they are painting.

- *Beside*: In this space position, trade flow requires the space beside the building elements. For example, the painting trade requires the space beside the wall they are painting.
- *Outside*: In this space position, trade flow requires the space beside the building element and outside of the building they are constructing. Normally, the trade working outside of a building requires scaffolding systems or other types of platforms to perform work. This makes the “outside” pattern different from the “beside” pattern. For example, the interior trade requires the space outside of the window they are installing and a scaffolding support.
- *Around*: In this space position, trade flow requires the space around the building element. For example, a concrete trade will occupy the space around a column that is being poured.

The Space Position Patterns and their visual representations, explanations and examples are summarized in Table 5.1.

The process of identifying working zones for building elements is more complex than just positioning. It is also affected by construction methods, project constraints, and the Trade Flow Space Model. The detailed procedure for identifying work zones will be discussed in section 5.4. The process for identifying a trade performing an activity may require combining several position patterns of a building element.

Table 5.1: Space Position Patterns and the corresponding visual representations, descriptions and examples

Space Position	Visual Representations	Descriptions	Examples
Over		Trade flow requires the space over the building element.	Pouring concrete; Placing flooring material.
Beneath		Trade flow requires the space beneath the building element.	Installing overhead ductwork; Painting a ceiling.
Beside		Trade flow requires the space beside the building element.	Painting interior wall; Constructing wall formwork.
Outside		Trade flow requires the space outside the building enclosure and next to the building element.	Installing windows with scaffolding; Constructing exterior brick walls.
Around		Trade flow requires the space around the building element.	Erecting wall panels.
Legend:	 Working zone;	 Building element to be constructed	

5.2.3 Defining working zones

The VPFP Model defines working zones based on the physical parameters of a building. Generally, a working zone is classified into building level, floor level, and room level. Normally, the smallest unit of a working zone is the room level except in buildings or facilities without clearly defined rooms. For example, a floor finishing trade will occupy the entire space for a room when working, as shown in Figure 5.2. As shown in the figure, the grey box occupying the room indicates the working zone while the brown slab beneath the grey box refers to the floor element that is being constructed by the trade.

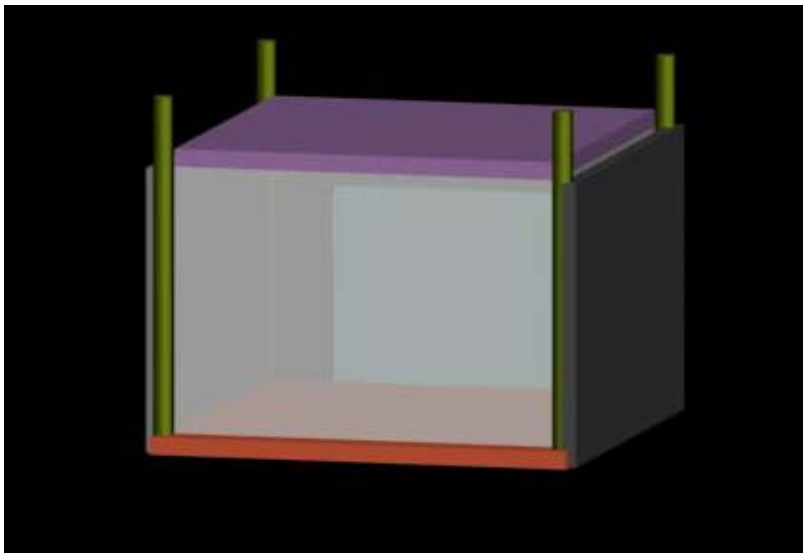


Figure 5.2: Working zone of floor finishing trade

A working zone can also be defined based on the column lines in a drawing when a room is not clearly defined. In this case, a concrete trade may require space from column line 1 to 4 and A to F of the first floor, when pouring a concrete slab.

5.3 Flow occupation patterns

The Flow Occupation patterns define the accessibility of Trade Flow occupation. The Flow Occupation Patterns describe how a trade occupies working zones. The accessibility of each flow occupation pattern is shown through a visual representation.

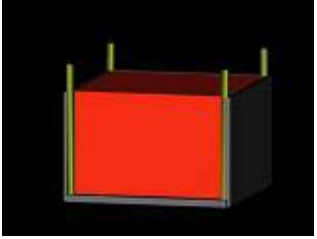
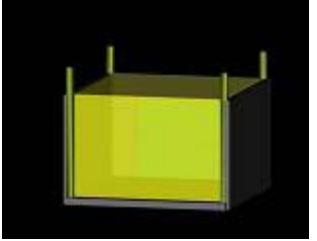
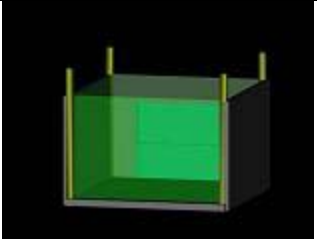

5.3.1 Flow occupation patterns

The Flow Occupation patterns define the trade flow occupation level by the trade's ability to share a working zone and the corresponding effect of sharing the space with another trade. These patterns present a conceptual method to define the occupation factor attribute of the trade flow, instead of a numerical index used in the approaches reviewed in Chapter 3. Three Flow Occupation levels are used in the patterns: 1) occupied, 2) partially occupied, and 3) accessible. These occupation levels are defined as follows:

- *Occupied*: A trade cannot share its occupied space, nor is the space sharable. For example, a foundation excavation trade needs the foundation area during the excavation period and cannot share the area with any other trades.
- *Partially Occupied*: A trade can share its occupied space, but it has to adjust its occupation to accommodate other trades. For example, the plumber normally requires the whole floor or hallway area for installation of the plumbing, but it is possible for the plumbing trade to share this space with other trades based on the coordination between trades. To accommodate other trades, the plumbing trade might be required to adjust the detailed schedule, material storage, and so on according to this coordination.
- *Accessible*: A trade can share its occupied space, and its work will not be affected due to sharing. For example, a surveying trade can typically share the space with other trade without affecting their work schedule.

These three occupation levels and their corresponding visual representations, descriptions and examples are summarized in Table 5.2.

Table 5.2: Flow Occupation Patterns

Occupation Patterns	Visual Representations	Description	Examples
Occupied		A trade cannot share its occupied space, nor is the space sharable.	Foundation excavation trade. The occupied space cannot be shared.
Partially Occupied		A trade can share its occupied space, but it has to adjust its occupation to accommodate other trades.	Piping trade and the duct work trade.
Accessible		A trade can share its occupied space, and its work will not be affected due to sharing.	Site layout trade or surveying trade.
Legend:  Working zone with occupation level			

5.3.2 Flow conflict taxonomy

It is essential for a site manager to be able to identify and understand different types of conflicts in a Trade Flow plan. For a site manager, different types of conflicts may require different levels of attention and different solutions. The conflicts between any two types of flow occupation levels are categorized in this section. Based on site observation and occupation level defined in the previous part, Taxonomy of flow conflicts types is developed to describe conflict types and the corresponding possible planning remedies. The objective of this taxonomy is to provide a solution map for the site manager based on the Occupation Level of each trade involved and the conflicts types. Table 5.3 shows

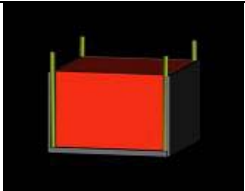
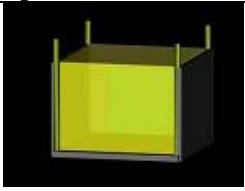
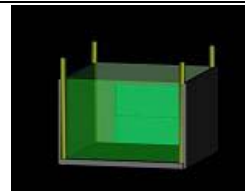
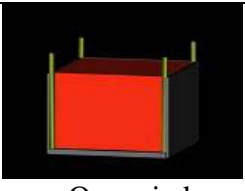
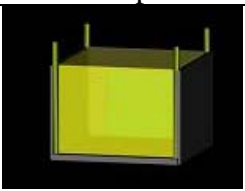
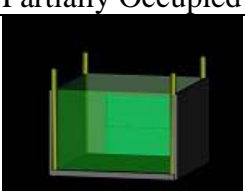
three levels of conflicts based on the Occupation Level of the trade involved. The suggested solution for each type of conflict is discussed as follows.

- *Severe Conflict*: For this type of conflict, at least one trade's occupation level is "occupied", which means the space cannot be shared. Coordination is needed between a site manager and the trades involved. The schedule, construction method, or planning sequence for the activities will probably need to be revised to resolve the conflicts.
- *Medium Conflict*: This type of conflict happens between partially occupied trades. Coordination is needed between the trades involved. The trades may need to adjust their method of performing construction activities to resolve any corresponding space conflicts.
- *Mild Conflict*: For this type of conflict, at least one trade's Occupation level is "accessible". Coordination is needed between the trades involved. No trade has to change its occupation to accommodate the sharing of the space.

5.4 Visual Trade Flow Planning Process Model

As the primary part of the Visual Trade Flow Planning Methodology, the Visual Trade Flow Planning Process Model defines a process to visually coordinate and sequence trade flow on a project. The Visual Trade Flow plan describes (1) the sequence of trade flow, (2) the spatial needs of each trade over time, and (3) the occupation level of each trade over time.

Table 5.3: Taxonomy of flow conflict types

		The Occupation Level of Trade One		
		 Occupied	 Partially Occupied	 Accessible
The Occupation Level of Trade Two	 Occupied	<i>Severe Conflict</i>	<i>Severe Conflict</i>	<i>Severe Conflict</i>
	 Partially Occupied	<i>Severe Conflict</i>	<i>Medium Conflict</i>	<i>Mild Conflict</i>
	 Accessible	<i>Severe Conflict</i>	<i>Mild Conflict</i>	<i>Mild Conflict</i>

The model is developed in the IDEF₀ modeling methodology. The methodology details are presented in Appendix A. The process model includes three levels of detail. Level 0 provides an overview of the model. Level 1 describes the four stages of the planning process which generate the primary output. Level 2 specifies details of each process, including decisions, supporting information and the sequence of the processes. The following sections explain detailed information for each level.

5.4.1 Level 0: Visual Trade Flow Planning

Level 0, the highest level, provides an overview of the inputs, outputs, controls, and mechanisms for the overall Visual Trade Flow Planning Process (see Figure 5.3).

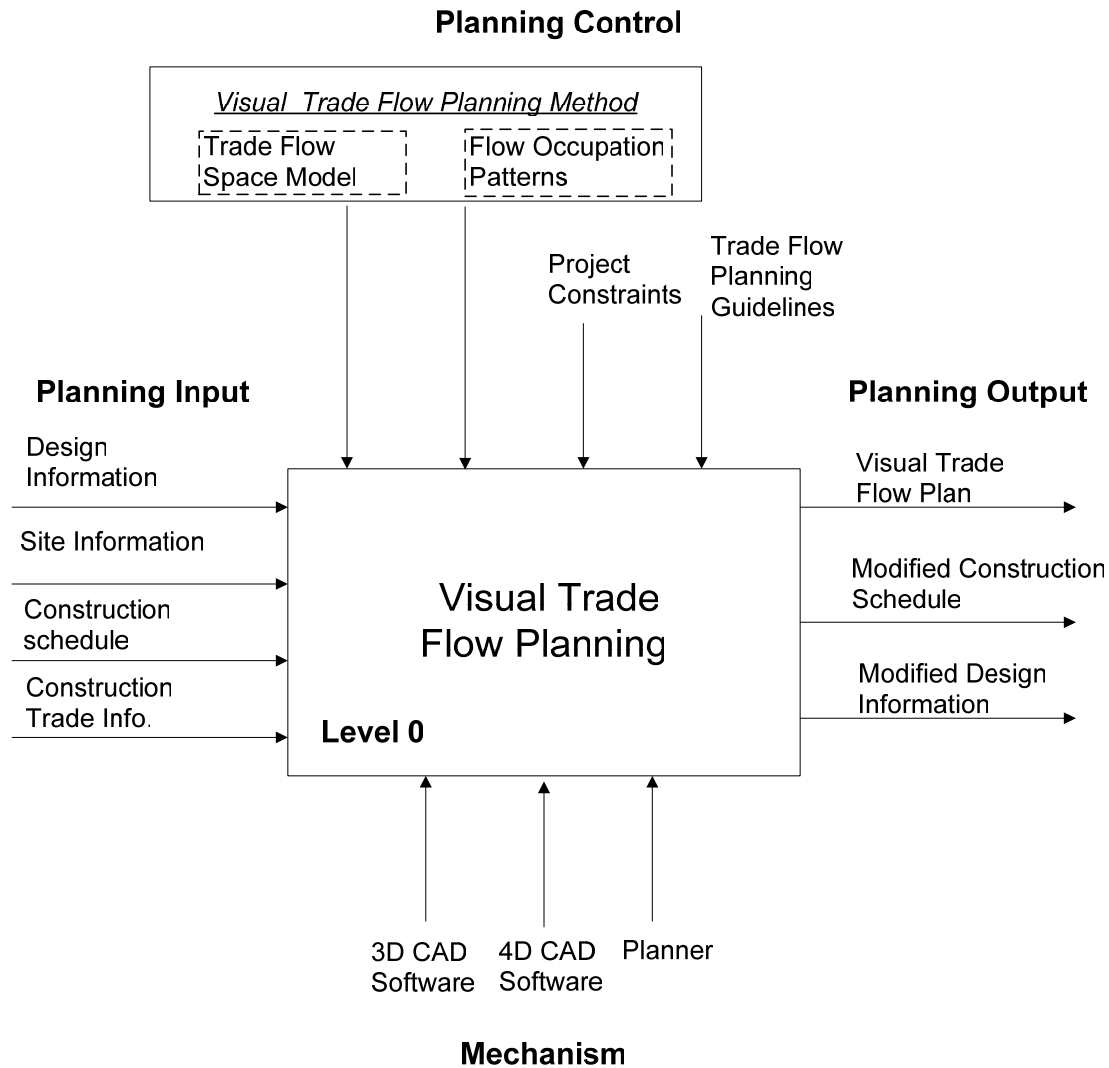


Figure 5.3: Visual Trade Flow Planning Process Model (Level 0)

5.4.1.1 Planning inputs

The information sources needed to make decisions throughout the planning process are included in the planning inputs. Inputs are indicated as arrows entering the left side of each process in the model. A description of each input is as follows:

- **Design Information:** This information includes the geometry and orientation of building elements along with additional information regarding the design. The geometric design information should be decomposed to the building element level to correspond to the production trade flow. The design information is developed

by the project designer. If the information is provided in the form of 2D drawings and specifications or other formats, a 3D model of the building must be developed before performing the visual trade flow planning.

- **Site Information:** The site information includes project location, the site conditions for the project, specific information that is critical for planning, and the site logistics including adjacent structure, utilities and site access locations.
- **Construction Schedule:** A preliminary schedule of construction activities is needed for the initial space flow review. The schedule should include the name of each construction activity, the duration of the activity, and a network showing the relationships between activities. An electronic version of the schedule can be developed by the general contractor or the construction manager of the project.
- **Construction Trade Information:** The construction trade information includes attributes about a trade contractor that will impact their potential to perform the construction plan. Specific attributes include the size, capacity, and availability of their workforce.

5.4.1.2 Planning outputs

The output of the planning process includes a Visual Trade Flow Plan, a modified construction schedule, and modified design information. The outputs describe the occupation and sequence of trade flow for the project. At the same time, the outputs also include suggested improvements to the construction schedule and project design. A definition of each output follows.

- **Visual Trade Flow Plan:** The Visual Trade Flow plan is an interactive 4D CAD plan which graphically represents the trade flow occupation and sequence. The visual plan will be able to be revised throughout the project to monitor the project progress based on the schedule. The site manager can use this visual trade flow plan for initial schedule review, either in weekly trade coordination meetings with subcontractor or in progress meetings with the owner.
- **Modified Construction Schedule:** The preliminary construction schedule is evaluated and improved during the trade flow planning process. In the modified

construction schedule, the schedule network may be reorganized to accommodate possible trade flow conflict solutions or improvements in coordination of the trade flow. The durations and other schedule parameters may also be adjusted accordingly.

- **Modified Design Information:** The project design is evaluated during the trade flow planning process. Design revision may be suggested based on the identification of possible design conflicts, possible constructability issues, and the potential to improve trade flow.

5.4.1.3 Planning controls

This section presents the items controlling or providing information that is important during the planning process. Plan control includes the Trade Flow Space Model, Flow Occupation Patterns, Project Constraints, and Flow Planning Guidelines. Each item is discussed as follows.

- **Trade Flow Space Model:** As defined in Section 5.2, this model indicates the position for space utilization by a trade based on the associated building elements. This model includes two parts: defining working zone and positioning the trade space.
- **Flow Occupation Patterns:** The Flow Occupation Patterns define the accessibility of space to allow trades to concurrently occupy the same space. The patterns present visual representations of three different levels of flow occupation and the taxonomy of flow conflict types.
- **Project Constraints:** Project constraints include project level issues that may have an effect on the Visual Trade Flow Planning process. These constraints may affect the decisions made in defining space availability, generating working zones, planning trade flow and evaluating trade flow processes.
- **Trade Flow Planning Guidelines:** Trade Flow Planning Guidelines consist of the knowledge of trade flow and ideal characteristics of production trade flow that needs to be considered during the flow planning process. The knowledge of trade flow refers to the understanding of the function of each trade and how to plan and sequence the trades on site. This knowledge helps determining the trade

occupation level and other planning related attributes. The characteristic of production trade flow considered in the guideline include flow continuity, avoidance of space conflicts and flow direction. These characteristics of flow provide the criteria that need to be used to determine flow effectiveness during the planning process.

(1) *Flow Continuity*: Flow Continuity refers to a production trade flow without unexpected variability in pace with a defined set of resources. For example, on an ideal project a trade contractor should be able to keep there crews busy 100% of the time without having to demobilize from the site.

(2) *Avoidance of Space Conflicts*: Space conflicts of flow lead to low productivity and possible safety issues. It is desirable to coordinate the flow to avoid potential space conflict between trades.

(3) *Flow Direction*: There are many different ways to plan the flow direction of each trade. Maintain consistent flow direction for related trades is essential for achieving good production.

The factors in Planning Control are shown as in Figure 5.4.

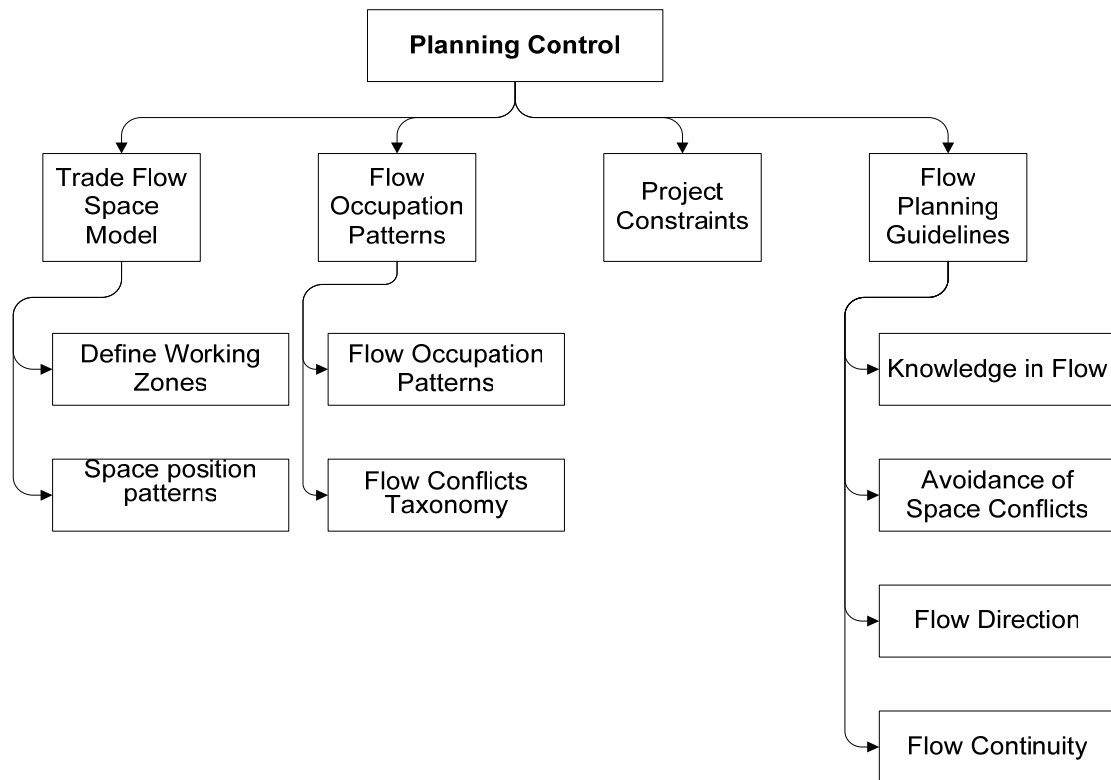


Figure 5.4: Factors in planning control

5.4.1.4 Planning mechanisms

Mechanisms define the resource needed to complete the process. This includes the planner and software application that support visual trade flow planning process.

