INTER-FIRM COLLABORATION IN THE IMPLEMENTATION OF
STRUCTURAL INNOVATIONS IN BUILDING CONSTRUCTION

by

Christopher J. Semlisy
B.E. in Civil Engineering, Cooper Union, 1997

Submitted to the Department of Civil and Environmental Engineering
in partial fulfillment of the requirements for the degree of
Master of Science in Civil and Environmental Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
February 1999

© Massachusetts Institute of Technology. All rights reserved.

Signature of Author

Department of Civil and Environmental Engineering
January 6, 1998

Certified by

E. Sarah Slaughter
Assistant Professor of Civil and Environmental Engineering
Thesis Supervisor

Accepted by

Andrew J. Whittle
Chairman, Departmental Committee on Graduate Studies
INTER-FIRM COLLABORATION IN THE IMPLEMENTATION OF STRUCTURAL INNOVATIONS IN BUILDING CONSTRUCTION

by

Christopher J. Semlies

Submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of Master of Science in Civil and Environmental Engineering

ABSTRACT

It is increasingly recognized that the development of many innovations typically requires collaboration across disciplines because an innovation in one area will often necessitate changes in other areas. In the construction industry, the problem is not merely one of interdisciplinary collaboration within a vertically integrated firm, but one of inter-firm collaboration over the life of a project because dozens of specialized firms typically work together on the delivery of built facilities.

Thus, firm boundaries and other factors can affect the success of the implementation of innovations in construction. The goal of this research is to gain an understanding of the factors that influence inter-firm collaboration in the development and implementation of construction innovations. Ten case studies of structural system innovations implemented on 17 projects were developed in order to analyze the role of these factors, including contract type, delivery system, transaction cost, bond, appropriation of costs/benefits, and sharing of competencies on inter-firm innovation.

The results from the case studies often contradict the expectations of principal-agent theory and other areas of management and economic theory related to inter-firm collaboration for innovation. For example, all of the innovations were implemented under outcome-based contracts. This result is surprising because the common perception in the literature is that the widespread use of outcome-based contracting hinders innovation. Also surprising was that, of the innovations introduced by contractors under outcome-based contracts, many were quality enhancing. However, one would expect that, due to the cost pressures of their contract, a contractor would be more likely to implement cost-saving innovations.

A strong relationship was found between innovative activity and the integration of the design and construction functions, supporting the belief that the traditional delivery system used in construction, which separates design from construction, is a barrier to innovation. In addition, it was found that, in this set of cases, contractors were more likely to introduce innovations on projects that used integrated delivery systems. It was also found that investment in co-specialized assets occurred in conjunction with outcome-based contracts. This finding contradicts the expected result, which is that such investment should occur most frequently in behavior-based contracting situations.

It is hoped that this knowledge will enhance our understanding of the process of innovation development and implementation in the construction industry in particular, and in other industries in general, specifically in fields where the design and realization of complex systems involves multiple firms. Owners can use this information to organize projects to implement innovations successfully and construction and other companies can use it to improve their strategies regarding innovation.

Thesis Supervisor: E. Sarah Slaughter
Title: Assistant Professor of Civil and Environmental Engineering
ACKNOWLEDGEMENTS

I would like to express my profound gratitude to my research advisor, Professor E. Sarah Slaughter. Throughout the course of this project, she has provided me with invaluable guidance and support. She helped me to understand areas of management and economics that were very new to me. She truly has a well-rounded set of knowledge in both technical engineering disciplines and management.

In addition, I am indebted to the dozens of engineering and construction personnel that I interviewed for this research. These men and women were kind enough to take the time out of their very busy schedules to answer my questions. It is encouraging to know that practitioners value this type of research and its benefits.

I also want to thank the Center for Innovation in Product Development at MIT for its financial support.

On a personal note, I would like to thank my girlfriend, Laura. She was supportive throughout this project, even at times that it took over my life. I also want to thank my family, which has supported me throughout my college career, always encouraging me to strive to reach my goals. Last, but not least, I would like to thank my classmates, especially John, Steve, and Chris, for keeping me sane.
# TABLE OF CONTENTS

1. **INTRODUCTION** ........................................................................................................................................... 12
   1.1. **PROBLEM STATEMENT** .......................................................................................................................... 12
   1.2. **RESEARCH OBJECTIVES** ....................................................................................................................... 13
   1.3. **RESEARCH SIGNIFICANCE** ..................................................................................................................... 13
   1.4. **THESIS ORGANIZATION** ......................................................................................................................... 14