- **Planner:** The planner is listed as mechanism because the planner here carries more responsibility than a normal planner in preconstruction or site project management. The planner is expected to perform but is not limited to the following tasks:
 - Compiling input information including design information, site information, construction schedule and construction trade information;
 - Reviewing the Trade Flow Space Model and Flow Occupation Patterns;
 - Analyzing the project constraints and Flow Planning Guidelines;
 - Determining the spatial needs of each trade over time and occupation level for each trade based on the trade flow knowledge;
 - Planning the trade flow based on the planning control and planning input through the use of the Visual Trade Flow Planning Process Model, and

- Documenting the planning output, including the Visual trade flow plan, any required construction schedule modifications and recommendations for design modifications if appropriate.
- **Software Application:** The primary applications required to perform the process are 3D modeling application(s) and 4D CAD application(s). The later integrates schedule information with the 3D model. The 3D software and 4D software listed in the mechanism generally refer to any applications with the required functions.

5.4.2 Level 1: Visual Trade Flow Planning Process

The Visual Trade Flow Planning process is decomposed into four processes in Level 1. First, the space availability of the building is defined. Then, the working zones are generated based on the building layout and space availability. Next, the trade flow sequence and occupation levels are visually planned with the working zones. Finally, the trade flow plan is evaluated in a visual interactive environment. The process decomposition is shown in Figure 5.5, and an IDEF₀ model is shown in Figure 5.6.

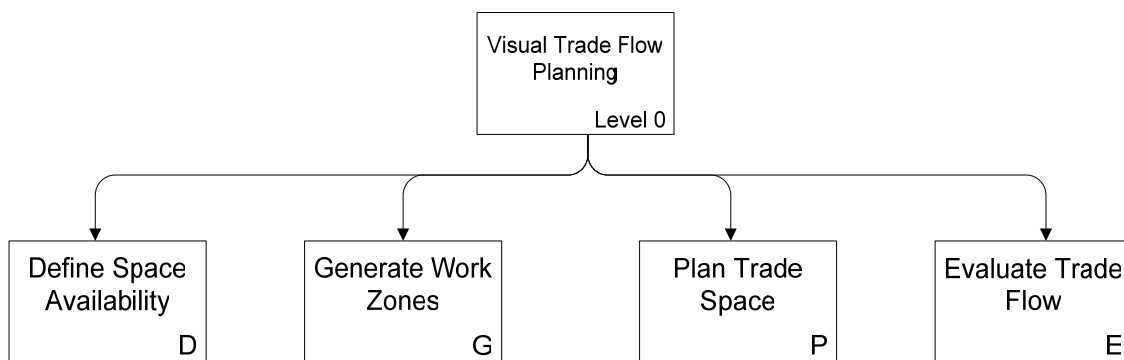


Figure 5.5: Process decomposition for the Visual Trade Flow Planning Process

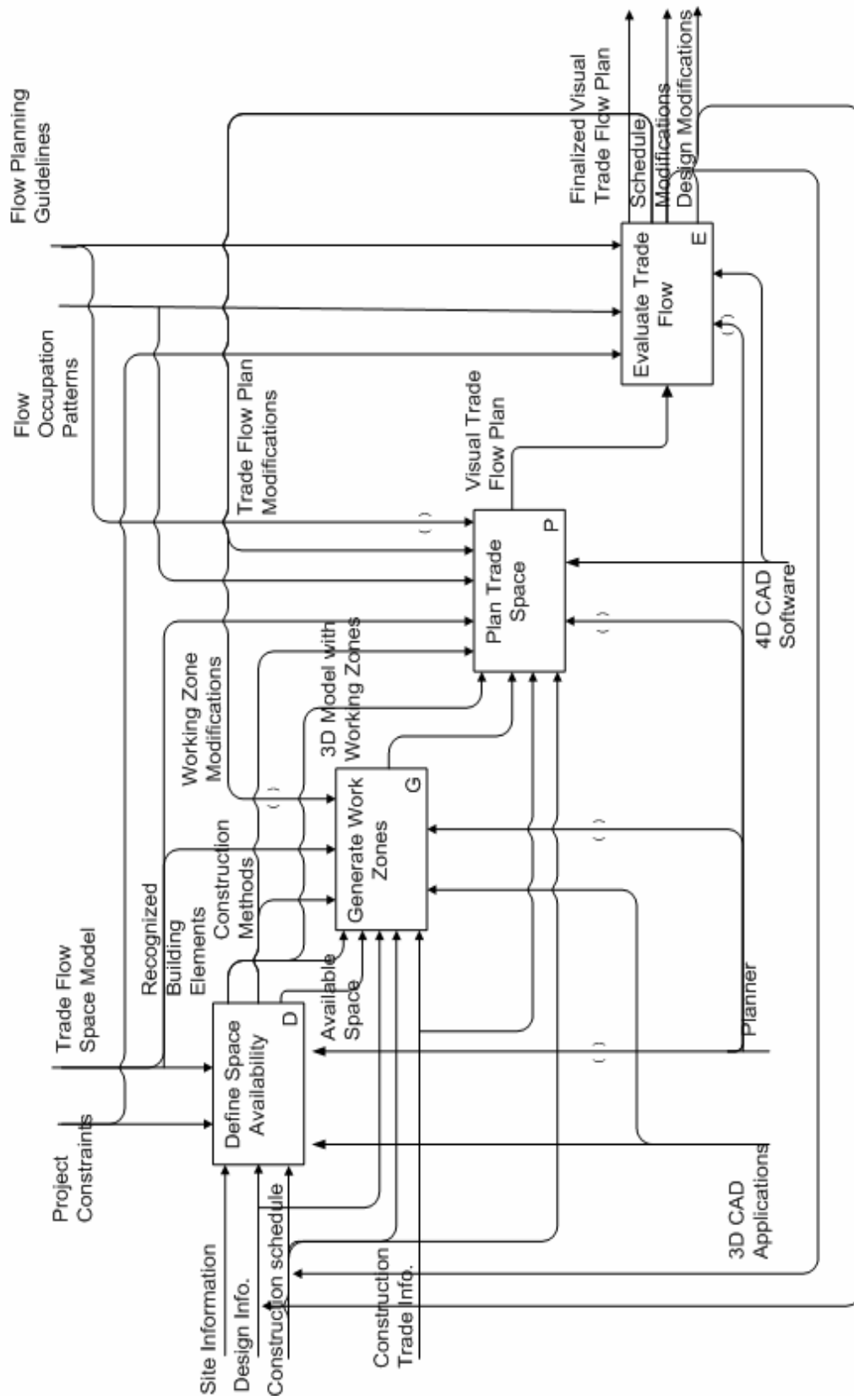


Figure 5.6: Level Visual Trade Flow Planning

5.4.2.1 Level 1: Define space availability (D)

In this process, building elements are identified after examining the project design and schedule information. Based on the identified building elements, the evaluated space availability, and other project constraints, construction methods are selected for the project. This process consists of three steps, shown in Figure 5.7. It is presented in the IDEF₀ format in Figure 5.8. The expected outputs of this process include: (1) the identified building elements which are the basic unit for further analysis, (2) evaluated available space on site, and (3) the construction method selections which determine trade flow occupation and material needs.

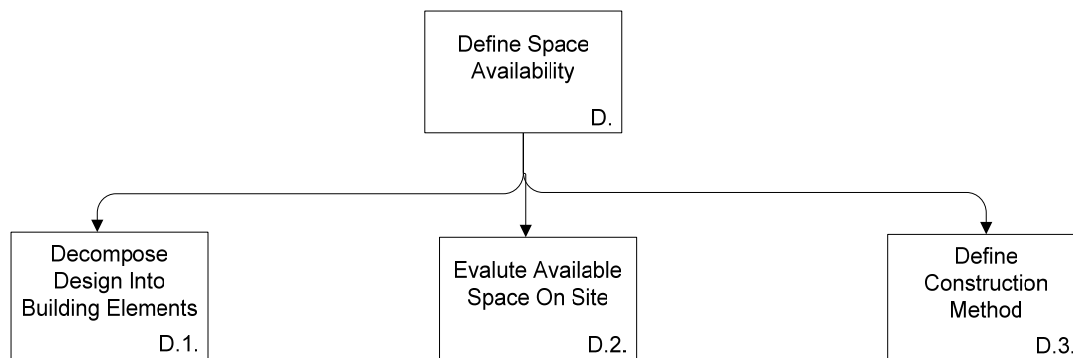


Figure 5.7: Define the space availability

5.4.2.1.1 Level 2: Decompose design into building elements (D.1)

The first step in the planning process is to decompose the building into the building element level and represent these building elements in a 3D model. These 3D graphical elements facilitate visual trade flow animation but not necessary for every building element. For example, the electrical trade may need to install small conduit, but most 3D models do not carry this level of detail design information for each conduit. In this case, the electric trade occupation can be represented through working zones without any corresponding 3D element(s).

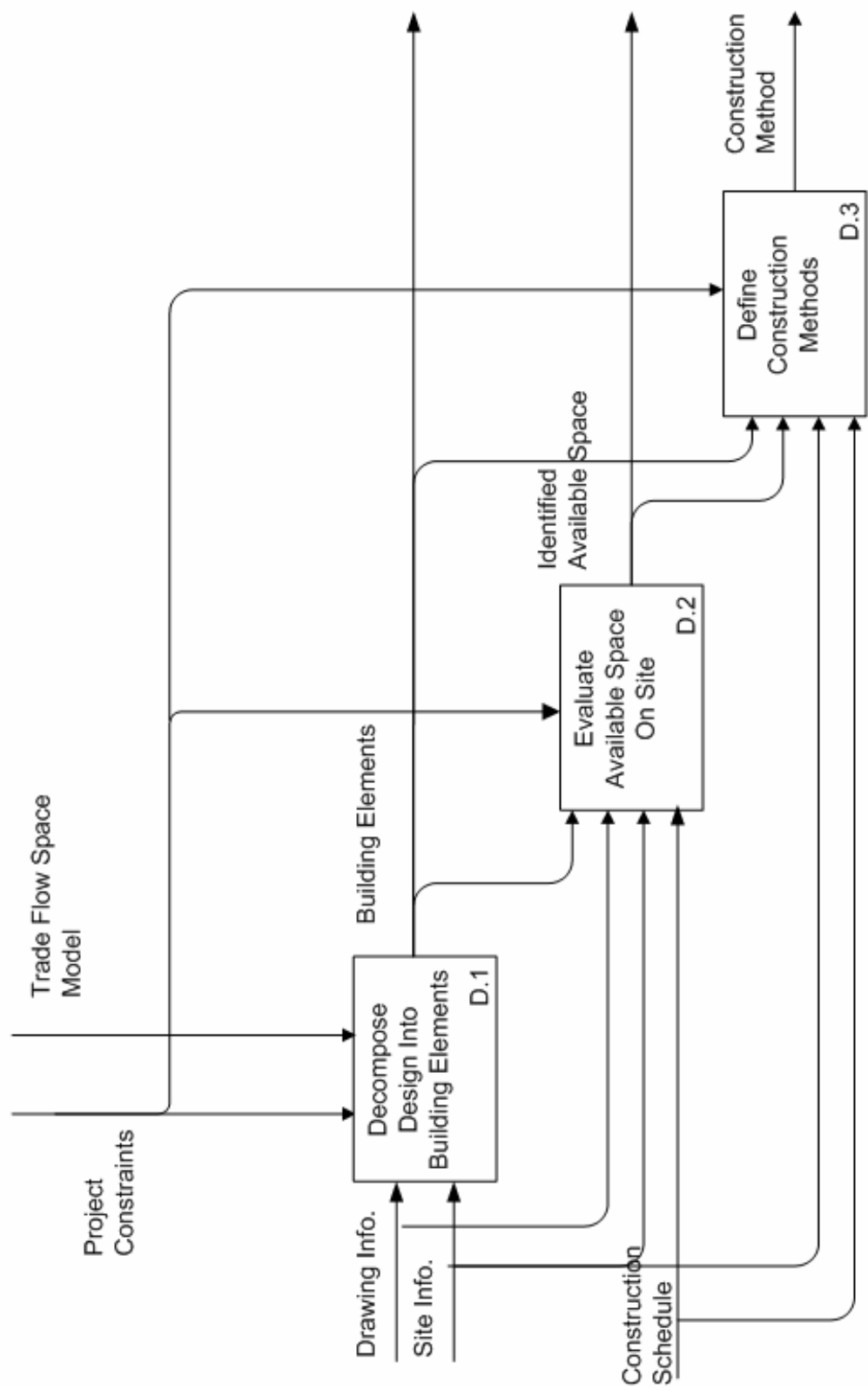


Figure 5.8: Level 2: Define space availability

5.4.2.1.2 Level 2: Evaluate available space on site (D.2)

This process focuses on the user defining the space availability based on the geometry of the building elements and the site conditions. With the defined building elements, the product model is examined to identify the space availability both inside and outside the building. Construction site information and the production model are needed in this step.

5.4.2.1.3 Level 2: Define construction method (D.3)

In this process, construction methods are determined for the building elements based on the space availability, element design and project constraints. This step is controlled by the project constraints, e.g. budget, the capacity of the trade, preference of the construction manager or subcontractors, equipment availability, and other factors.

5.4.2.2 Level 1: Generate work zones (G)

This process produces a definition of the available space on site with working zones. The input to the generation of working zones includes building elements information, available space, design information, preliminary construction schedule and construction trade information. The design information should be provided in 3D format. In this process, construction methods and the Trade Flow Space Model affect the decisions made in defining work zones. The 3D CAD applications provide a platform to generate work zones. The output of this process is a 3D model of the building with defined working zones.

This process is decomposed into four steps: identify room/work-unit level working zones, identify floor level working zones, identify building level working zones, and integrate working zones into drawings, as shown in Figure 5.9.

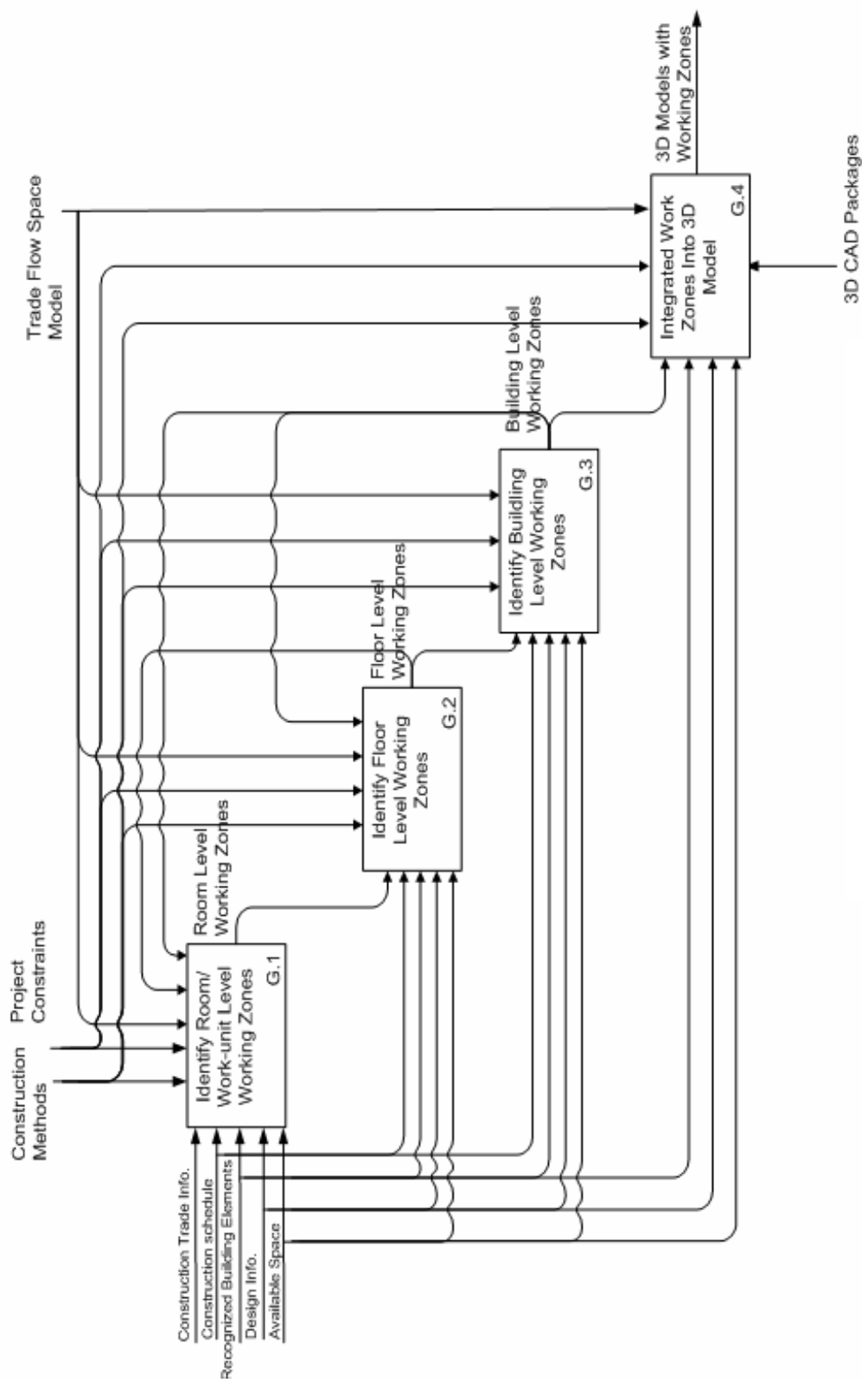


Figure 5.9: Level 2: Generate work zones

5.4.2.2.1 Level 2: Identify room/work-unit level working zones (G.1)

This process includes the identification and development of working zones at the room or work-unit level. The factors that contribute to the identification process include design information, construction trade information, the preliminary construction schedule, the available space information, and the building elements identified in the previous process. Based on the identified construction method and building elements, five typical working zone location patterns are defined following the Trade Flow Space Model. The main part of this process is to identify the smallest unit of a working zone. Normally, working zones are defined at a room level. An exception is made when a smaller unit is necessary to manage the construction of a building element within a space that requires a high level of trade coordination. For that specific area, a smaller working zone unit can be defined. The feedback from the floor level and building may be needed for the working zone adjustment.

5.4.2.2.2 Level 2: Identify floor level working zones (G.2)

This step balances and regroupes the working zones defined at the room level to make them consistent and reusable at each floor level. The building geometry in the drawing information and space availability are the main factors affecting the decisions. The redundant working zones are consolidated or combined to a single zone to reduce the amount of working zones used. The feedback from the building level and the changes at the room level may cause working zones to be adjusted.

5.4.2.2.3 Level 2: Identify building level working zones (G.3)

This process comprises the evaluation of the working zones from the floor level to make them consistent at the building level. The multi-story working zones and the working zones around building elements that pass through multiple rooms or floors are coordinated in this process. The expected output of this process is a definition of all working zones.

5.4.2.2.4 Level 2: Integrate work zones into 3D model (G.4)

After the working zones are defined at the room, floor and building levels, the zones must be graphically integrated into the 3D CAD model. During this process, each working zone is set to transparent to make the building elements visible. A 3D model of the building with defined working zones is expected as the output of this step. The control elements for this process are the project constraints and the Trade Flow Space Model. The 3D CAD packages supporting this process should have the function to support the setting of transparency for each 3D object generated along with the capacity to export the CAD data in a format supported by the 4D CAD application used in future processes.

5.4.2.3 Level 1: Plan trade space (P)

This process defines the primary processes for planning the trade flow. The control factors of this process include the defined construction methods, the Trade Flow Space Model, Flow Occupation Patterns, and the Flow Planning Guidelines. The process is supported by 4D CAD software. The expected output of this process is an interactive visual trade flow plan.

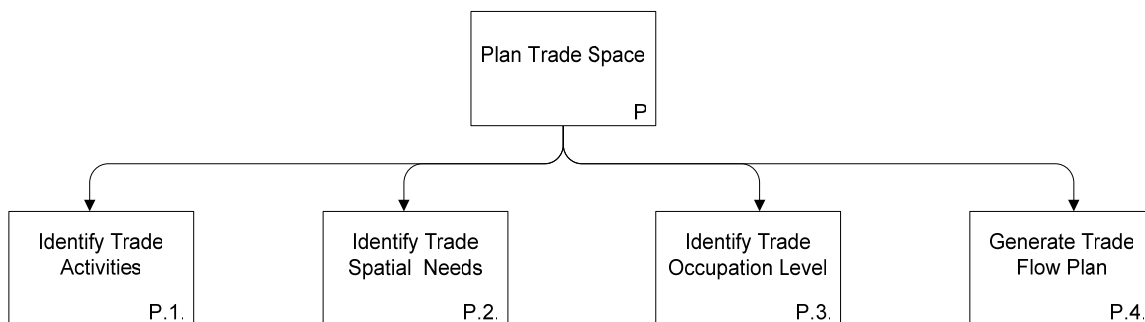


Figure 5.10: Plan trade space process

This process consists of four steps: Recognize trade activities (P.1), Identify trade spatial needs (P.2), Identify flow occupation level (P.3) and Generate trade flow plan (P.4), as shown in Figure 5.10. The IDEF₀ model is shown in Figure 5.11.

5.4.2.3.1 Level 2: Identify trade activities (P.1)

This step defines the relationship between the trades and the construction activities in the preliminary construction schedule. The schedule is regrouped according to the construction trade information, recognized building elements, preliminary construction schedules and the 3D model with defined working zones. The activities performed by the same trade are grouped together based on these inputs. The control element of this step is the defined construction methods. The identified activities belonging to the same trade are grouped as the output of this process.

5.4.2.3.2 Level 2: Identify trade spatial needs (P.2)

This process identifies the spatial needs of each trade over time based on the identified activity-trade relationship. The other inputs include the recognized building elements, preliminary construction schedule, construction trade information, and the 3D model with working zones. The control elements of this process consist of defined construction methods, the Trade Flow Space Model, and the Flow Planning Guidelines.

This process can be further decomposed into three sub-steps at Level 3: Identify trade occupation period; Identify associated building elements within the period; and Identify associated working zones, as in Figure 5.12.

- *Level 3: Identify Trade Occupation Period:* In this sub-process, a specific period of time is identified with trade information, identified activities of the trade, and construction schedule. Based on the activities' duration of a specific trade in the schedule, a period of time and the related construction activities during this period are identified.

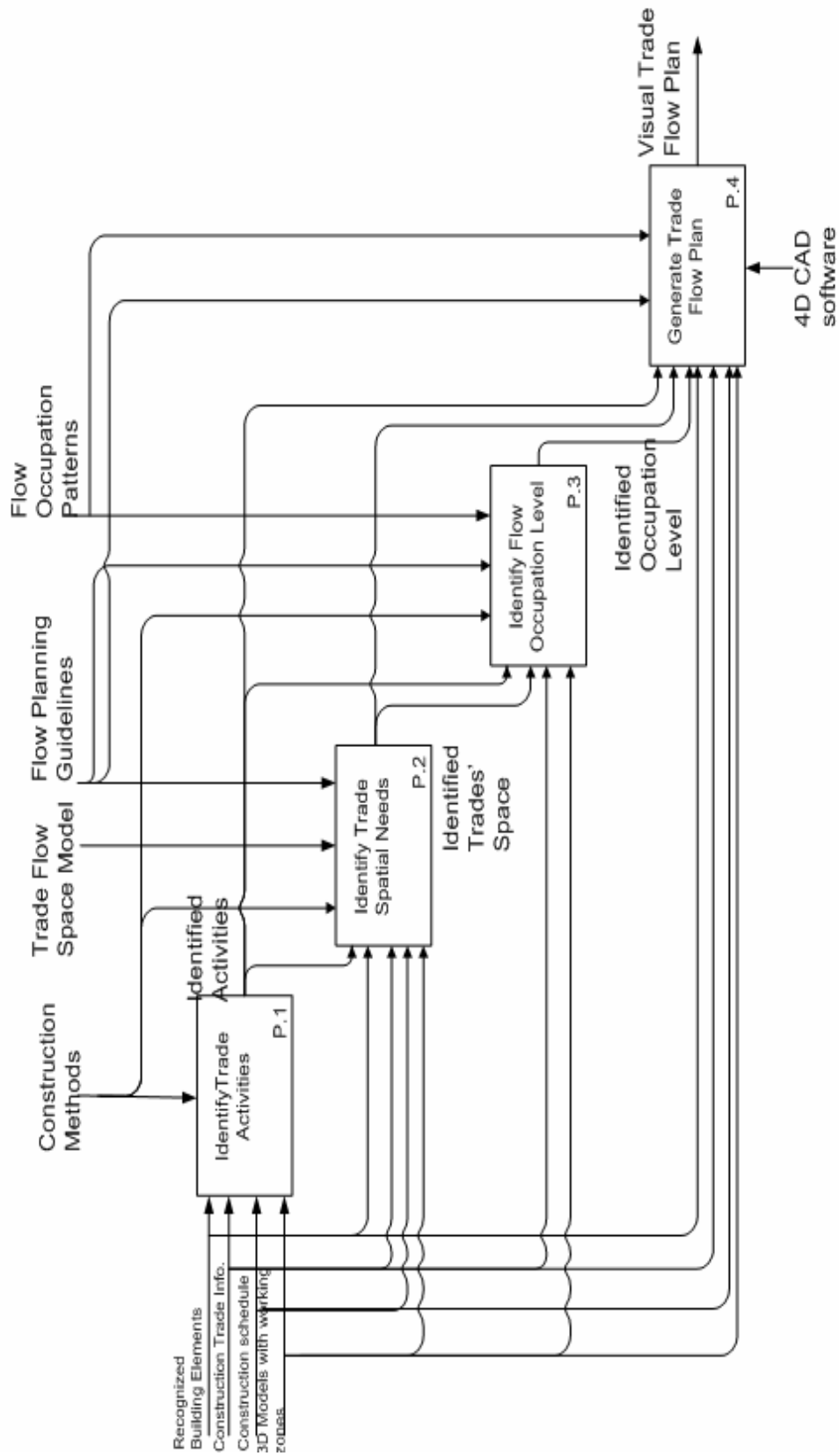


Figure 5.1.1: Level 2: Plan trade space

- *Level 3: Identify Associated Building Elements:* Based on the identified period of time and recognized building elements, the associated building elements are identified within the specific period.
- *Level 3: Identify Associated Working Zones:* Based on the identified building elements and the 3D drawings with working zones, the working zones associated with a trade during a specific period are identified in this sub-process. The control elements of this sub-process include construction methods, the Trade Flow Space Model, and the Flow Planning Guidelines. The IDEF₀ diagram of this level is illustrated in Figure 5.13.

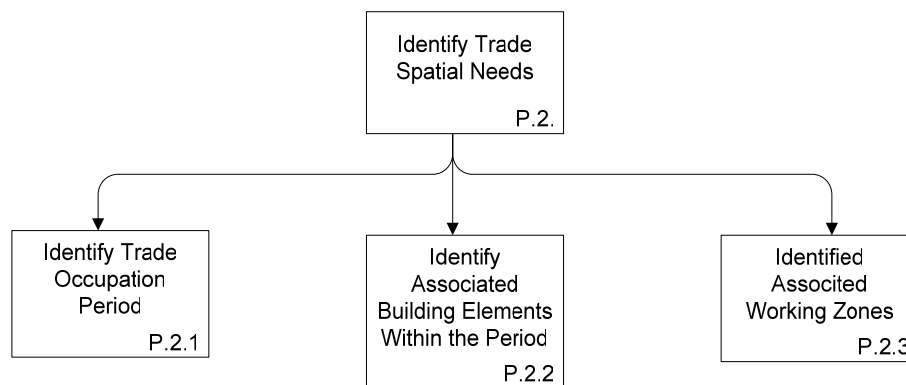


Figure 5.12 Identify Trade Spatial Needs

5.4.2.3.3 Level 2: Identify flow occupation level (P.3)

This process identifies the flow occupation level of each trade. The input of this step consists of an identified trade, identified construction activities, construction trade information, and the 3D model with working zones. This process is controlled by the construction methods, the Flow Occupation Patterns, and the Flow Planning Guidelines and performed by the planner. Based on the planning control, the planner evaluates spatial needs of each trade based on the construction activities the trade performed, the construction methods and other related information. After the evaluation, occupation level of each trade is defined and visually represented by the planner in the 3D model.

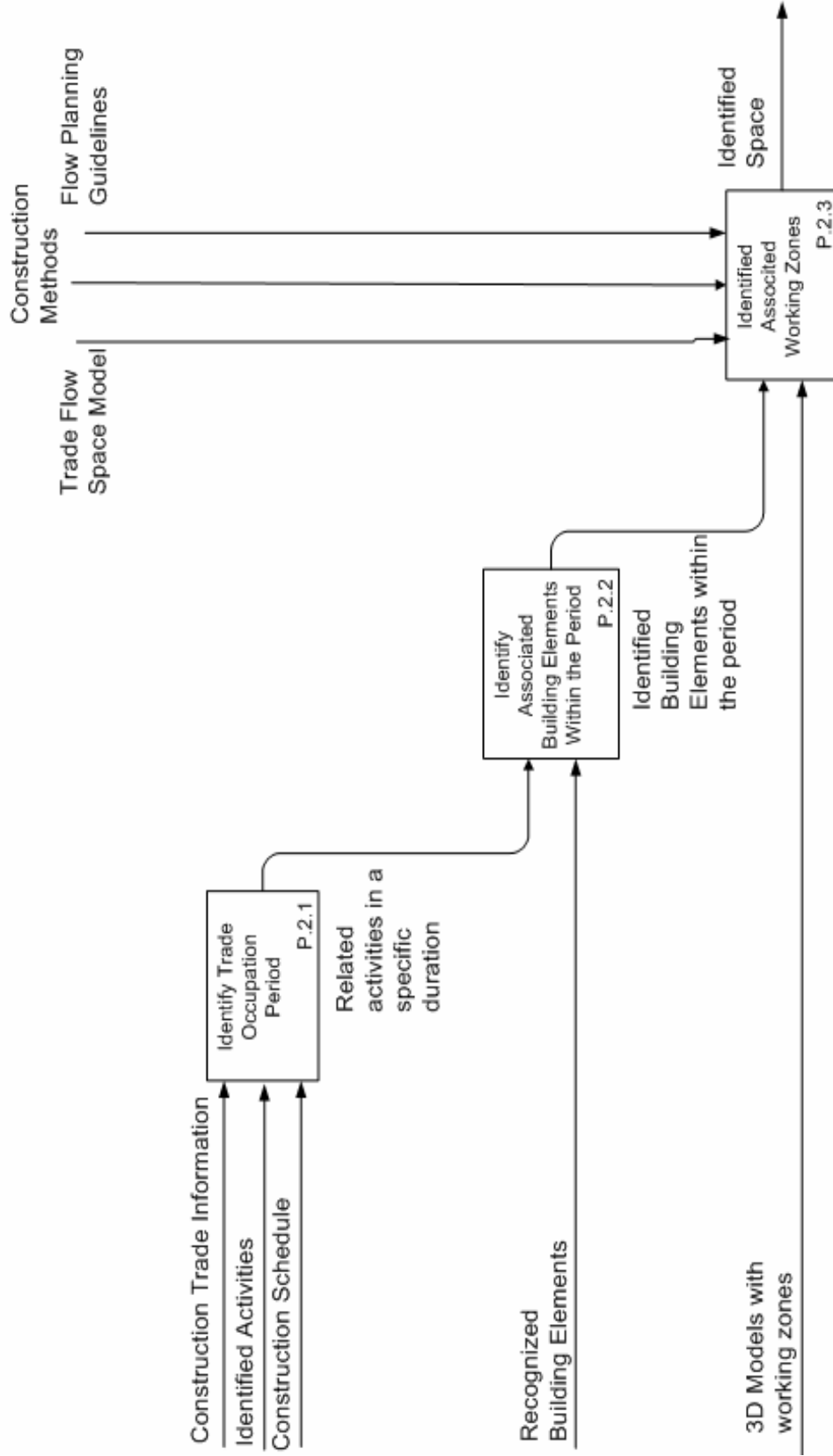


Figure 5.13 Level 3: Identify trade spatial needs

5.4.2.3.4 Level 2: Generate trade flow plan (P.4)

With the identified space needs of each trade and the occupation level of each working zone, the trade flow plan is generated. The other inputs include the identified activities for each trade, recognized building elements, construction trade information, construction schedule, and 3D model with working zones. This step is controlled by the Flow Occupation patterns and the Flow Planning Guidelines. A visual Trade Flow plan is the output of this process.

5.4.2.4 Level 2: Evaluate trade flow (E)

With the support of a 4D CAD application, the production trade flow plan is evaluated. The potential flow conflicts are identified, the causes are found, and the solutions are provided, as in Figure 5.14. The IDEF₀ format of the diagram is presented in Figure 5.15.

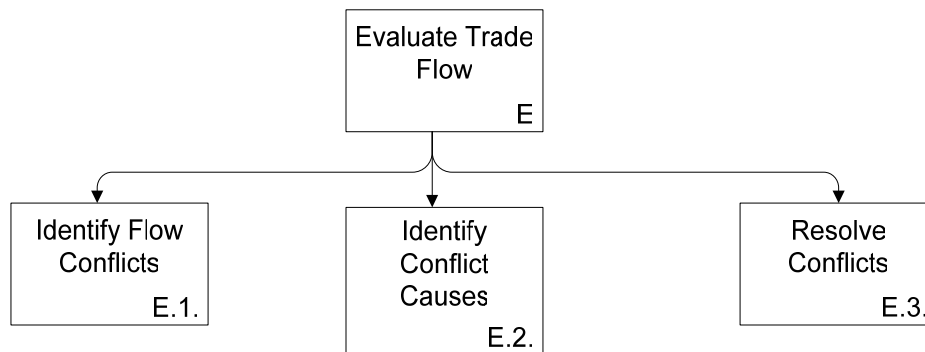


Figure 5.14: Evaluate the trade flow

5.4.2.4.1 Level 2: Identify flow conflicts (E.1)

This process encompasses the evaluation of the visual production trade flow plan based on the three rules defined in the Flow Planning Guidelines: 1) Flow continuity, 2) Flow direction, and 3) Flow interruption. The output of this process is a list of potential conflicts.

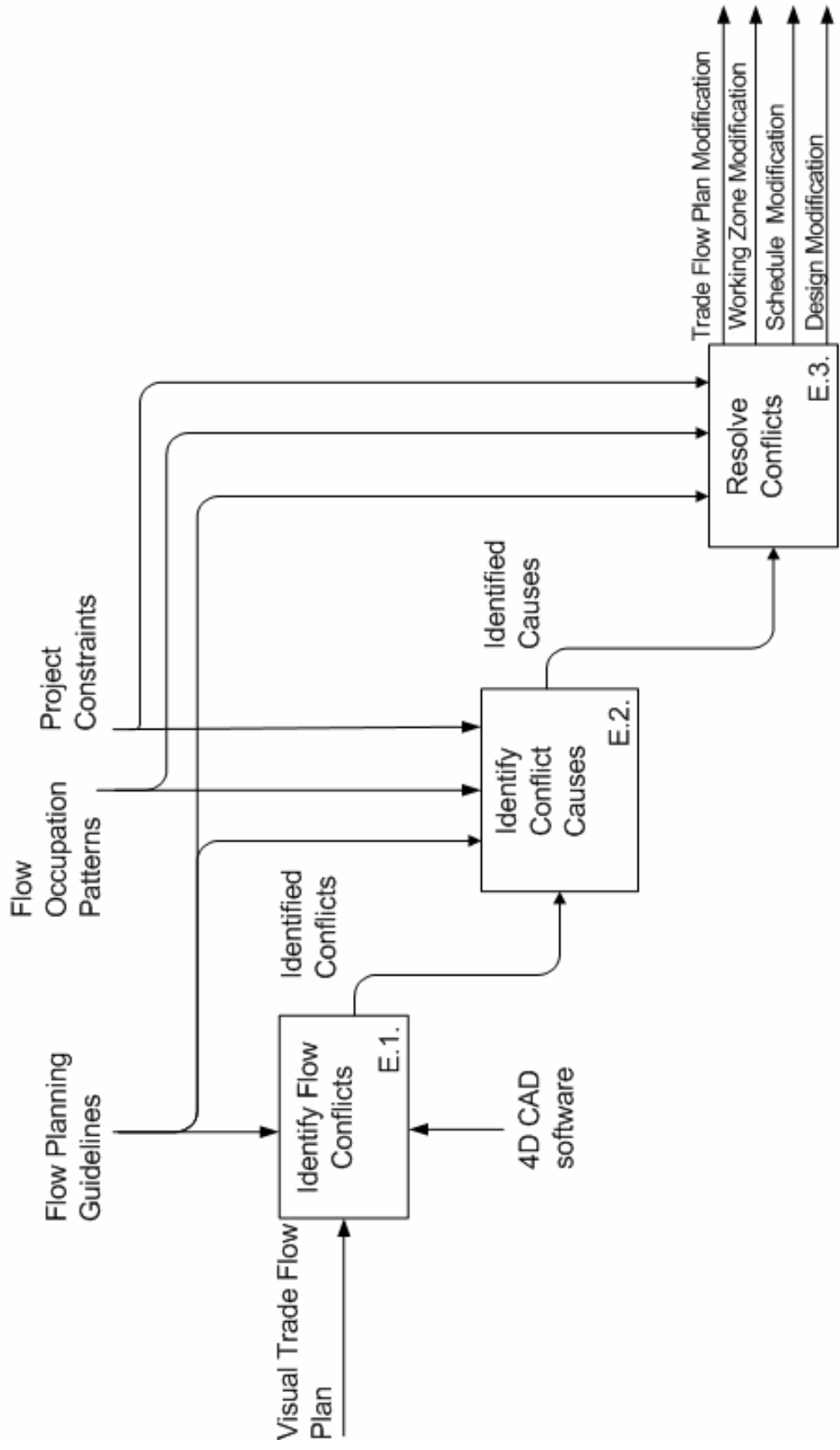


Figure 5.15: Level 2 Evaluate trade flow

5.4.2.4.2 Level 2: Identify conflicts cause (E.2)

During this process, the trade flow is analyzed and the cause of the identified conflicts is determined. The control elements of this process consist of the Flow Planning Guidelines, the Flow Conflicts Taxonomy of Flow Occupation Patterns, and project constraints. The expected output of this process is a definition of causes for each conflict identified in the previous process.

5.4.2.4.3 Level 2: Resolve conflicts (E.3)

This process provides the possible resolution of each conflict based on the identified causes. The control elements of this process consist of the Flow Planning Guidelines, Flow Occupation Patterns, and project constraints. The modification of the trade flow plan, working zones, schedule information, and design information are suggested in this process to resolve potential space conflicts.

The Flow Conflict Taxonomy discussed in Section 5.3.2 presents solution guidelines based on the level of the conflicts, e.g. severe conflict, medium conflict or mild conflict. Different levels of conflicts require different levels of attention from the site manager and the trades involved. With the guideline of the taxonomy, the site manager and the trades can focus on discussing the severe conflicts at the coordination meeting, while placing the coordination of the medium and mild conflict among the specific trades involved.

5.5 Summary

This chapter presented the Visual Trade Flow Planning Methodology. The structure of the methodology and a detail explanation of the three major parts: the Trade Flow Space Model, the Flow Occupation Patterns, and the Trade Flow Planning Process Model were presented. A detailed process description of the Trade Flow Planning Process Model was illustrated in IDEF₀ format. In the next chapter, the methodology will be shown using a case study project based on an expanded trade space plan for the School of Architecture and Landscape Architecture Project.

CHAPTER 6

ILLUSTRATIVE CASE STUDY: SALA BUILDING PROJECT

This chapter demonstrates the Visual Trade Flow Planning (VTFP) methodology through a case application on the School of Architecture and Landscape Architecture (SALA) Building project. The objective of this case study was to evaluate the methodology through developing a visual trade flow plan on an actual construction project. First, a detailed visual trade flow planning process is introduced. Then, based on the planning procedure, the Trade Flow Space Model, Flow Occupation Patterns and the Trade Flow Planning Process Model are evaluated.

6.1 Case Study Project Background

The School of Architecture and Landscape Architecture (SALA) Building project is located at the University Park campus of The Pennsylvania State University. This project is currently under construction and is scheduled for completion in spring of 2005. The SALA Building will provide a physical and academic environment for the Architecture Department and the Landscape Architecture Department.

The SALA Building is a \$23.5 million project with 111,000 square-feet of space and started construction in August 2003. The new building will have advanced space for teaching and learning including multipurpose classrooms; undergraduate and graduate studio space; critique and display areas; a model building workshop; photography and copy stand spaces; special computer laboratories; social spaces; and administration, faculty, and staff offices; common space; an amphitheater for lectures and conferences; and an arts and architecture library. (Penn State: College of Arts and Architecture 2004).

Based on the 2D CAD drawings for the project, a research team consisting of students from the departments of Architectural Engineering, Architecture, and Landscape Architecture from Penn State, developed a 3D CAD model in Graphisoft ArchiCAD[®],

commercially available CAD application. The model included both the substructure and superstructure of the building. Major building elements of the model include the piles, steel, concrete slabs, walls, façade, stairs, doors and windows (see Figure 6.1).

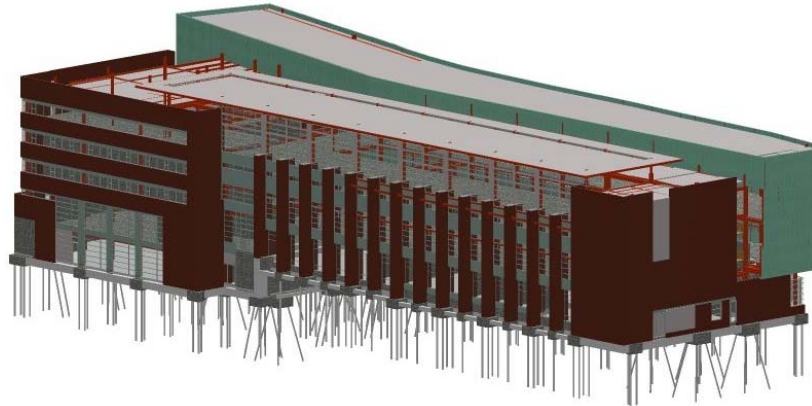


Figure 6.1: 3D CAD model of the SALA Building in ArchiCAD®

6.2 Developing the Visual Trade Flow Planning Model (VTFP)

Following the VTFP methodology, a visual trade flow plan was developed for the SALA Building for a detailed three week time period on the project (from July 5th, 2004 to July 24th, 2004). First, the input of the planning process was identified. Then, the detailed four steps in visual plan developing procedures (defining space availability, generating work zones, planning trade space and evaluating trade flow) were performed. During this process, eight site visits were performed to the SALA Building construction site and feedback was collected from the site engineers regarding the Trade Flow Space Model, Flow Occupation Patterns and the Trade Flow Planning Process Model

6.2.1 Input

The planning included the collection of design information from the general contractor and the modeling team, gathering site information, obtaining the construction schedule and collecting construction trade information.