2. **LITERATURE REVIEW** ................................................................................................................................. 16
   2.1 **PRINCIPAL-AGENT AND TEAM THEORY** ................................................................................................. 16
       2.1.1 **Contracts in Construction** .................................................................................................................. 18
       2.1.2 **Multi-task, Multi-agent Situations** ....................................................................................................... 19
       2.1.3 **Organizational Structure/Delivery Mechanisms in Construction** ....................................................... 20
   2.2 **MECHANISMS OF INTER-FIRM COLLABORATION** .............................................................................. 21
   2.3 **INTER-FIRM COLLABORATION FOR INNOVATION** ............................................................................. 24
   2.4 **INNOVATION IN CONSTRUCTION** ........................................................................................................... 26
       2.4.1 **Classification of Innovations** ............................................................................................................... 26
       2.4.2 **Who Innovates** ....................................................................................................................................... 28
       2.4.3 **Implementation and Diffusion of Innovations** ...................................................................................... 29

3. **THEORETICAL FRAMEWORK** ...................................................................................................................... 30
   3.1 **THEORY AREA #1: PRINCIPAL AGENT AND TEAM THEORY** .......................................................... 30
       3.1.1 **Variable #1: Distribution of benefits, costs and risks** ........................................................................ 30
   3.2 **THEORY AREA #2: MECHANISMS OF INTER-FIRM COLLABORATION** ........................................... 32
       3.2.1. **Variable #1: Project Value Chain** ..................................................................................................... 32
       3.2.2. **Variable #2: Bond** .................................................................................................................................. 33
       3.2.3. **Variable #3: Team Protocol** ............................................................................................................... 33
       3.2.4. **Variable #4: Objectives** ...................................................................................................................... 34
   3.3 **THEORY AREA #3: INTER-FIRM INNOVATION** ..................................................................................... 34
       3.3.1. **Variable #1: Nature of the Innovation** ............................................................................................... 34
       3.3.2. **Variable #2: Appropriation of Innovation Benefits** ........................................................................ 35
       3.3.3. **Variable #3: Sharing of Competencies** ............................................................................................ 36

4. **METHODOLOGY** ............................................................................................................................................... 37
   4.1 **LITERATURE REVIEW** ............................................................................................................................. 37
   4.2 **INNOVATION DATA SAMPLE** ............................................................................................................... 38
   4.3 **VALIDATION OF DATA** ............................................................................................................................ 40

5. **CASE STUDIES** .............................................................................................................................................. 43
   5.1 **TRIO STRUCTURAL SYSTEM** .................................................................................................................. 43
       5.1.1. **Brief description** .................................................................................................................................... 43
       5.1.2. **Innovation development and use** ....................................................................................................... 45
           5.1.2.1. Development ..................................................................................................................................... 45
           5.1.2.2. Use - Chapultepec Tower, Mexico City, Mexico .............................................................................. 45
   5.2 **SPECIAL TRUSS MOMENT-RESISTING FRAME (STMF)** ................................................................ 52
       5.2.1. **Brief description** .................................................................................................................................. 52
       5.2.2. **Innovation Development and Use** .................................................................................................... 54
           5.2.2.1. Gateway Oaks IV, Sacramento, California ....................................................................................... 54
           5.2.2.2. Johnson Ranch Corporate Headquarters, California .................................................................... 57
           5.2.2.3. Roseville Corporate Center, California .......................................................................................... 59
5.3. HYBRID MOMENT-RESISTING PRECAST CONCRETE FRAME .......................................................... 62
  5.3.1. Brief description .................................................................................................................. 62
  5.3.2. Innovation development and use ......................................................................................... 63
    5.3.2.1. Development ............................................................................................................... 63
    5.3.2.2. Use - Roosevelt Field Mall Parking Garages, Long Island, New York .................. 64
    5.3.2.3. Use - Eugene Parking Garage, Eugene Oregon ..................................................... 66

5.4. DUCTILE PRECAST CONCRETE FRAME ............................................................................... 70
  5.4.1. Brief description ................................................................................................................ 70
  5.4.2. Innovation development and use ....................................................................................... 71
    5.4.2.1. Development ............................................................................................................. 71
    5.4.2.2. Use - Wiltern Center Garage, Los Angeles, CA ....................................................... 72