- **Design Information:** The design information for the SALA building included two parts, the 2D drawings provided by the general contractor and the 3D model developed by the research team. The 3D model was developed based on the 2D drawings. In the 3D model, all the elements were drawn with the appropriate color and texture.
- **Site Information:** Since the SALA building was located at the university campus, the construction site was relatively congested. For example, the movement of the mobile crane was limited by the site fence and the finished building structure (see Figure 6.2).



Figure 6.2: Site condition: the movement of the crane is limited by the site fence

- **Construction Schedule:** A three-week look-ahead schedule was provided by the general contractor from July 5th to July 24th, 2004 including 36 activities performed by 12 different construction trades. A detailed concrete pour sequence and joint layout drawing was provided by the concrete subcontractor.
- **Construction Trade Information:** During the study period, there were 12 construction trades working at the site, including the concrete contractor, rough carpentry contractor, steel contractor, metal stud contractor, electric contractor, site work contractor, stair pan contractor, fire proof contractor, masonry contractor, roofing contractor, and fire protection contractor. All contractors confirmed their crew and equipment availability during the study period at the weekly coordination meeting.

6.2.2 Define space availability

Based on the inputs, the building elements' availability was identified during this process.

6.2.2.1 Recognize building elements (D.1)

Based on the three week look-ahead schedule and the 3D CAD model of the SALA Building, the availability of the building elements in the 3D CAD model were identified (see Table 6.1). If an activity could be represented as the existence of one or several building elements in the 3D model, then the activity was defined as related to a building element, then a "yes" was placed in the according cell in the Table 6.1. If the related building elements were not included in the 3D model, a "No" was placed in the cell. For example, the concrete trade will pour the curb of the basement area along column line 13. This activity can be regarded as related to the existence of the curb 3D objects along the 13 line at the basement area in the 3D model. On the contrary, the activity that steel trade bolt-up and detail the north side high roof deck cannot be referred to any building elements in the 3D model. The completing activity is related to the bolts, however, the bolts are too detail to be included in the 3D model. As shown in table 6.1, only 14 of 36 construction activities had related building elements in the 3D model.

Three different production flow modeling strategies, modeling with 3D components (building elements) and work zones, modeling with work zones, or no modeling, will be developed after building elements are identified. The activities with related building elements will be modeled with 3D component and zones. For the activities without related building elements in 3D model but occurring in the related area, the location of the related building elements will be identified and work zones will be generated. While, those activities without related building elements in the 3D model and occurring at separate locations from 3D model will not be modeled in the production flow plan. For example, pouring concrete will be modeled with 3D component and work zones, while steel completing will be modeled with work zones. For the piping work, which performs along the access road and are not included in the 3D model related area, will be not be modeled in this planning.

Table 6.1: Building element availability and the corresponding modeling solution

	Construction Activities	Building Element's availability in 3D model	Solutions
	Concrete Contractor		
1.1	Curb at Basement Area - 13 line	Yes	Component and zone
1.2	Slab on Grade Pour Sequence, 26 & 29(Jury Area & Mech. Room)	Yes	Component and zone
1.3	Slab on Grade Pour Seq. 28 (Lower Library Area)	Yes	Component and zone
1.4	Slab on Grade Pour Seq. 25 & 24 (Upper Library & Ad. Off.)	Yes	Component and zone
1.5	Deck Pour 18 & 23 Mech. Room 1 to 2 Line	Yes	Component and zone
	Rough Carpentry Contractor		
2.1	Sheathing East Elevation - Office	No	Zone
2.2	Roof Blocking	No	Zone
2.3	Sheathing Clear Story Soffit & Wall	No	Zone
	Steel Contractor		
3.1	North Side - High Roof Deck Complete	No	Zone
3.2	East Elevation Ready for Sheathing and Brickwork	No	Zone
3.3	North Elevation 13 to 10 Ready for Sheathing & Brick	No	Zone
3.4	North Elevation 10 to 1 line Tube Steel Complete	Yes	Component and zone
3.5	South Elevation Tube Steel 13 to 10 Line	Yes	Component and zone
3.6	Stair 3 Area Complete	Yes	Component and zone
3.7	South Elevation Tube Steel 10 to 1 Line	Yes	Component and zone

3.8	West Elevation	No	Component and zone
	<u>Metal Stud Contractor</u>		
4.1	Perimeter Metal Stud at A Line, Basement & Level 1	Yes	Component and zone
4.2	Metal Stud Brick Back-up at Stair 1	No	Zone
4.3	Parapet Metal Stud	No	Zone
	<u>Electric Contractor</u>		
5.1	Conduit at High Roof Deck	No	Zone
5.2	Outlets at Step Studio 211	No	Zone
	<u>Mechanical Contractor</u>		
6.1	RWC & SRWC Piping	No	Not Modeling
6.2	HP Steam Line	No	Not Modeling
6.3	Set Roof Drains	No	Zone
	<u>Site Layout Contractor</u>		
7.1	24" Chilled Water Line	No	Not Modeling
7.2	HP Steam Line	No	Not Modeling
7.3	Base Paving at SALA Dr.	No	Not Modeling
7.4	Complete 8" CHWS&R Pipe into SALA Building	No	Not Modeling
7.5	Concrete Curb & Sidewalk at SALA Dr.	No	Not Modeling
	<u>Carpentry Contractor</u>		
8.1	Install Stair 3 Pans	No	Zone
	<u>Fire Proofing Contractor</u>		
9.1	Fire Proof Level 1 - 1 to 2 Line	No	Zone
	<u>Masonry Contractor</u>		
10.1	Interior CMU at Level 1	Yes	Component and Zone
10.2	CMU at Stepped Studio 211	Yes	Component and Zone
10.3	Brick Piers along B Line	Yes	Component and Zone
	<u>Roofing Contractor</u>		
11.1	Roofing Office Block Area 13/9 - A/G (Start July 19)	Yes	Component and zone
	<u>Fire Protection Contractor</u>		
12.1	Sprinkler Pipe Rough-in at Clearstory Roof	No	Zone

6.2.2.2 Evaluate the available space on site (D.2)

Eight site visits were performed to the SALA Building construction site and the site condition information was collected. The site space availability, both inside and outside the building, was identified. For the space inside the building, the material storage is a concern. Using the roofing as an example, the metal stud trade stored a large amount of metal studs on the roof (see Figure 6.3). For the site space outside the building, the construction equipment accessibility was identified as an issue. Taking the basement area at the east side for example, the deep basement excavation prevented large construction equipment from accessing this area (see Figure 6.4).



Figure 6.3: Site space condition: Material storage on the roof



Figure 6.4: Site space condition: Accessibility issue outside of the building

6.2.2.3 Define construction methods (D.3)

This process determined the construction methods for the construction activities based on the location of activities, the related building elements and the site space availability.

This step was controlled by the project constraints. For example, the steel trade used a light mobile crane to install the tube steel at the south elevation of the building (see Figure 6.5) while the masonry trade erected the scaffolding to build the brick piers along the B line (see Figure 6.6)



Figure 6.5: Steel trade installing tube steel due to the congested site



Figure 6.6: Masonry trade scaffolding for brick piers along B Line

6.2.3 Generate work zone (G)

For the SALA project during the study period, the major work on site was primarily structural work and no rooms were clearly defined at this stage. In this case, the work zones were generated crossing the room level, the floor level and the building level based on each construction activity. After the working zones were generated based on the trade space model, these zones were integrated into the 3D model. Based on the analysis in the last process, work zones were generated for the 29 modeling activities out of the total number of 36. All of the five work zone position patterns were used in this step (see Table 6.2).

6.2.4 Plan trade space (P)

This step plans the trade space with identified building elements, a 3D model with work zones, construction schedule and construction trade information.

6.2.4.1 Recognize trade activities (P1)

The main purpose of this step is to regroup the construction activities based on the construction trade information. As shown in Table 6.1, all activities were grouped by each trade.

6.2.4.2 Identify trade spatial needs (P2)

With generated work zones and grouped activities, the spatial needs for each trade during the study period were identified. A trade may be linked to several work zones, while a work zone can be assigned to several trades.

6.2.4.3 Identify trade occupation level (P3)

Trade occupation level for each trade activities were identify in this step. Examples for different occupation levels for different trades at the roof area are shown in Table 6.3.

6.2.4.4 Generate trade plan (P4)

A visual Trade Plan was generated at this step by grouping trade activities, identifying special needs for each trade, and evaluating occupation levels for each activity. The visual trade flow plan was generated in the Common Point Project 4DTM application.

This generation process is similar to a normal 4D model. Basically, the grouped trade activities are linked with the 3D CAD components through Common Point Project 4DTM. In addition to linking the activity with the 3D component, the grouped trade activities are also linked with the identified spatial needs, e.g. the identified working zones. The occupation level for each activity is also assigned via an activity type in the modeling application. This provides the integration needed to visually illustrate the trade flow plan.

Table 6.2: Space position pattern examples

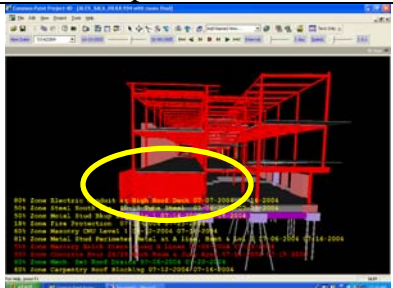
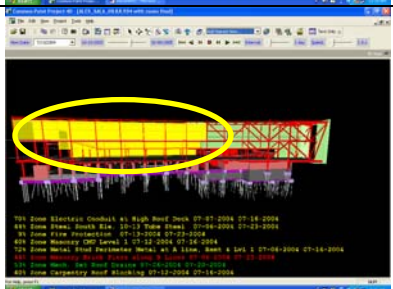
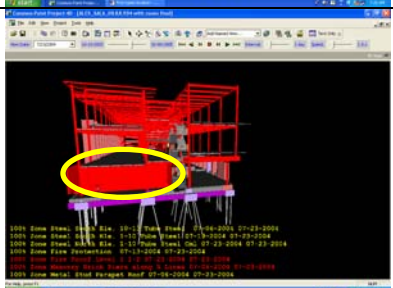
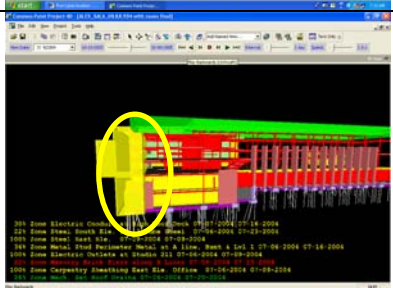
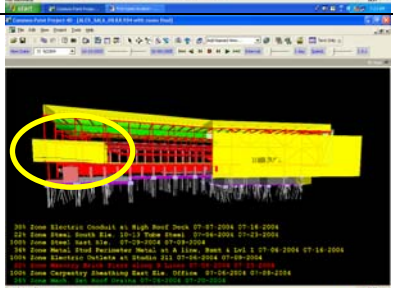
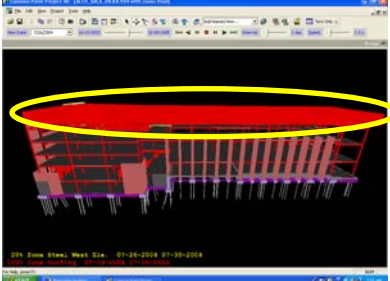
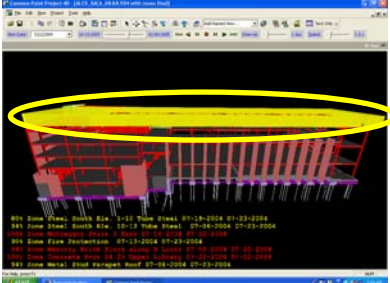
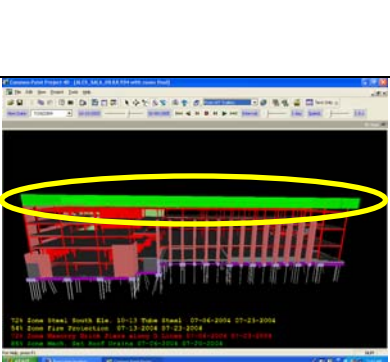
Space Position	Visual Representations	Descriptions	Activity Name
Over		Trade flow requires the space over the building element.	<i>Slab on Grade Pour Sequence, 26 & 29 (Jury Area & Mech. Room).</i>
Beneath		Trade flow requires the space beneath the building element.	<i>Sprinkler Pipe Rough-in at Clearstory Roof.</i>
Beside		Trade flow requires the space beside the building element.	<i>Fire Proofing at Level 1 - 1 to 2 Line.</i>
Outside		Trade flow requires the space at the outside of the building enclosure and next to the building element.	<i>East Elevation Ready for Sheathing and Brickwork.</i>
Around		Trade flow requires the space around the building element.	<i>Setting up electrical outlets at Step Studio 211.</i>

Table 6.3: Flow occupation pattern examples at roof area

Occupation Patterns	Visual Representations	Explanations	Activity Descriptions
Occupied		A trade cannot share its occupied space, nor is the space sharable.	<i>Roofing Office Block Area:</i> Roofing trade needs the roofing area and is not able to share the space.
Partially Occupied		A trade can share its occupied space, but it has to adjust its occupation to accommodate other trades.	<i>Parapet Metal Stud at the roofing area.</i> Metal stud trade is able to share the space but some internal work sequences must be adjusted to accommodate other trades.
Accessible		A trade can share its occupied space, and its work will not be affected due to sharing.	<i>Set Roof Drains.</i> Mechanical trade only needs a small amount of the space and is able to share without impacting the work sequence.

6.2.5 Evaluate trade flow

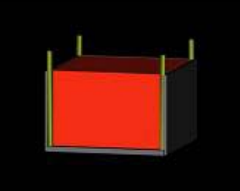
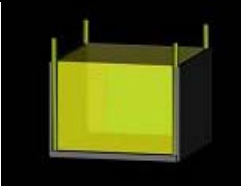
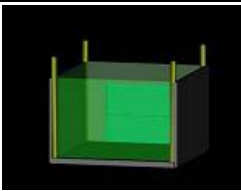
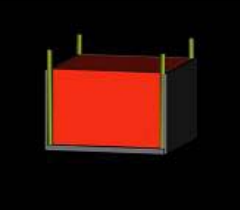
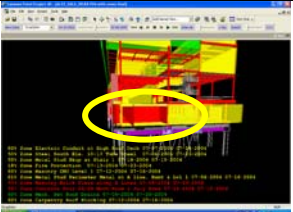
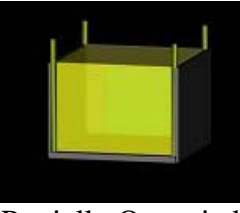
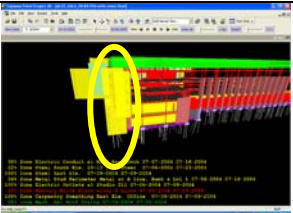
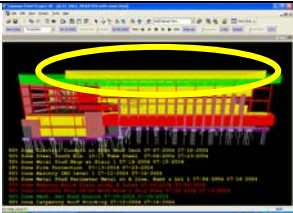
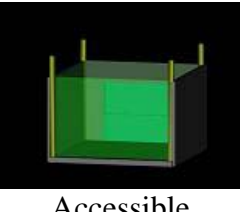
The visual trade plan was evaluated through the use of Common Point Project 4D™.

Three types of conflicts were identified in this process (see Table 6.4).

- Conflict 1:** A severe conflict was identified between the concrete trade and masonry trade on July 14th, 2004 at the mechanical room area on Floor 1 (see Figure 6.7). Concrete trade will pour the slab of the mechanical room at the first floor while masonry trade will build interior CMU wall for the first floor. The site manager's provided his comments on this conflict as follows:

“These two contractors (concrete trade and masonry trade) will not work in the same specific area at the same time. The CMU wall would either be built on the concrete footers or on top of the concrete slab. Either way, the concrete contractor would have to go in first and then the masonry contractor could come in the day after it was poured.”

Table 6.4: Identified conflict types

		The Occupation Level of Trade One		
		 Occupied	 Partially Occupied	 Accessible
The Occupation Level of Trade Two	 Occupied	N/A	 Conflict 1	N/A
	 Partially Occupied		 Conflict 2	 Conflict 3
	 Accessible			N/A

For this conflict, if the masonry did shows up but they could not perform their work due to the space conflict, the costs incurred would include the manpower that was scheduled that day plus any equipment that may have been rented for that day. 12 laborers are required for CMU work so the estimated cost of the conflict

would be:

$$\$50 / \text{worker hours} \times 12 \text{ masons} \times 8 \text{ hours} = \$ 4,800$$

A possible solution to resolve this conflict is to reschedule the interior wall activities and break them into a more detailed sequence. For example, the activity of building the interior wall for the first wall could be divided into three activities, e.g. construct interior wall at the first floor from column line 1 to 4, 4 to 10 and 10 to 13. In this way, when concrete trade is working at the mechanical room, the masonry trade is working on the CMU wall from column line 1 to 4, which locates at the other end of the building.

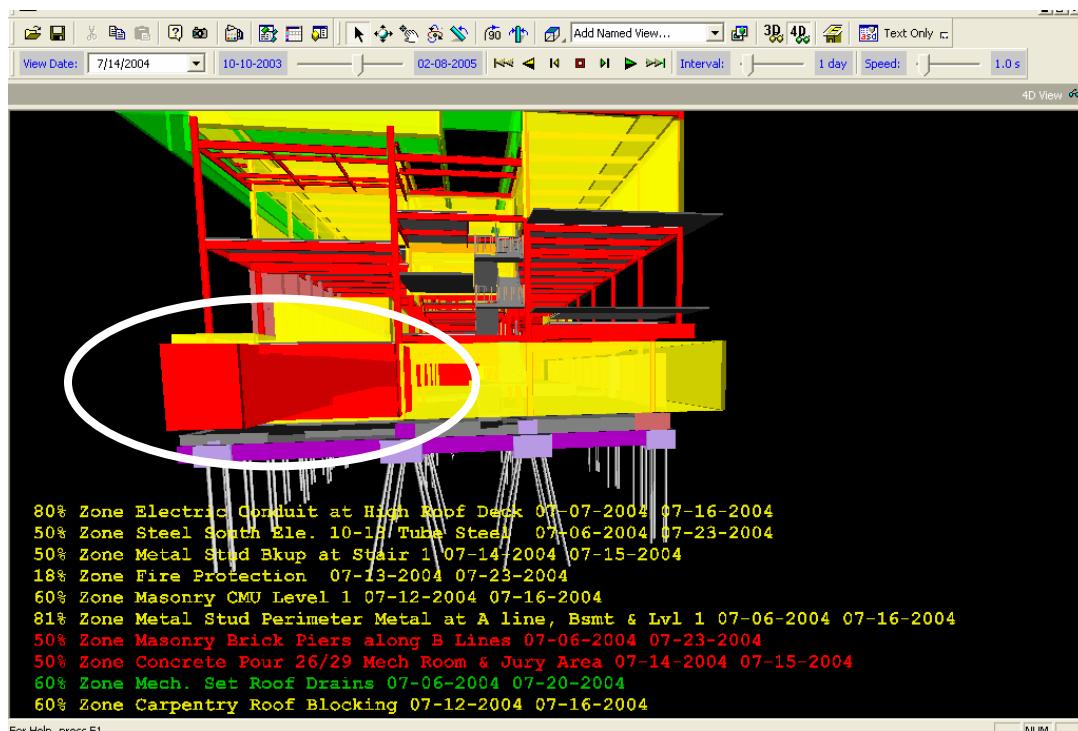


Figure 6.7: Severe conflict between masonry and concrete trade

- Conflict 2:** A medium conflict was identified between the steel and carpentry trades. Both trades need the space at the end of the east elevation to perform construction work (see Figure 6.8). The site manager's provided his comments on

this conflict as follows:

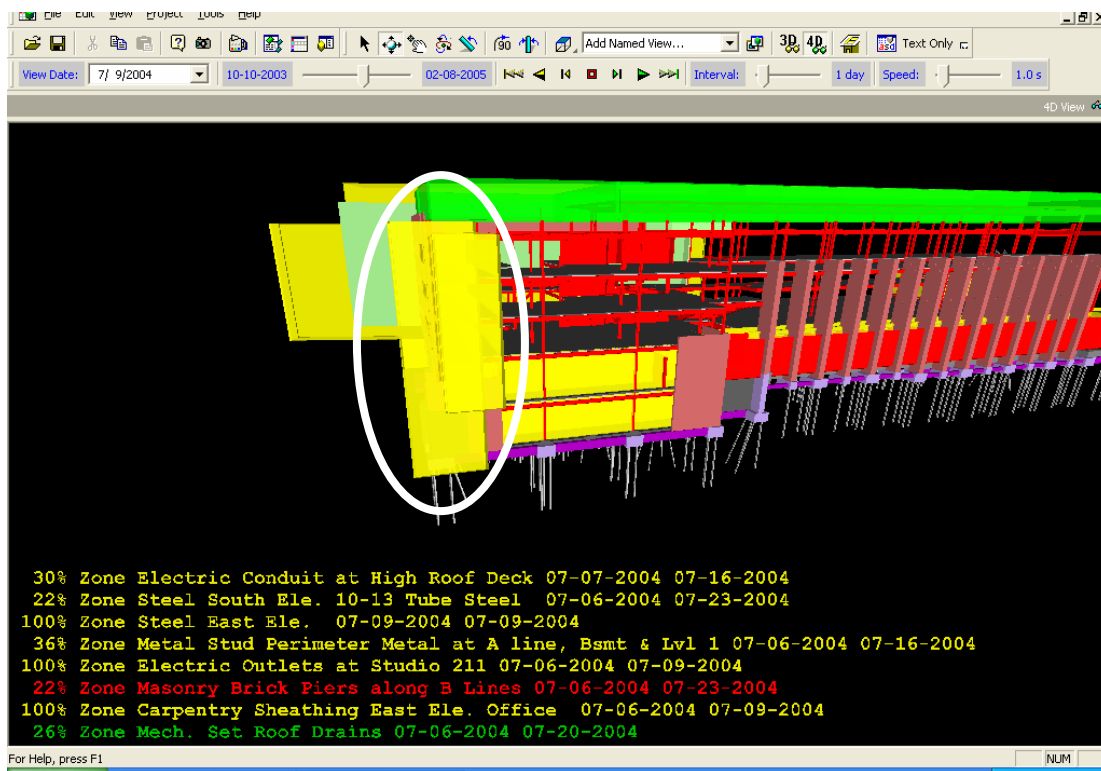


Figure 6.8: Medium conflict between carpentry trade and steel trade

“The steel has to be complete before the plywood sheathing can be installed. So the steel contractor would be finishing the steel with the carpentry contractor putting up plywood behind him”

Since the occupation level for each trade is partially occupied, the two trades are going to share the space with some adjustment of their internal construction sequence. For example, the steel trade could start from the first floor to the third floor, and the carpentry contractor could follow the steel contractor to install the plywood sheathing provided they were adequately protected. If the coordination between the steel contractor and the carpentry contractor does not work, the cost could include labor and equipment. For the carpentry contractor, 4 workers and two lifts are required for this construction activity. Therefore, the total cost could be \$ 2, 000, as in Table 6.5.