5.5. PRECAST CONCRETE SLURRY WALL ............................................................................... 76
  5.5.1. Brief description ................................................................................................................ 76
  5.5.2. Innovation development and use ....................................................................................... 78
    5.5.2.1. Development ............................................................................................................. 78
    5.5.2.2. Use - Old Colony Rail Line, Kingston, MA ............................................................... 79
    5.5.2.3. Use - Seaport Hotel, Boston, MA ............................................................................. 81
    5.5.2.4. Use - Pilot House, Boston, MA .............................................................................. 85

5.6. HYBRID PARKING SYSTEM ............................................................................................... 89
  5.6.1. Brief description ................................................................................................................ 89
  5.6.2. Innovation development and use ....................................................................................... 90
    5.6.2.1. Development ............................................................................................................. 90
    5.6.2.2. Use - Dow Jones Garage, Princeton, New Jersey ................................................... 90
    5.6.2.3. Use - Tufts Health Plan Garage, Watertown, Massachusetts .................................. 93

5.7. DOUBLE HELICAL RAMP ..................................................................................................... 97
  5.7.1. Brief description ................................................................................................................ 97
  5.7.2. Innovation development and use ....................................................................................... 98
    5.7.2.1. Development ............................................................................................................. 98
    5.7.2.2. Use - Logan Airport West Garage, Boston, Massachusetts ................................... 98
    5.7.2.3. Use - Empress Casino Garage, Hammond, Indiana ............................................... 101

5.8. FABRIC ROOF ....................................................................................................................... 104
  5.8.1. Brief description .............................................................................................................. 104
  5.8.2. Innovation development and use ...................................................................................... 106
    5.8.2.1. Development ........................................................................................................... 106
    5.8.2.2. Use - JFK Airport International Arrivals Building Temporary Domestic Baggage Claim Area, New York, New York ...................................................... 107

5.9. TENSION BRACED DOME .................................................................................................. 112
  5.9.1. Brief description .............................................................................................................. 112
  5.9.2. Innovation development and use ..................................................................................... 112
    5.9.2.1. Development ........................................................................................................... 112
    5.9.2.2. Use - Marine Midland Arena, Buffalo, New York .................................................. 112

5.10. MOVEABLE ARCHED SCAFFOLD ..................................................................................... 118
  5.10.1. Brief description .......................................................................................................... 118
  5.10.2. Innovation development and use ................................................................................. 119
    5.10.2.1. Development ......................................................................................................... 119
    5.10.2.2. Use - Grand Central Station Renovation, New York, New York ....................... 119

6. ANALYSIS ............................................................................................................................... 124
  6.1. THEORY AREA #1: PRINCIPAL AGENT AND TEAM THEORY ................................................. 124
    6.1.1. Variable #1: Distribution of benefits, costs and risks ............................................... 124
      6.1.1.1. Measure #1: Contracts ......................................................................................... 124
TABLE OF FIGURES

FIGURE 1.1 - SEPARATION OF DESIGN AND CONSTRUCTION FUNCTIONS IN DESIGN-BID-BUILD .......... 13
FIGURE 2.1 - INNOVATION CLASSIFICATIONS (HENDERSON AND CLARK 1990) .......................... 27
FIGURE 3.1 - ORGANIZATION CHART FOR DESIGN-BID-BUILD ........................................ 31
FIGURE 4.1 - CASE STUDY METHODOLOGY ........................................................................ 40
FIGURE 5.1.1 - CROSS-SECTION OF A FLUID VISCOUS DAMPER (CONSTANTINOU AND SYMANS 1993) .... 43
FIGURE 5.1.2 - FLUID VISCOUS DAMPERS INSTALLED IN A STEEL FRAME (ELNESSER ET AL. 1997) ........ 44
FIGURE 5.1.3 - PROJECT ORGANIZATION CHART FOR CHAPULTEPEC TOWER ....................... 48
FIGURE 5.1.4 - VALUE CHAIN FOR CHAPULTÉPEC TOWER .................................................. 49
FIGURE 5.1.5 - TIMELINE FOR THE CHAPULTEPEC TOWER PROJECT .................................. 51
FIGURE 5.2.1 – CLOSE-UP VIEW OF A SPECIAL TRUSS; THE THINNER DIAGONALS YIELD DURING AN EARTHQUAKE (ROSENBAUM 1998) ...................................................... 52
FIGURE 5.2.2 – COMPARISON OF CONNECTION TYPES (JD2 PRODUCT LITERATURE) ............... 53
FIGURE 5.2.3 – PROJECT ORGANIZATION CHART FOR GATEWAY OAKS ................................ 55
FIGURE