Table 6.5: The conflict cost breakdown of carpentry contractor

Item	Unit cost	Unit	Duration	Total
Crew	\$50/hour	4	8 hours	\$1,600/day
Equipment	\$200/day	2	1 day	\$400/day
Total				\$2,000/day

- Conflict 3: A mild conflict was identified between the mechanical trade and the carpentry trade (see Figure 6.9). Although both trades are working at the roof area, the mechanical trade will need a small amount of space to install the roof drains and is willing to share the space with the carpentry trade. No specific action is needed to be taken to solve the conflicts. The site manager's provided his comments on this conflict as follows:

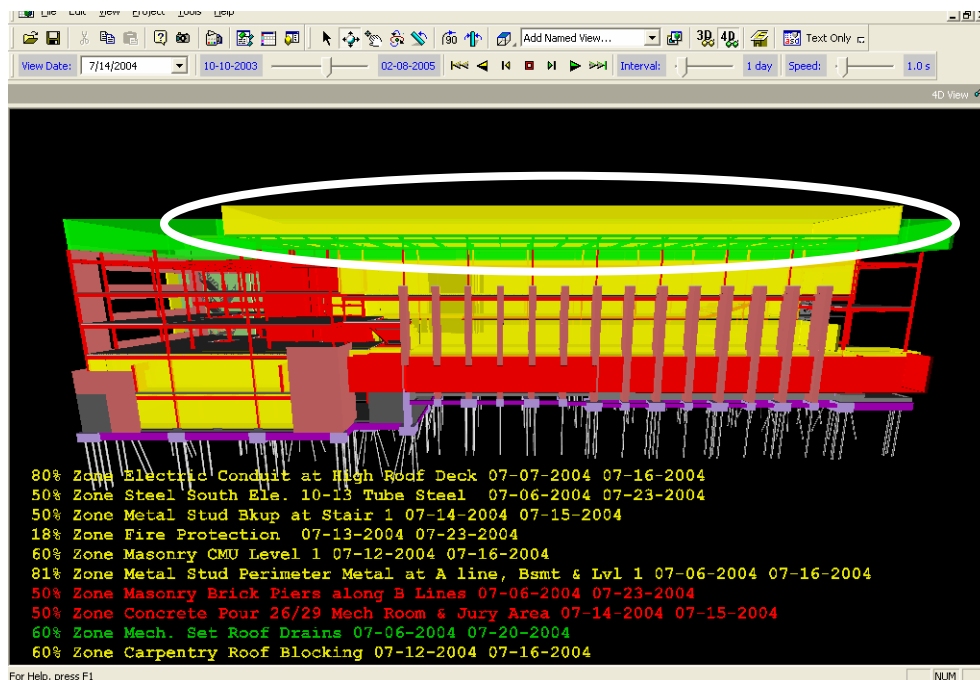


Figure 6.9: Mild conflict between mechanical and carpentry trade

“The mechanical contractor and the carpentry contractor could both be working on the roof at the same time. The mechanical contractor would be installing the roof drains, which are spaced across the roof, but in the middle of the roof area. The carpentry contractor would be installing plywood at the roof

perimeter, basically on the backsides of the parapet walls.”

6.3 Evaluate the visual production flow planning methodology

The Trade Flow Space Model, Flow Occupation Patterns and the Trade Flow Planning Process Model were evaluated in this following the development of the model.

- **The Trade Flow Space Model:** This model includes two major components: defining work zones and positioning working zones. In this case study, 29 construction activities of 12 different trades were modeled in the visual trade flow plan. Work zones were defined and positioned for each activity following the Trade Flow Space Model. Five different space position patterns covering all the work zone positions were needed for this case study.
- **Flow Occupation Patterns:** Three different occupation levels were defined in the flow occupation patterns. In this case study, among the 29 modeled activities, 20 of them were identified as partially occupied, 8 occupied and 1 accessible. During the site visit and interviews with site engineers, the “ability to share” a space was identified as one of the main space planning concepts used for coordinating trades. It was common to hear the site crew communicating with each other about construction space in this phase. After a short description, they had accepted the three occupation level concept very quickly. For flow conflict resolution, the Flow Conflicts Taxonomy matched well with the actual solutions implemented on site for the three types of conflicts identified in the case study.
- **The Trade Flow Planning Process Model:** With the support of the Flow Space Model and the Flow Occupation Patterns, a visual trade flow plan was developed for the case study following the four major steps: defining space availability, generating work zones, planning trade space and evaluating trade flow. Following the process model, the generated visual trade flow plan demonstrated the spatial needs and occupation level for each trade during the study period with graphical representations. During the Trade Flow evaluation, three different types of conflicts were identified and resolved based on the flow conflict taxonomy.

6.4 Summary

The Visual Trade Flow Methodology (VTFM) provided a means to plan and communicate the trade flow plan for the case study project. This chapter evaluated the methodology through the detailed analysis of a three week time period on the SALA Building case study. The VTFM was able to identify potential trade flow conflicts within the look-ahead schedule. Also, the model visualized the trade occupation level and the conflicts type. The next chapter will present the results of two experiments conducted to test the methodology with a case study based on the National Air and Space Museum Project.

CHAPTER 7

CASE STUDY: NASM PROJECT EXPERIMENT PROCEDURES AND RESULTS

National Air & Space Museum case study was conducted to test the application of the visual trade flow planning methodology in a complete construction process, from the foundation to the building close-up. This case study included two experiments to evaluate the effectiveness of the methodology in visually planning trade flow. One experiment was performed in a graduate-level production planning course in Architectural Engineering at The Pennsylvania State University. The objective of this experiment was to evaluate the methodology in a class environment and identify the comparative advantages of the methodology in representing the flow occupation conflicts, flow direction, and flow continuity. The second experiment involved the application of the methodology to the evaluation of the visual trade flow from the points of view of the trade contractor. This experiment was performed with four graduate students in Architectural Engineering. The experiment procedures and results are discussed in detail in the following sections.

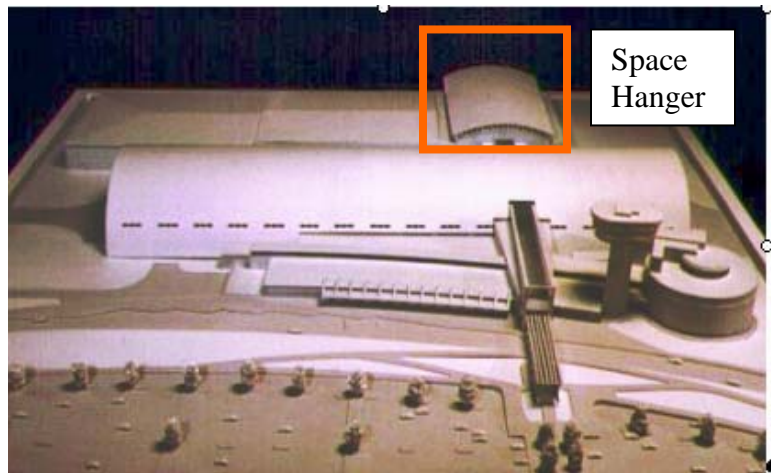
7.1 Case Project Background

The National Air & Space Museum Project in the initial study (reference Chapter 4) was used for this case study (see Figure 7.1). The design of the Air and Space Museum contains four major components:

- The Main Exhibit Hanger consists of an arched Tri-truss design, hanging mezzanine walkways, counter-weighted Exhibit doors, and a rubber membrane roof.
- The Space Hanger, which will contain the Space Shuttle Enterprise, consists of a “space frame” truss design, sliding exhibit doors, rubber membrane roof, and metal panel exterior.
- The Observation Tower is an egg shaped design that is fastened above a twelve-

story shaft. The exterior is composed of angled glazing and metal panels. The shaft is wrapped in metal panels.

- Public Amenities includes classrooms, a retail shop, a restaurant, and an IMAX theater. The exterior consists of metal panels, curved glazing, and metallic ceramic tile.



(a) NASM project scale model



(b) NASM Project layout

Figure 7.1: NASM Project drawings

This case study focused on the construction process of the Space Hanger portion of the project only. Major trades involved in the construction included a concrete contractor, steel fabrication contractor, steel erection contractor, roof decking contractor, roofing contractor, glazing contractor, curtain wall contractor, mechanical contractor, and sprinkler contractor. The Space Hanger can be divided into the following major building elements: subbase, columns, roof trusses, roof decking, side gallery decking, roofing membrane, side framing, main HVAC ducts, sprinkler system, side panels, windows, glazing, wall panels, side roof, main framing, return air ductwork, and side gallery HVAC ductwork.

The construction schedule for the Space Hanger provided by the general contractor included 270 construction activities. The construction duration was approximately 30 months based on the construction manager's schedule.

7.2 Visual Trade Flow Plan Development

To study the comparative advantages of the Visual Trade Flow Planning methodology, two trade flow plan models of the construction sequence of the Space Hanger were developed, including the work of the concrete contractor to the roofing contractor. Both models used the Visual Trade Flow Planning concept to represent the trade flow. Different visual representation methods were used in the different models. The first model was a Component 4D CAD model, in which 3D CAD Components (building elements) were used to visually illustrate the flow of work. The second model was developed using the trade flow space model and the flow occupation patterns. A 4D software package, Common Point Project 4DTM, was used as the platform for both models to integrate the construction schedule with the visual representation, e.g. 3D building elements or visual flow occupations.

To evaluate the effectiveness of both models in representing the characteristics of the trade flow, three flaws were intentionally placed within both of the trade flow plan models. The main purpose was to test if the participants could identify these errors with

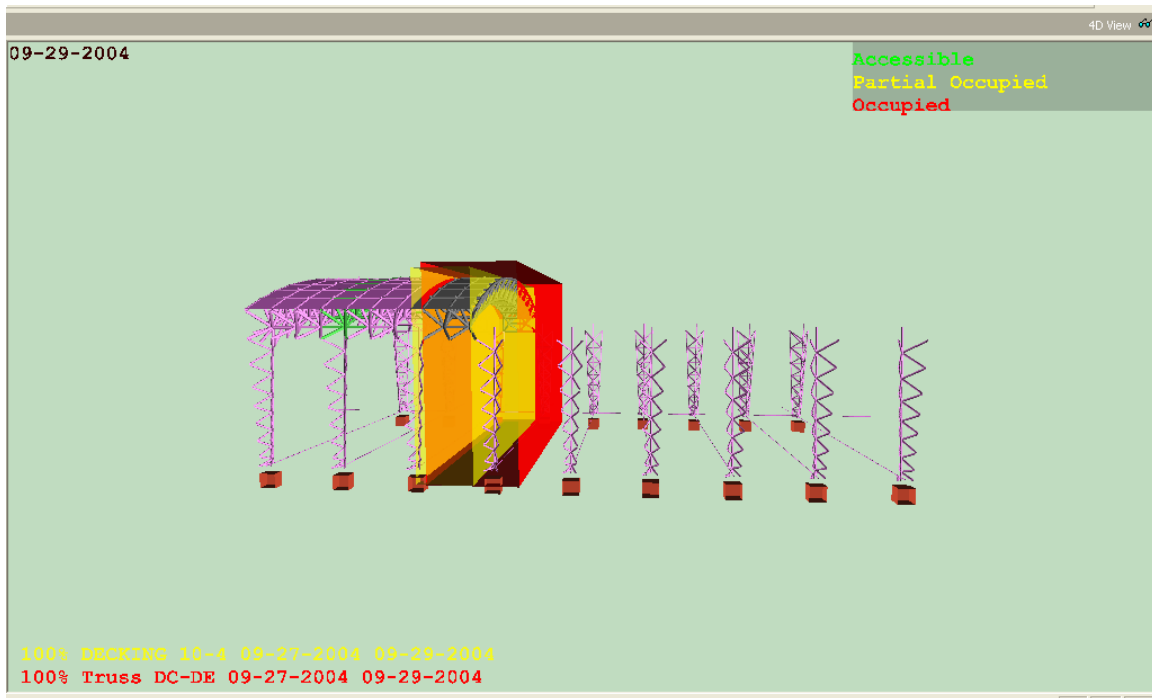
the models presented to them. To compare the flow plan models with the current trade flow planning method at the construction site, these flaws were put into the CPM schedule of the project as well. Based on the characteristics of good flows, the flaws were designed to include a flow occupation conflict, an inappropriate flow direction and disrupted flow.

The flow occupation conflict between the truss trade and the decking trade is shown in Figure 7.2. In this example, the trade spatial needs included space required by the crew and the equipment. For truss installation, a mobile crane was used for erection of the trusses. The conflict arises when both trades require the space below the building elements. In Figure 7.2 (a), the overlap of the “red” deck and “red” truss indicates the flow occupation conflicts; while in Figure 7.2 (b), the overlap of the trade occupation shows the possible trade flow conflict. The visual representation of Figure 7.2 (b) indicates that the conflict is a medium conflict between the ‘occupied’ status of the truss trade and the ‘partial occupied’ status of the metal decking trade. Based on the flow conflicts taxonomy, this conflict could be resolved through an adjustment to the schedule of activities.

An inappropriate flow direction was embedded in the schedule between the fire protection trade and other trades primary trades for the Space Hangar work. The fire protection trade travels in a direction that is opposite the direction of the other trades, e.g., truss trade and decking trade. To better view the fire protection trade, a clipping view is used in Component 4D to clearly show the flow direction (see Figure 7.3).



(a)



(b)

Figure 7.2: Flow conflict between the decking trade and the truss trade
(a) Component 4D model, and (b) Visual Trade Flow 4D model

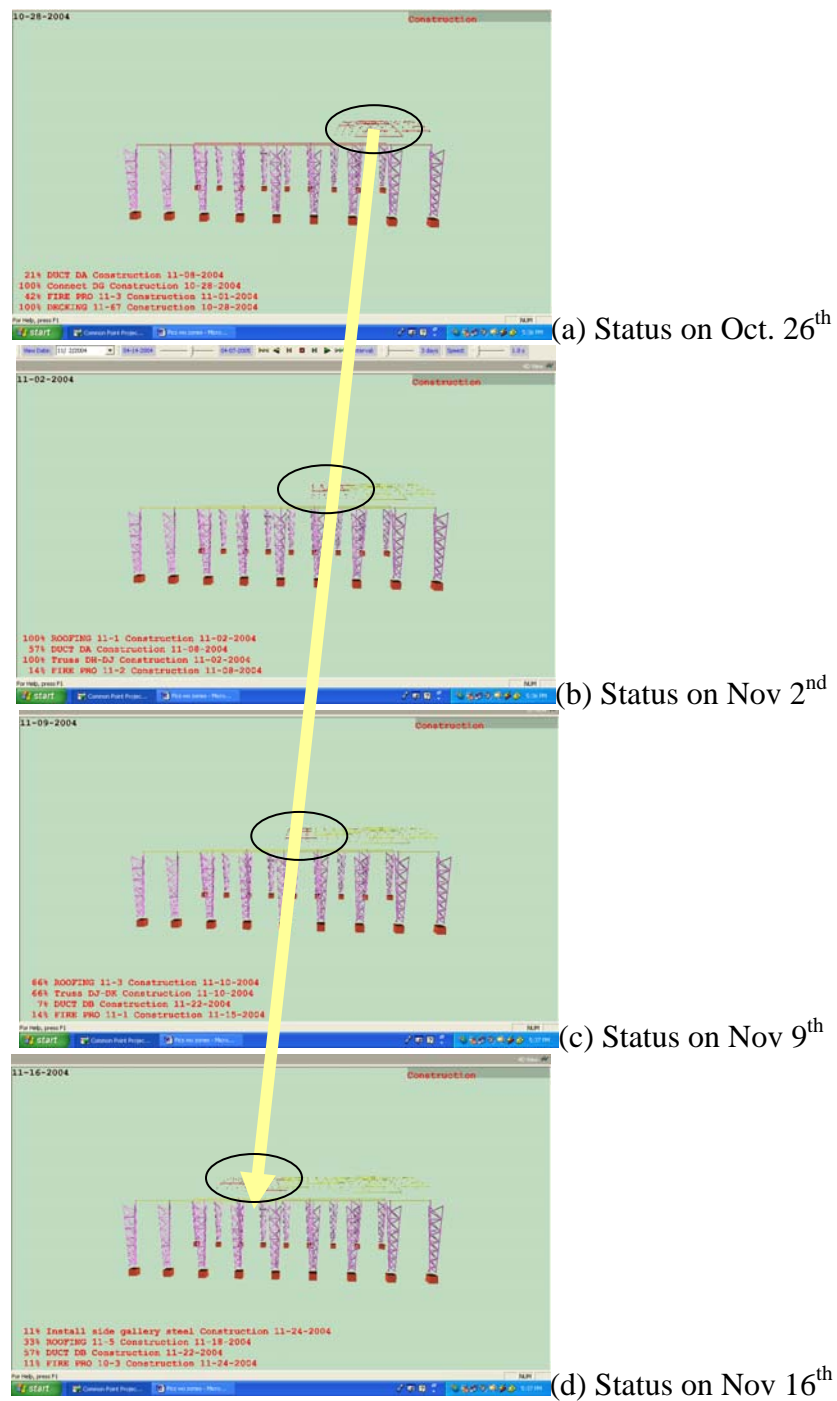
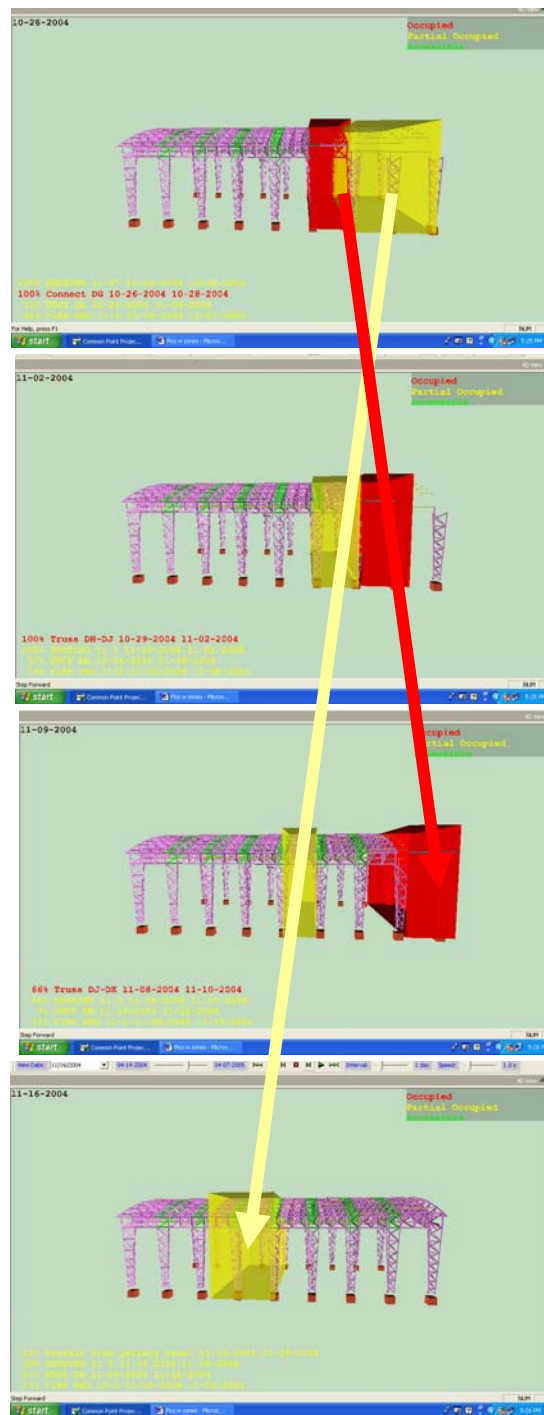


Figure 7.3: Component 4D model– Inappropriate flow direction: Fire protection (yellow arrow) runs at the opposite direction with truss trade (not show in the clipping view)

The flow can also be illustrated in the Visual Trade Flow 4D model as shown in Figure 7.4. This model more clearly illustrates the flow by graphically displaying the entire space required by the trade, instead of just the components install by the trade.



(a) Status on Oct. 26th

(b) Status on Nov 2nd

(c) Status on Nov 9th

(d) Status on Nov 16th

Figure 7.4: Visual Trade Flow 4D model – Inappropriate flow direction: Fire protection trade (yellow arrow) travels in the opposite direction of truss trade (red arrow)

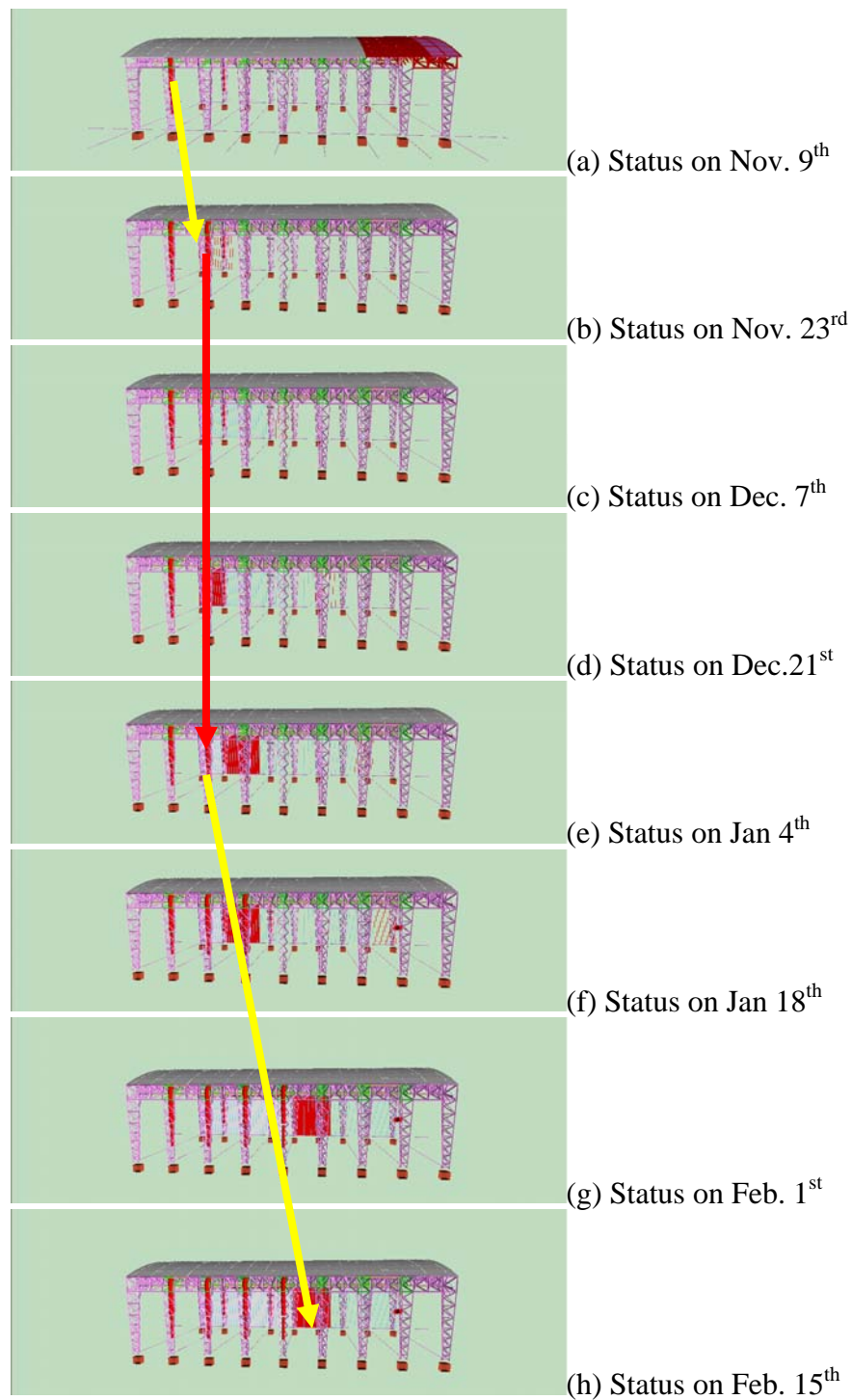


Figure 7.5: Component 4D model: Disrupted flow (yellow arrow indicates the normal flow and red arrow indicates the unexpected pause from Nov. 23rd to Jan. 4th).

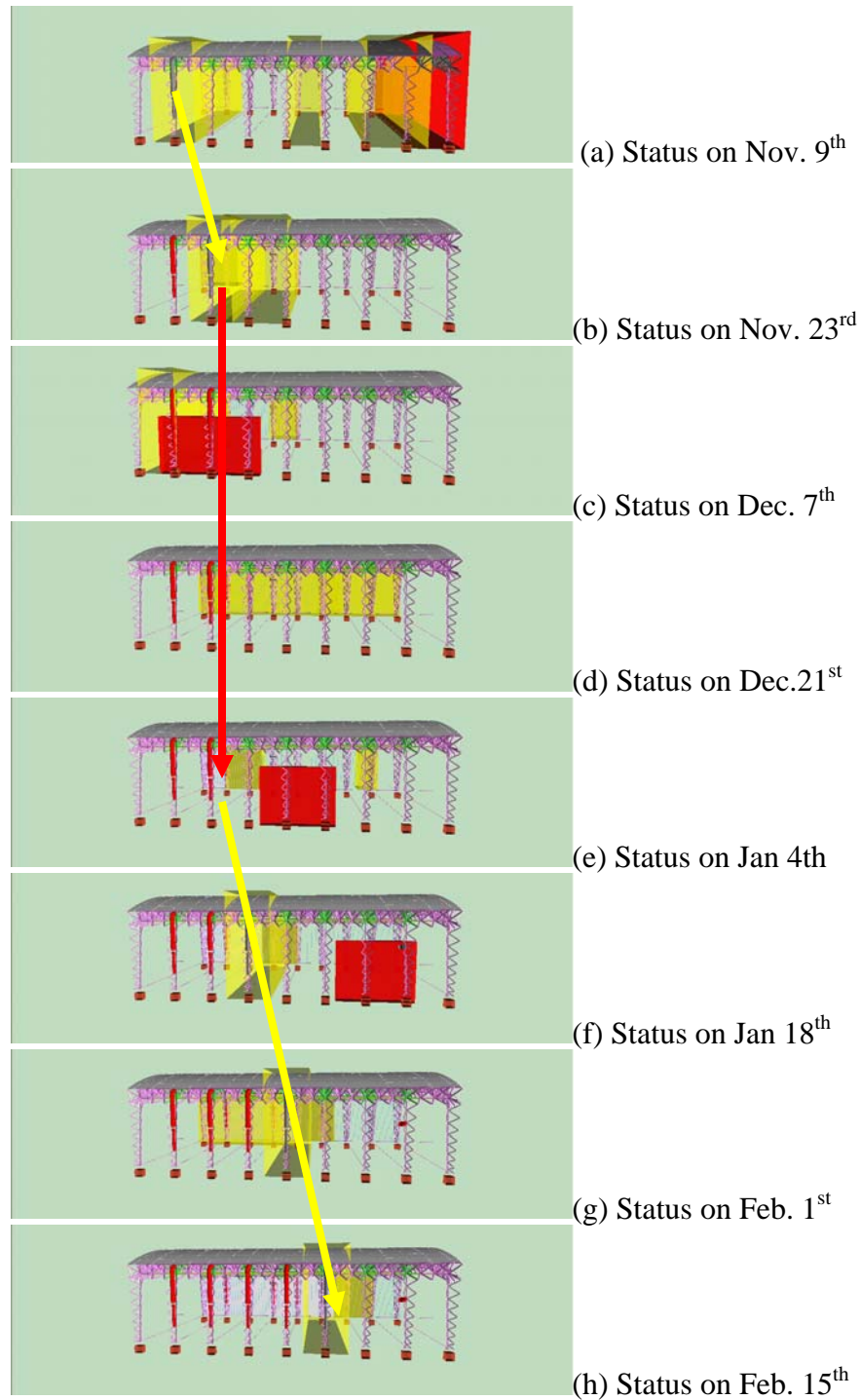


Figure 7.6: Visual Trade Flow 4D model: Disrupted flow (yellow arrow indicates the normal flow and red arrow indicates the unexpected pause from Nov. 23rd to Jan 4th).

The third embedded conflict or inefficiency is an example of disruption in flow. The ductwork flow was planning to be suspended for 6 weeks. In both Figure 7.5 and Figure

7.6 this disruption is illustrated. These figures indicate consistent flow with a yellow arrow and a pause in work with a red arrow.

7.3 Experiment I: Graduate Production Management Course

This experiment was performed in the AE597A class of 19 students at The Pennsylvania State University. The primary objective was to evaluate the methodology in a class environment and gain feedback from the construction management students. This experiment was designed to identify the comparative advantages of the methodology in representing the flow occupation conflicts, flow direction, and flow continuity. After the experiment, a questionnaire was distributed out to gather feedbacks from the participants. The class experiment was approved by Office for Research Protections at The Pennsylvania State University. The Informed Consent Form with the approval stamp of IRB # 18806 for this application is contained in Appendix A.

7.3.1 Experiment procedures

This experiment included two steps. First, all the participants were asked to review 2D drawings and the CPM schedule of the case study to identify the improper construction trade flow. Second, the participants were divided into two groups. Each of them was provided with one trade flow plan model and was instructed to identify the preset flaws from one of the two different models (Component 4D of Trade Flow 4D). All students were provided with a general orientation to the Commonpoint 4D software application so that they were familiar with the navigation and display characteristics of the application. Group A was provided with the trade flow plan model and provided instruction related to the characteristics of the trade flow space model and the flow occupation patterns used in the trade flow plan model. Group B was provided with the Component 4D model. At the end of the experiment, the participants of both groups were instructed to finish an identical questionnaire survey.

7.3.2 Results

Based on the survey and the feedback, the effectiveness of the Visual Trade Flow Planning methodology was compared with the 2D drawings plus CPM schedule. Then, the trade flow model was evaluated based on three major tasks: 1) identifying construction space conflicts, 2) visualizing the direction of trade flow, and 3) evaluating flow continuity for a trade. A value on a 1 to 5 scale was used in the first several questions on the survey to assess the effectiveness of the 2D drawings and the 4D. Feedback and comments were also gathered through open-end questions. The survey form is included in Appendix C. The results are summarized in Figure 7.7.

Effectiveness of 4D VS 2D: In the evaluation of construction trade flow model, Group A (with the Trade Flow 4D plan model) rated 2D drawings with CPM schedules as a 2.8 and 4D CAD with 4.7, in which, 1 refers to not effective and 5 refers to very effective. Group B indicated a similar opinion by rating 2D with 2.7 and 4D with 4.7.

Effectiveness in evaluating flow characteristics: In three major tasks (identifying construction conflicts, visualizing the direction of trade flow and evaluating flow continuity) Group A's rating using the Visual Production 4D CAD model was almost equally to that of Group B's using the Component 4D model.

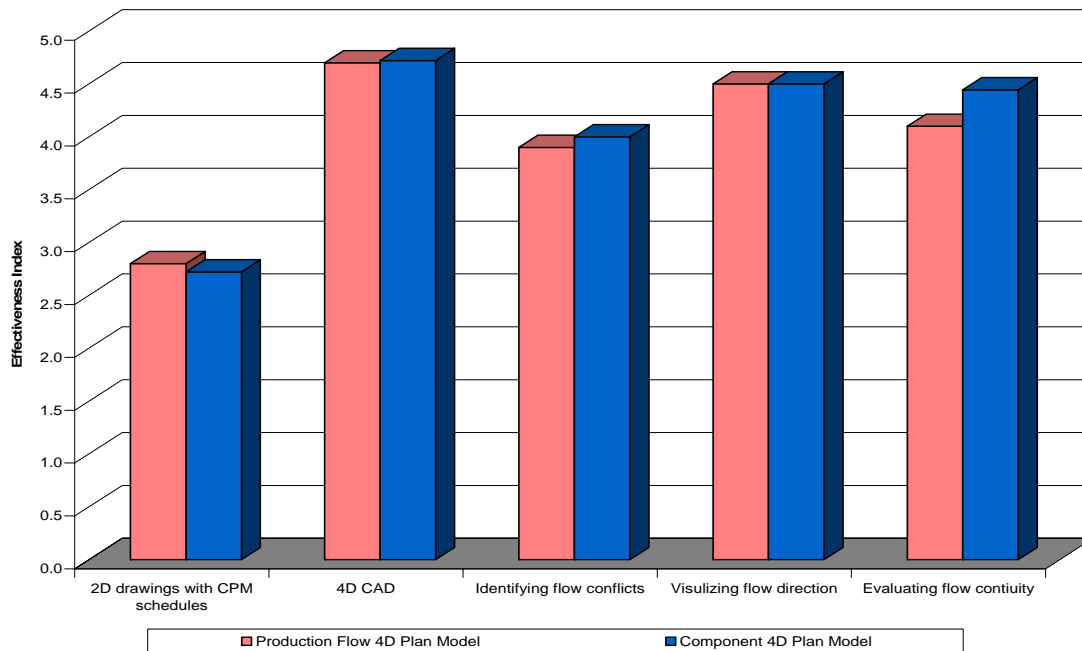


Figure 7.7: Survey results of Experiment I

7.3.3 Discussion

The results illustrated the positive attitude of the participants towards the use of 4D CAD models in general for representing trade flow. Similar feedback was also noted in the answers to the open ended questions. Some of the reactions of the participants were as follows:

- “You can tell who is going to be doing work in a certain space at any given time”
(Group B participant)
- “(The Trade Flow 4D plan model) visualizes multiple trades in one sequence.”
(Group B participant)

When analyzing the comparative advantage of the two 4D models, the difference in rating between participants using the Trade Flow 4D or Component 4D models was not significant. Furthermore, among the flaws identified by both groups, most of the conflicts were flow occupation conflicts. The number of flaws identified related to the flow direction or continuity was very limited. This was an unexpected and interesting result. Based on the perceptions of the students, they stated that both 4D CAD models

were effective in evaluating trade flow with an average rating around 4. But, very limited flow direction or flow continuity flaws were actually identified with the use of either the Trade Flow 4D or the Component 4D models. One possible explanation is that the participants only had a limited amount of time during the regular course period to complete several tasks within a total duration of 75 minutes. This included evaluating the trade flow with 2D drawings plus CPM schedule, learning how to navigate in a 4D CAD application, and evaluating trade flow with the 4D CAD models. They simply did not have adequate time to perform a detailed analysis of the flow flaws that require more information, e.g., direction issues or continuity issues. The classroom environment also limited the opportunities for communication and interaction between the participants and the experiment organizer related to these characteristics of the trade flow plan. Therefore, it decided to evaluate the trade flow planning methodology in a more controlled environment.

7.4 Experiment II: Architectural Engineering Graduate Students

To further investigate specific characteristics of the results of the first experiment, a second experiment was performed which provided more time for performing the evaluation of the space plan for the NASM Project. The objective of this experiment was to further evaluate the value of the different 4D models for representing trade flow (Component 4D vs. Trade Flow 4D). Four graduate students from the Architectural Engineering Department participated in this experiment. No time limitation was set for their model evaluation which was different from Experiment I which limited the students to the time in the class. Furthermore, the participants were specifically focused on the identification of trade flow issues with the use of 4D CAD technologies. There was no comparison between 4D CAD and 2D CAD and CPM scheduling included in this experiment.

7.4.1 Experiment Steps

This experiment started with approximately 30 minutes of instruction on the use of the 4D CAD application. To better understand the software package, each participant loaded, viewed and operated a sample 4D model (not the NASM Model). Next, one of the

experiment organizers introduced the case project background and all the trades and building elements involved in this case study to provide a general familiarity of the different building components to the participants. The participants were then randomly divided into Group A and Group B. Group A was provided with the Trade Flow 4D Model and they were provided with a further description of the flow space model and the flow occupation patterns. Group B was provided with the Component 4D Model. Each participant in the study was asked to review the model provided to them and then identify the different flow items identified throughout their evaluation of the model. They documented each flow issue by writing the conflicts on a form (see Appendix D). After each member was complete, the two participants in Group B were instructed to review the Trade Flow 4D Model to see if they could identify items that they had not identified in the Component 4D Model.

7.4.2 Results

This experiment lasted around 3 hours including the time to learn the Common Point Project 4DTM application. Each participant identified an average of five flow occupation conflicts, 1.5 inappropriate flow direction, and 1.5 interrupted flows.

With a more controlled environment, the results indicated the effectiveness of the Trade Flow plan models in evaluating flow characteristics. The results were discussed in the following three groups, flow occupation conflicts, flow direction and flow continuity. The results from Group B are very interesting. After identifying 10 flow conflicts with Component 4D Model over one hour and twenty minutes, one participant in Group B identified 5 additional flow conflicts with the Trade Flow 4D Model within 15 minutes. The second Group B participant identified one additional conflict when provided with the Trade Flow 4D Model. The additional effect of using the Trade Flow 4D Model for the participants is demonstrated in Figure 7.8.

Flow Occupation Conflicts: All the participants identified the preset flow occupation conflicts. More over, several potential flow occupation conflicts in the original schedule were identified. As shown in Figure 7.9, a severe flow congestion

occurred among the sheet metal trade, framing trade, fire protection trade and decking trade. Even though there is no direct conflict, this could require additional coordination due to the trade congestion in the area.

Flow direction: All participants indicated the preset flow direction conflict between the flow directions of the fire protection trade related to the other trades. In addition, the direction of the glazing trade was identified by one participant with Trade Flow 4D.

Flow Continuity: All participants identified the preset flow continuity issue related to a six week delay of the ductwork installation. In addition to this issue, the interrupted flow of the window trade and framing trade in the original schedule were identified by one participant using the Trade Flow 4D Model.

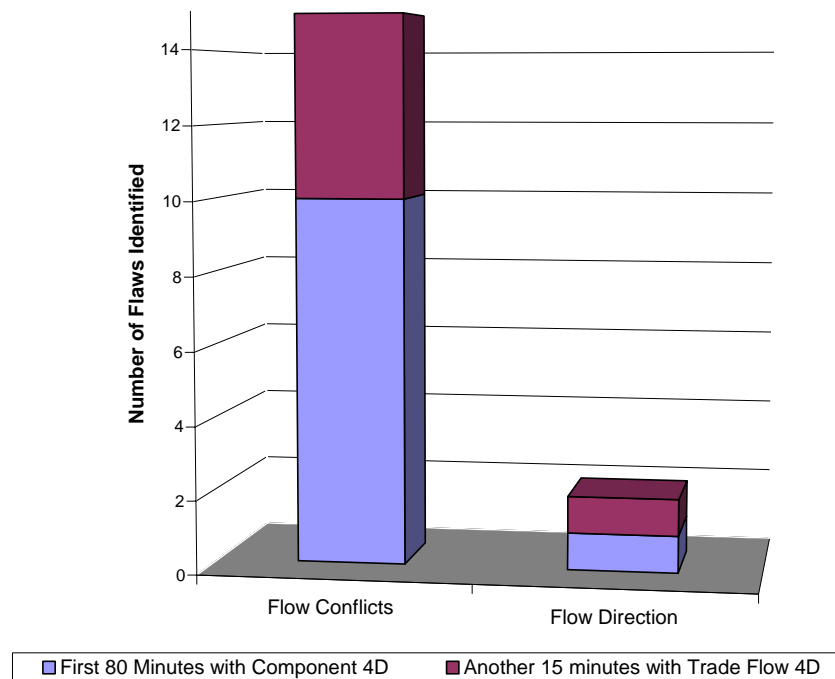
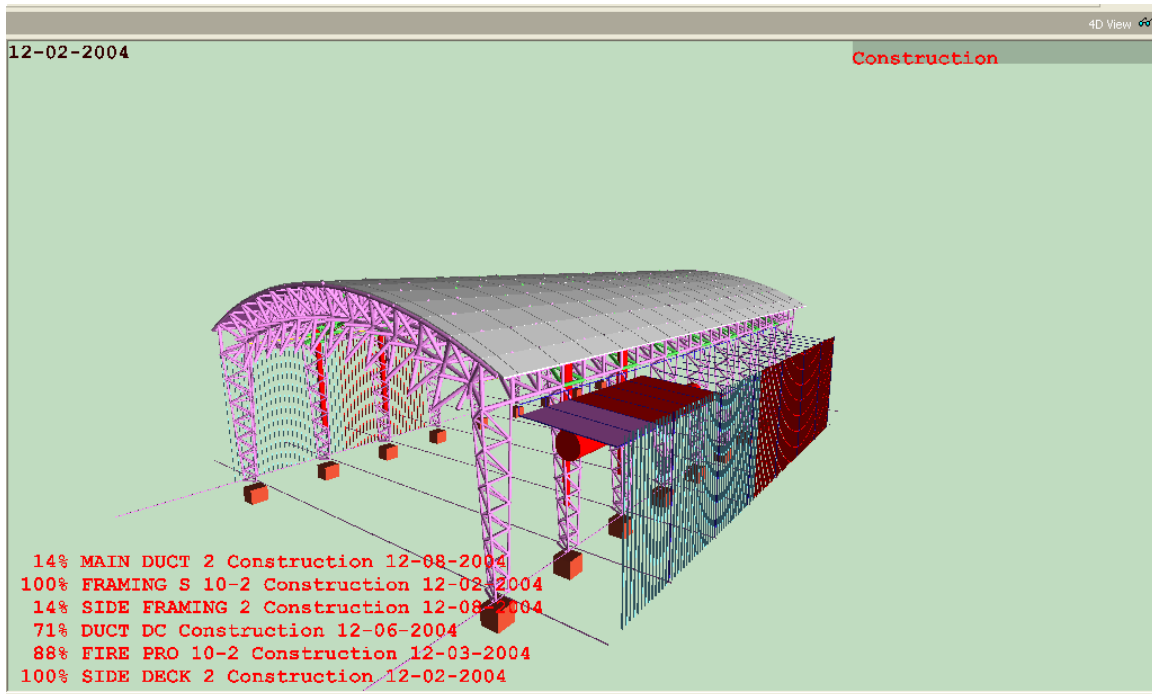
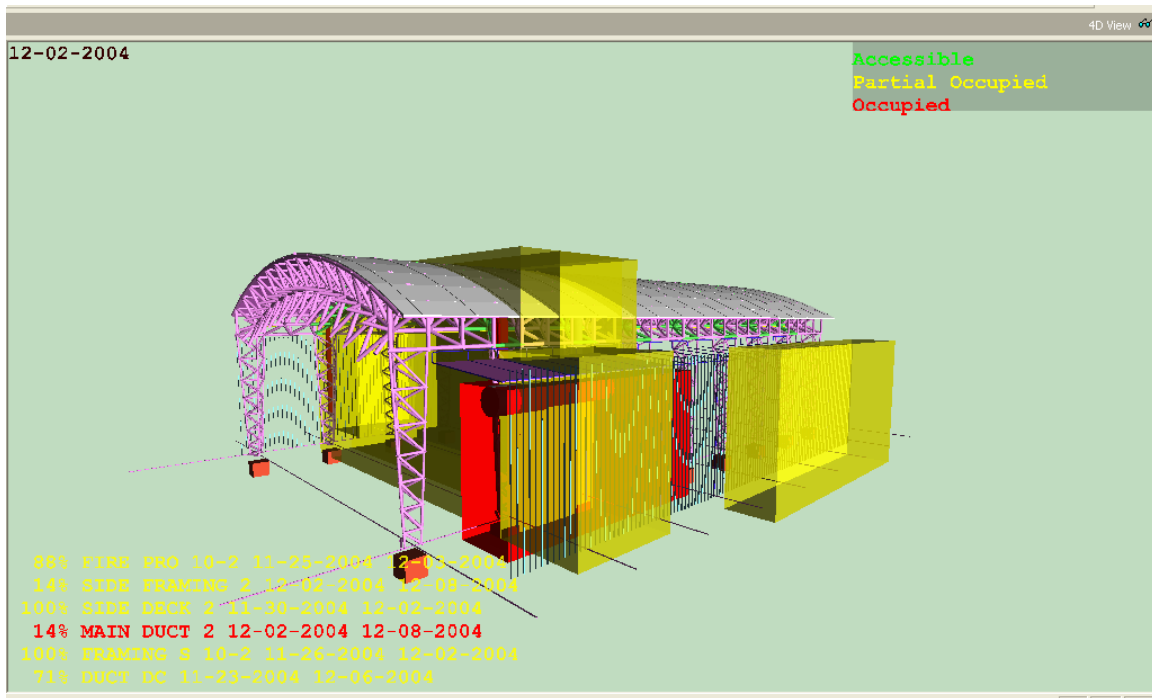


Figure 7.8: Additional effect of Trade Flow 4D Model



(a) Component 4D Model



(b) Trade Flow 4D Model

Figure 7.9: Multiple trade occupation conflicts in original schedule

The experimental results provide valuable insights into the effectiveness of the Visual Trade Flow Planning methodology. The results illustrated that the Trade Flow 4D Model, developed through the use of the methodology, provided additional value when performing trade flow analysis since it aided the participants in the identification of flow conflicts which could not identify with 2D drawings plus CPM schedules or with the traditional Component 4D Model. The additional effect of Trade Flow 4D is also very significant and it helped the participant to identify flow conflicts and flow direction issue which they did not identify with a Component 4D Model.

The Trade Flow 4D Model also aided in the identification of potential congested areas. As shown in Figure 7.9, there was no physical conflict between building elements; however, the visual Trade Flow 4D Model aids in the identification of a potential flow occupation problem due to the large number of trades in close proximity during the construction process.

Another advantage of this methodology was to represent the small building elements with large flow occupations. For example, it is difficult to see the sprinkler pipes in the Component 4D Model due to their relatively small size in 3D model. However, with the Trade Flow 4D Model was an explicit visual representation of the space needed for installing the pipes, these space occupation requirements become much more obvious. For larger components, it appears that people can better visualize the space requirements with the use of the additional visual occupation information.

CHAPTER 8

CONCLUSIONS

This chapter provides a summary of the research results from the study. The contributions and limitations of the research are presented along with a discussion of the future research areas in the Visual Trade Flow Planning methodology.

8.1 Research Summaries

This research introduced and evaluated a Visual Trade Flow Planning (VTFP) methodology to assist in the proper planning of trade flow on construction projects. The structure of the methodology was described, including the visual Trade Flow Space model, the flow occupation patterns and the Trade Flow Planning Process Model.

The visual trade flow model defined the spatial needs for a trade and the 3D visual space representation patterns for construction trade occupation. The identification of zones was elaborated with five typical space position patterns for each zone: Over, Beneath, Beside, Outside, or Around.

The trade flow occupation patterns define the trade flow occupation level by considering the trade's ability to share a space and the corresponding effect of sharing the space with another trade. The three flow occupation levels defined in the model are Occupied, Partially Occupied, and Accessible. To define the flow occupation conflicts, the taxonomy of flow conflict types was developed to describe conflict types along with potential conflict solutions for the various conflict types.

The Visual Trade Flow Planning Process Model introduced a process to visually coordinate and sequence trade flow on a construction project. The visual trade flow plan defines (1) the sequence of trades, (2) the spatial needs of each trade over time, and (3) the occupation level of each trade over time.

Two case studies were performed to test the methodology. The first case study tested the methodology on the School of Architecture and Landscape Architecture Building project. In this case study, the Trade Flow Space Model was examined through modeling 29 construction activities performed by 12 different trades. It included five space position patterns and their combination was capable of addressing all the work zone positions for the construction activities. The flow occupation patterns were evaluated during the modeling process of this case study. Based on the process model, the visual trade flow plan was developed and evaluated. Several trade flow conflicts were identified with the visual trade flow plan. The resolution suggested by the occupation patterns and the taxonomy of the occupation conflicts matched the site engineer's feedback.

Additional evaluation was performed on the National Air and Space Museum Project focused on the evaluation of the effectiveness of the methodology in representing trade flow characteristics: flow occupation, flow direction and flow continuity. The initial experiment on this project illustrated that participants perceived positive value from the Trade Flow 4D Model and the Component 4D Model for representing the flow characteristics. A second experiment on this case study was performed to gain additional insights. This experiment illustrated that participants could clearly identify more flow conflicts if provided with both the Trade Flow 4D Model and the Component 4D Model.

8.2 Research Contributions

The contributions of the study are:

- *Clear definition of trade flow evaluation guidelines:*

Based on the literature review, limited research had focused on outlining the

primary attributes of evaluating a trade flow in the construction industry. In this research, three attributes of trade flow were summarized, including flow direction, flow continuity and avoiding flow occupation conflicts. These three attributes were also embedded into the Visual Trade Flow Planning Methodology.

- *Method to visually represent trade flow based on the flow evaluation guidelines;*

The Trade Flow Model and the Flow Occupation Patterns were developed in this research. These two models not only visually represented the three attributes in graphical construction space modeling, e.g. defined working zones, space position patterns and the occupation factor, but also included a visual construction conflict taxonomy. With this construction conflict taxonomy, a solution guideline was provided for different level construction conflicts.

- *Detailed implementation examples to assist in industry implementation.*

The detailed visual trade flow planning procedures were introduced with the illustrative case study of SALA building. A step-by-step breakdown was provided to demonstrate the process of visual trade flow planning.

8.3 Research Limitation

Several limitations of this research are as follows:

- **The interaction between user and the visual space plan:** The Visual Trade Flow Plan is generated and navigated in a 4D CAD application. During the trade flow plan review process, it is desirable to modify the work zone size and locations based on the reviewer's feedback. However, the 4D CAD application used in these case studies does not currently have the function to modify the geometry data within the 4D CAD model. The user must modify the geometry data in a 3D CAD application. After the work zones are modified, they need to be transferred into the visual trade flow plan. In this case, the inefficient of work

zone modifications makes it difficult to modify during meetings or discussions.

- **Limited case study application:** Two case studies were performed to validate the visual trade flow planning methodology. The major construction activities modeled in both case studies were structural related work. It is desirable to perform more case studied to model the construction activities at the building enclosure and finishing stages.

8.4 Future Research

The suggestions for future research are discussed in the following sections.

8.4.1 Comprehensive flow modelling

The trade flow concept in construction includes three types of flow: location flow, material flow and assembly flow. In the literature review chapter, a car production and a site production example were used to explain these three different types of flow. The Visual Trade Flow Planning Methodology provided a graphical representation of the location flow and partially covered the assembly flow, focusing on the trade movement. Future research could focus on providing a visual representation methodology to integrate material flow into the modeling.

8.4.2 Interactive work zones generator

Future research could focus on an automated tool to facilitate the interactive work zone generation. As discussed in the limitation section, the modification and updating of the work zones is still a detailed and time-consuming process. First, the user must change the geometry in a 3D CAD application. Then, these modified work zones need to be integrated with the 3D model. Finally, trades and the modified work zones should be linked in the 4D CAD application. It is desirable to have a tool to accomplish the work zone geometry creation and revisions within one software application.

8.5 Concluding Remarks

The trade flow concept in construction introduces an innovative method for viewing construction activity modeling. The visual trade flow planning methodology provides a means to graphically represent trade flow in construction. With the advances in information technology and construction modeling concepts, a more interactive trade flow planning methodology can help general contractors, construction managers and subcontractors to accomplish projects more safely, on time, with less costs, and better quality.

BIBLIOGRAPHY

- Akinci, B., and Fischer, M. (2000). "4D WorkPlanner - A prototype system for automated generation of construction spaces and analysis of time-space conflicts." *Eighth International Conference on Computing in Civil and Building Engineering (ICCCBE-VIII)*, Stanford University, CA, 740-747.
- 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.
- Ballard, G. (2000). "The last planner system of production control," Ph.D. Thesis, The University of Birmingham, Birmingham, UK.
- Dawood, N., and Mallasi, Z. (2002). "Registering space requirements of construction operations using Site-PECASO model." *Distributing Knowledge In Building, CIB W78 International Conference.*, The Aarhus School of Architecture, Denmark.
- Dawood, N., Sriprasert, E., Mallasi, Z., and Hobbs, B. (2002). "Development of an Integrated Information Resource Base for 4D/VR Construction Process Simulation & Visualization." *Distributing Knowledge In Building, CIB W78 International Conference.*, The Aarhus School of Architecture, Denmark.
- Fischer, M., Haymaker, J., and Liston, K. (2003). "Benefits of 3D and 4D models for facility managers and AEC service providers." 4D CAD and visualization in construction: developments and applications, R. R. A. Issa, I. Flood, and W. J. O'Brien, eds., A.A. Balkema Publishers, Lisse, 1-32.
- Fischer, M., and Kunz, J. (2003). "Impact of information technology on facility engineering." *Leadership and Management in Engineering*, 3(2), 100-103.
- Guo, S. J. (2002). "Identification and resolution of work space conflicts in building construction." *Journal of Construction Engineering and Management, ASCE*, 128(4), 287-295.
- Koo, B., and Fischer, M. (2000). "Feasibility study of 4D CAD in commercial construction." *Journal of Construction Engineering and Management, ASCE*, 126(4), 251-260.
- Koskela, L. (1992). "Application of the new production philosophy to construction." 72, CIFE, Stanford University.
- McKinney, K., and Fischer, M. (1997). "4D analysis of temporary support." *Fourth Congress in Computing. in Civil Engineering. 1997. Philadelphia, PA*, 470-476.
- Messner, J. I., Yerrapathruni, S. C., Baratta, A. J., and Riley, D. R. (2002). "Cost and schedule reduction of nuclear power plant construction using 4D CAD and immersive display technologies." *Computing in Civil Engineering: Proceedings of the International Workshop of Information Technology in Civil Engineering*, 136-144.
- Penn State: College of Arts and Architecture. (2004). "Giving to Penn State: Stuckeman Family Building (SALA)." [Http://www.development.psu.edu/Buildings/SALA.aspx](http://www.development.psu.edu/Buildings/SALA.aspx) Accessed: July 9, 2004,

- Riley, D., and Sanvido, V. E. (1997). "Space planning for mechanical, electrical, plumbing and fire protection trades in multi-story building construction." *Construction congress V*, Minneapolis, MN, USA, 102-109.
- Riley, D. R. (2000). "The role of 4D modeling in trade sequencing and production planning." *Proc. of Construction Congress VI*, 1029-1034.
- Riley, D. R., and Tommelein, I. D. (1996). "Space planning tools for multistory construction." *3rd Congress on Computing in Civil Engineering*, 718-724.
- Riley, D. S., Victor E. (1997). "Space planning method for multistory building construction." *Journal of Construction Engineering and Management, ASCE*, 123(2), 171-180.
- Sanvido, V. E., Khayyal, S. A., Guvenis, M. M., Norton, K. J., Hetrick, M. S., Muallem, M. A., Chung, E. K., Medeiros, D. J., Kumara, S. R. T., and Ham, I. (1990). "An integrated building process model." *Technical Report No. 1*, Computer Integrated Construction Research Program, University Park, PA.
- Sanvido, V. E., Kuntz, K. A., Lynch, T. D., Messner, J. I., and Riley, D. R. (1994). "Information modeling and applications." *First Congress on Computing in Civil Engineering*, Washington, D.C., 786-789.
- Songer, A. D., Diekmann, J. E., and Karet, D. (2001a). "Animation-based construction schedule review." *Construction Innovation*, 2001(1), 181-190.
- Songer, A. D., Diekmann, J. E., Rasheed, K.-A., and Hays, B. (2001b). "Construction schedule using 3-D CAD and walk-thru." *Construction Innovation*, 2001(1), 191-207.
- Tan, B., Horman, M. J., Messner, J. I., and Riley, D. R. (2003). "Increasing the understanding of lean principles with advanced visualization technologies." *International Group of Lean Construction, 11th Annual Conference*, Blacksburg, VA.
- Thabet, W. Y. (1992). "A space constrained resource constrained schedule system for multi-story buildings," Ph.D Thesis, Virginia Polytech. Insti. & State University, Blacksburg, VA.
- Tommelein, I. D., Riley, D., and Howell, G. (1999). "Parade game: impact of work flow variability on succeeding trade performance." *The 7th international group for lean construction conference*, Berkeley, CA.
- Yerrapathruni, S. (2003). "Using 4D CAD and immersive virtual environments to improve construction planning," M.S. Thesis, The Pennsylvania State University, University Park, PA.

<p>ORP USE ONLY: The Pennsylvania State University Office for Research Protections</p> <p>Approval Date: 06/10/04 M. Becker</p> <p>Expiration Date: 06/09/05 M. Becker</p>

APPENDIX A

Human Subject Consent Form

INFORMED CONSENT FORM FOR SOCIAL SCIENCE RESEARCH

The Pennsylvania State University

Title of Project: Trade-Oriented Construction Virtual Space Planning

Principal Investigator: Bo Tan

Other Investigator(s): John Messner

1. Purpose of the Study: This experiment is one part of ongoing Pennsylvania State University research on Visual Construction Space Planning. The objective of this research aims at developing a methodology of planning construction space visually at the trade level. The intent of this questionnaire is to gain a better understanding of the participant's view of trade sequencing and space planning.
2. Procedures to be followed: Participation in this research will involve completing a questionnaire after an actual class. The class is a part of the AE 597A requirement. The questionnaire is for the research.
3. Discomforts and Risks: None. Completing the questionnaire will not affect your grade in AE 597A.
4. Benefits:
 - a. The benefits to participants include gaining some experience of up-to-date information technology and learning how to integrate those technologies with construction industry.
 - b. The benefits to society include helping researcher to develop a methodology of planning construction space visually at the trade level.
5. Duration/Time: The questionnaire will require approximately 5 minutes of your time
6. Statement of Confidentiality: The questionnaire is anonymous. The participants' personal information will not be collected during the experiment.
7. Right to Ask Questions: Participants have the right to ask questions and have those questions answered. If you have any questions on any aspect of the study, please contact me or Dr. Messer at the address below. For any additional information concerning your rights as a research participant, please contact the Office of Research Protection, 212 Kern Graduate Building, University Park, PA, 16802; or by telephone at (814) 865-1775.
8. Compensation: No compensation will be provided to participants in this research.
9. Voluntary Participation: Participation is voluntary. You can withdraw from the study at any time by not completing the survey. You can decline to answer specific questions.

You must be 18 years of age or older to consent to participate in this research study. If you consent to participate in this research study and to the terms above, please complete the questionnaire and return to the investigator. Please keep this form for your records and future reference.

Bo Tan
M.Sc.Student, Architectural Engineering
Department,
The Pennsylvania State University
104 Engineering Unit A, University Park,
PA 16802, USA
814-863-6786 (office) 814-863-4789(fax)
btan@psu.edu

Dr. John Messner,
104 Engineering Unit A, The Pennsylvania
State University,
University Park, PA 16802;
(814) 865-4578 (office) 814-863-4789(fax)
jmessner@enr.psu.edu

APPENDIX B

IDEF₀ Process Modeling Methodology

The Visual Trade Flow Planning Methodology was presented using the IDEF₀ modeling methodology. This appendix describes the IDEF₀ methodology. This description was adapted from Sanvido et al. (1990). In this section, the ICAM Definition (IDEF) Method is described. The structure and schematic representation of the IDEF₀ methodology is discussed, and the diagramming methodology is explained. For a detailed description, the reader is referred to publications by the Integrated Computer Aided Manufacturing organization (Integrated 1981).

The Integrated Computer Aided Manufacturing (ICAM) Definition Method (IDEF) is a set of structured analysis techniques for performing system analysis. Its main purpose is to provide engineering methods for analyzing and designing complex systems, and is used to understand and manage such systems (Wallace et al. 1987). IDEF supports multiple views of the system, and allows the system to be modeled from three different perspectives:

B.1 Schematic Presentation

Each box in the diagram represents a function that is an activity, action, process, operation, or a transformation (Integrated 1981). One or more inputs are transformed into one or more outputs using the mechanisms provided. The transformation process is controlled by one or more controls. Data is defined as any information or physical object that is transformed, constrains the function, or results from the function. The data entities are represented schematically in Figure B.1.

Five entity types are used in the IDEF₀ modeling methodology: function, input, output, control, and mechanism. Each is briefly described below (Integrated 1981):

- **Function:** An activity, action, process, operation, or transformation that is described by an active verb and an object is a function. The box in Figure E.1 shows the function.
- **Input:** An input is an entity that undergoes a process or operation, and is typically transformed. It enters the left of the box, and may be any information or material resource.
- **Output:** Shown exiting the right side of the box, outputs include entities, such as data, which result from a process or objects that are created by a function.
- **Control:** Control elements are entities that influence or determine the process of converting inputs to outputs. Controls may limit the activity or allow the activity to occur but will not be affected by the activity itself. On the diagram, controls are shown entering the topside of the box.

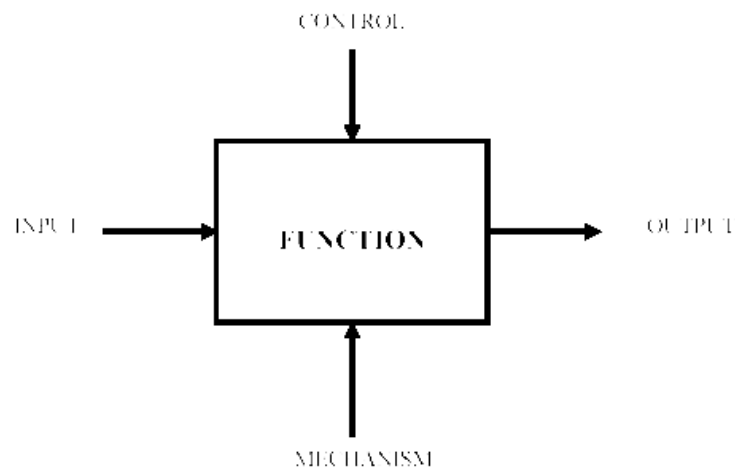


Figure B.1: Schematic Presentation of the Function Box

- **Mechanism:** Shown on the bottom side of the box, mechanisms are entities, such as a person or a machine, which perform a process or an operation. It describes how a process is accomplished.

An example is shown in Figure B.2, which demonstrates the use of each data entity type.

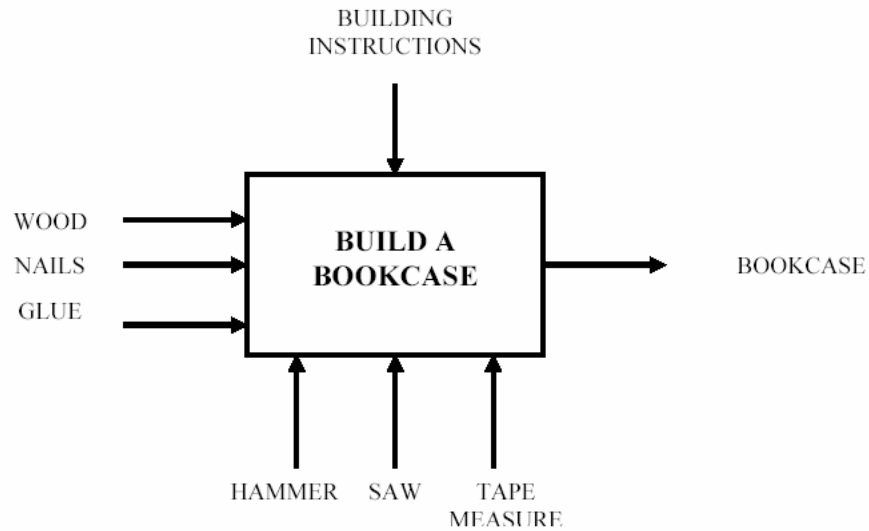


Figure B.2: Example of a Function Box Center

B.2 STRUCTURE OF IDEF₀

IDEF₀ represents a system by means of a model composed of diagrams, text, and glossary. The model is a series of diagrams with supportive documentation that divide a complex subject into its component parts (Integrated 1981). The diagrams consist of boxes and arrows that express the functional activities, data, and function/data interfaces. Text accompanies each diagram that narrated the activities in the diagram. In the glossary, all terms used in the diagrams are defined.

B.2.1 Hierarchy of IDEF₀ Diagrams

IDEF₀ starts by representing the whole system as a single box with arrow interfaces to the environment external to the system. This box is decomposed into between three to six functions, each of which may be further decomposed into sub processes. This top-down decomposition process may be continued, generating between three to six “child” or detail diagrams for each function on any given level. A hierarchy of diagrams results, as shown in Figure B.3.

B.2.2 Gradual Exposition of Detail

The number of functions in each diagram is limited to a minimum of three and a maximum of six. This limits the level of detail and complexity in any diagram while preventing the diagram from being trivial. The level of detail is also controlled by the position of the diagram in the hierarchy of diagrams. Each level of decomposition increases the amount of detail, resulting in a gradual exposition of detail. Decomposition along any given node is discontinued when the level of detail is sufficient for the application of the model.

B.2.3 Modularity of IDEF₀ Diagrams

When a box is decomposed, the scope of the function and its interface arrows create a bounded context for the sub-functions. The scope of the detail diagram fits completely inside its parent function, and the interface arrows of the parent box match the external arrows of the detail diagram. Therefore, all arrows that enter or exit the detail diagram must be the same arrows that interact with the parent diagram.

B.2.4 Numbering the IDEF₀ Diagrams

The highest level in the model which is the single the box representation of the system is labeled A-0. The next level of decomposition shows the major functions of the system and is called the A0 level. Each box in this level is labeled from A1 through A6. Further decomposition leads to additional digits placed after a decimal point, so that the diagram resulting from decomposing the first function on four successive levels represented by A1.111. This numbering system allows the user to retrace the steps of decomposition through the parent function of each diagram. The models developed in this report place the decimal after the letter, e.g., D.1.

B.3 Tunneled Arrows

To maintain integrity of the model, the diagrams must remain consistent from one level to the next. All data entities that interface with a function box must appear on its detail diagram as arrows entering or leaving the boundaries of the detail diagram. Exceptions may be made,

however, with arrows that are tunneled. Tunneling indicates that the data conveyed by these arrows are not relevant to the particular level of detail.

Examples of tunneled arrows are shown in Figure B.3. Tunneling on the connected end (e.g. C3, O1) indicates that the data entity may not be shown in lower levels of detail. Tunneling on the unconnected end (e.g. I1, C2) represents data entities, which may not be present in the higher level diagrams.

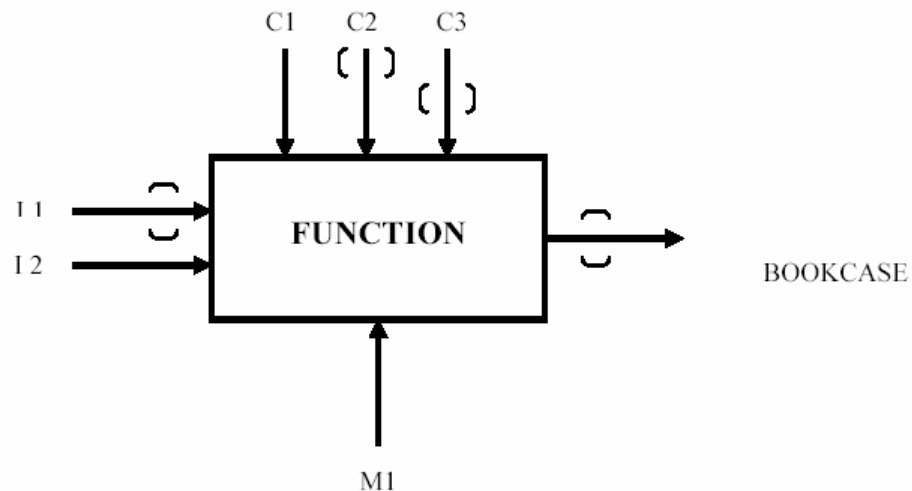


Figure B.3: Example of Tunneling

It is possible for tunneled data entities to not appear for several levels, and then reappear as a tunneled arrow. To reduce confusion, such data entities should be labeled at their origin.

B.4 READING IDEF0 DIAGRAMS

The IDEF₀ model is a series of diagrams arranged in a hierarchical manner. The model is a read top-down, and the following sequence should be followed in reading it (Integrated 1981):

1. Scan the boxes in the diagrams to get a general impression of what is being described.

2. Refer back to the parent diagram and note the arrow connections to the diagrams. Try to identify a “most important” input, control, mechanism, and output.
3. Find the central theme of the current diagram. Try to determine if there is a main path linking the “most important” input or control and the “most important” output.
4. Mentally walk through the diagram from upper left to lower right, using the main path as a guide. Study the overall content of the diagram.
5. Read the text provided to gain a further understanding of the author’s intent.

APPENDIX C

Survey Form for Graduate Production Management Course



A Tool for Evaluating Construction Flow

AE 597A Production Management in Construction

Objective:

To develop skills in new technologies for evaluating production flow in construction operations. You will learn how to identify construction production flow flaws with a 4D modeling tool.



Background:

Production flow is an essential concept in construction production management. In this course, you have learned the basic concept of construction flow.

4D CAD modeling is a new information technology tool used by the planners, designers and engineers to analyze and visualize many aspects of the construction project, including 3D design, sequence of construction, and the relationships between schedule, cost and resource availability data. In the 4D model the temporal and spatial aspects of the project are linked, as they are during the actual construction process. This helps visualize the project.

This class is designed to give you a tool to help you to understand the production flow in a construction project. The Space Hangar of the National Air & Space Museum project is the subject of this class. The space hanger is a part of new National Air & Space Museum, which was an addition to the original project that was built.

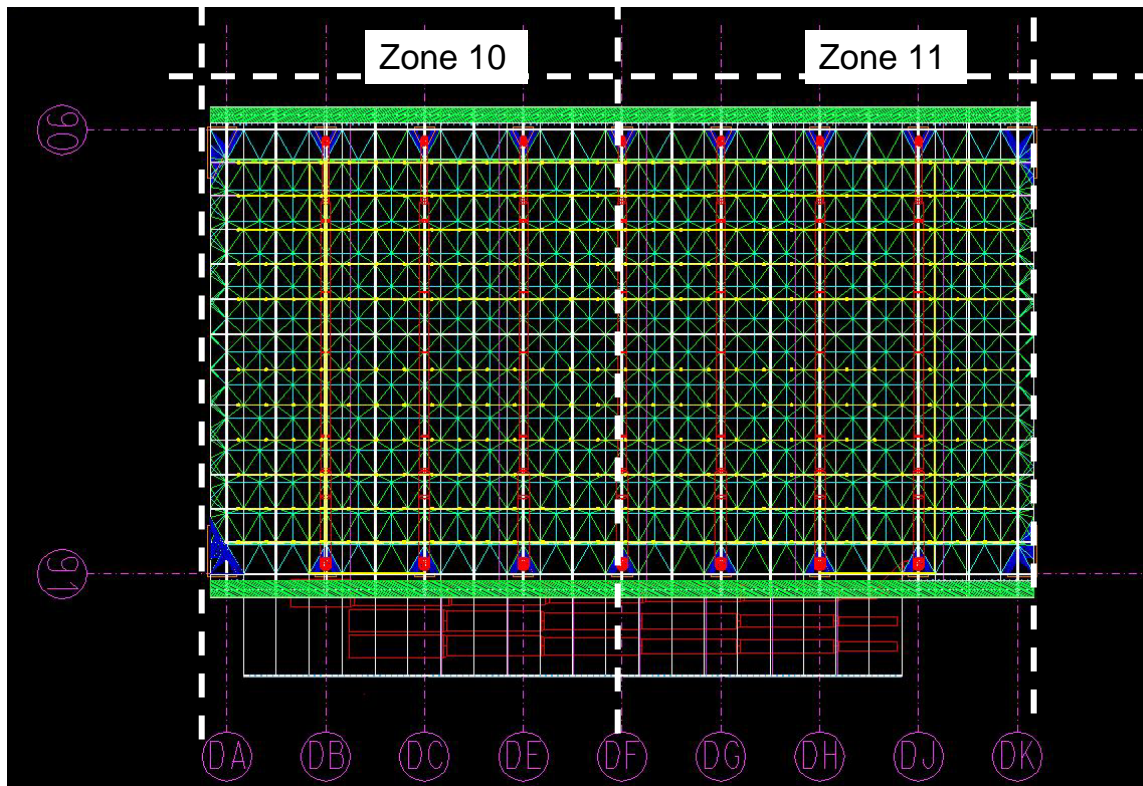
Outline:

This experiment involves two steps, both involving the review of construction flow in a construction plan for the Space Hangar of the National Air & Space Museum.

Task:

Your first task is to evaluate the flow of each construction work in the Space Hangar of the National Air & Space Museum project shown overpage. Copy the experiment files from Y drive to a local folder. Restore the schedule file called "NASM", Version 1 with Primavera Project Planner using command Tools-Project Utilities-Restore. Keep an eye on working zone specification in the schedule. To help you identify the involved trade and construction activities, the key components to the space hangar is listed as following:

- Sub base
- Columns
- Roof Truss
- Roof Decking
- Side Gallery Decking
- Roofing Membrane
- Side Framing
- Main HVAC Duct
- Fire Proofing system
- Side panel
- Windows
- Glazing
- Wall panels
- Side Roof
- Main framing
- Return Air Duct
- Side gallery HVAC Duct



Review the Schedule:

The 2D drawing and the CPM schedule are available for review. Several section drawings are available in the folder your copied. Review and evaluate the flow. After reviewing, answer the following:

- **Think about which contractors would do which part of the project. Connect the contractor to the work.**
- **Do you see any improper construction flow? Identify these. What are the characteristics that make good flow? What were you looking for? Please specify the improper flow and the trades involved.**

▪ Sub base	▪ Concrete Contractor
▪ Columns	▪ Steel fabricator Contractor
▪ Roof Truss	▪ Steel erector Contractor
▪ Roof Decking	▪ Roof decking Contractor
▪ Side Gallery Decking	▪ Roofing Contractor
▪ Roofing Membrane	▪ Sheet metal Contractor
▪ Side Framing	▪ Glazing Contractor
▪ Main HVAC Duct	▪ Curtain wall Contractor
▪ Fire Proofing system	▪ Mechanical Contractor
▪ Side panel	▪ Fire protect Contractor
▪ Windows	▪ Concrete Contractor
▪ Glazing	▪ Steel fabricator Contractor
▪ Wall panels	▪ Steel erector Contractor
▪ Side Roof	▪ Roof decking Contractor
▪ Main framing	▪ Roofing Contractor

Review the 4D CAD Model:

Review the 4D model of the Space Hangar of the National Air & Space Museum project. Open Common Point 4D 1.90 and have a quick tour using command in Toolbar: Help-Online Demo/Tutorial. Go through the Tutorial 1: The Basic Elements of Project 4D. You can refer to this tutorial for detailed information regarding the steps of running a 4D model. After tutorial, open NASM A in Common Point 4D and review your answers. Make additions and corrections.

- **Think again about which contractors would do which part of the project. Connect the contractor to the work.**
- **Do you see any other instances of improper construction flow? Identify these. What are the characteristics that make good flow? What were you looking for? Please specify the improper flow and the trades involved.**

▪ Sub base	▪ Concrete Contractor
▪ Columns	▪ Steel fabricator Contractor
▪ Roof Truss	▪ Steel erector Contractor
▪ Roof Decking	▪ Roof decking Contractor
▪ Side Gallery Decking	▪ Roofing Contractor
▪ Roofing Membrane	▪ Sheet metal Contractor
▪ Side Framing	▪ Glazing Contractor
▪ Main HVAC Duct	▪ Curtain wall Contractor
▪ Fire Proofing system	▪ Mechanical Contractor
▪ Side panel	▪ Fire protect Contractor
▪ Windows	▪ Concrete Contractor
▪ Glazing	▪ Steel fabricator Contractor
▪ Wall panels	▪ Steel erector Contractor
▪ Side Roof	▪ Roof decking Contractor
▪ Main framing	▪ Roofing Contractor

Please answer the following questions

Group: _____

1. Which tool, 2D plus schedule or the 4D tool you used, is more effective in evaluating the construction flow?

2D Equally Effective 4D
 1 2 3 4 5

Please Explain:

2. (If you used **Component 4D** during the experiment) please compare and evaluate the Component 4D and Visual Space 4D.

3. Do you feel any value would be added to the 4D model if the space occupation of each trade were explicated represented, as in Visual Space 4D?

	<i>Make it Complex</i>		<i>Neutral</i>		<i>A lot</i>
1. Identify construction conflicts:	1	2	3	4	5
2. Represent direction of the flow	1	2	3	4	5
3. Evaluate the flow continuity	1	2	3	4	5
4. Perform Construction Space Planning	1	2	3	4	5
5. Sequence construction trades on site	1	2	3	4	5

Comments: _____

APPENDIX D

Survey Form for Architectural Engineering Graduate Students

A Tool for Evaluating Production Trade Flow



Background:

Production flow is an essential concept in construction production management. In this experiment, you will learn the basic concept of construction flow.

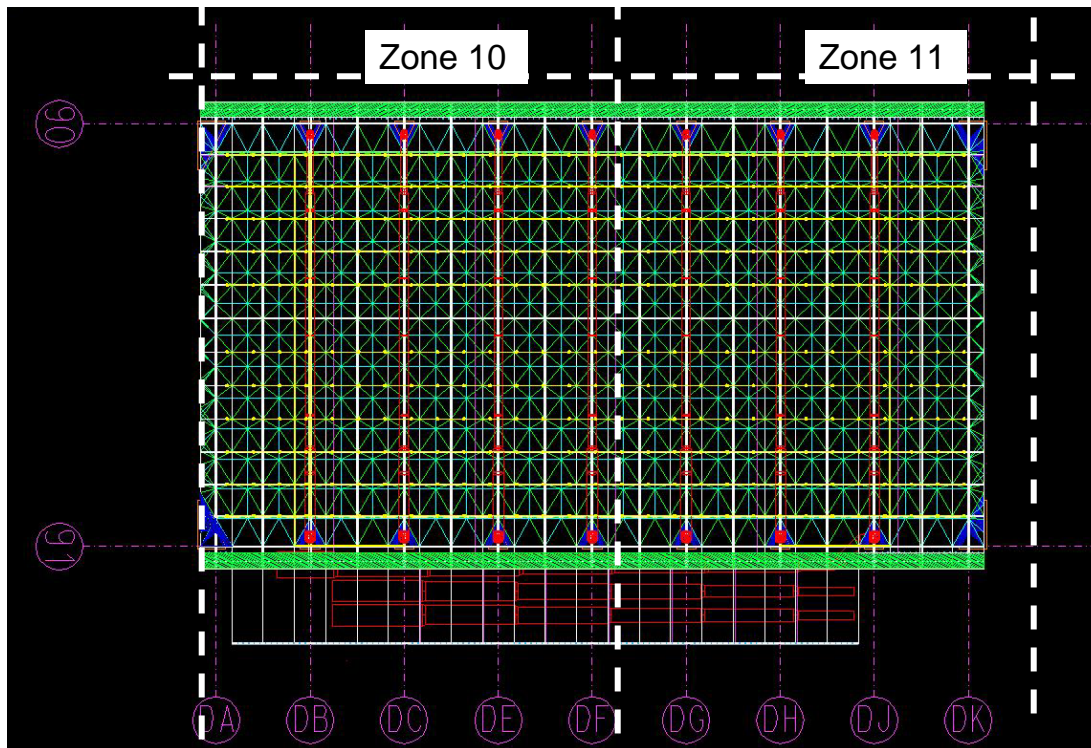
4D CAD modeling is a new information technology tool used by the planners, designers and engineers to analyze and visualize many aspects of the construction project, including 3D design, sequence of construction, and the relationships between schedule, cost and resource availability data. In the 4D model the temporal and spatial aspects of the project are linked, as they are during the actual construction process. This helps visualize the project.

This experiment is designed to give you a tool to help you to understand the production flow in a construction project. The Space Hangar of the National Air & Space Museum project is the subject of this class. The space hangar is a part of new National Air & Space Museum, which was an addition to the original project that was built.

Task:

Your task is to evaluate the flow of each construction work in the Space Hangar of the National Air & Space Museum project shown overpage. To help you identify the involved trade and construction activities, the key components to the space hangar is listed as following:

- Sub base
- Columns
- Roof Truss
- Roof Decking
- Side Gallery Decking
- Roofing Membrane
- Side Framing
- Main HVAC Duct
- Fire Proofing system
- Side panel
- Windows
- Glazing
- Wall panels
- Side Roof
- Main framing
- Return Air Duct
- Side gallery HVAC Duct



Review the 4D CAD Model:

Review the 4D model of the Space Hangar of the National Air & Space Museum project. Open Common Point 4D 1.90 and have a quick tour using command in Toolbar: Help-Online Demo/Tutorial. Go through the Tutorial 1: The Basic Elements of Project 4D. You can refer to this tutorial for detailed information regarding the steps of running a 4D model. After tutorial, open NASM A in Common Point 4D and review your answers. Make additions and corrections.

- **Think again about which contractors would do which part of the project. Connect the contractor to the work.**

▪ Sub base	▪ Concrete Contractor
▪ Columns	▪ Steel fabricator Contractor
▪ Roof Truss	▪ Steel erector Contractor
▪ Roof Decking	▪ Roof decking Contractor
▪ Side Gallery Decking	▪ Roofing Contractor
▪ Roofing Membrane	▪ Sheet metal Contractor
▪ Side Framing	▪ Glazing Contractor
▪ Main HVAC Duct	▪ Curtain wall Contractor
▪ Fire Proofing system	▪ Mechanical Contractor
▪ Side panel	▪ Fire protect Contractor
▪ Windows	▪ Concrete Contractor
▪ Glazing	▪ Steel fabricator Contractor
▪ Wall panels	▪ Steel erector Contractor
▪ Side Roof	▪ Roof decking Contractor
▪ Main framing	▪ Roofing Contractor

- **Do you see any construction trade space conflicts among the flow? Identify these. Please specify the improper flow and the trades involved.**

- **The direction of the flow is another main concern in construction production management. Different flow direction may lead to different demand of equipment, material storage, amount of crew, etc. Inappropriate direction of one trade may have a strong effect on the productivity of other trades. Do you see any other conflicts of the flow direction among the trade? Identify these. Please specify the improper flow direction and the trades involved.**

- **Flow continuity is one of the main characteristics to measure production flow. The unexpected variability in pace or even pause of the production flow normally causes delay of site crews, induces double handling of material, promotes the unnecessary build up of site inventory, and impedes the start of successive trades. Do you see any interruption of the flow? Identify these. Please specify the improper flow direction and the trades involved.**

Please answer the following questions

Group: _____

2. How do you rate the effectiveness of the tool in evaluating the construction flow?

Not Effective *Neutral* Very Effective
 1 2 3 4 5

Please Explain:

2. (If you used **Component 4D** during the experiment) please compare and evaluate the Component 4D and Visual Space 4D.

3. Do you feel any value would be added to the 4D model if the space occupation of each trade were explicated represented, as in Visual Space 4D?

	<i>Make it Complex</i>		<i>Neutral</i>		<i>A lot</i>
1. Identify construction conflicts:	1	2	3	4	5
2. Represent direction of the flow	1	2	3	4	5
3. Evaluate the flow continuity	1	2	3	4	5
4. Perform Construction Space Planning	1	2	3	4	5
5. Sequence construction trades on site	1	2	3	4	5

Comments:
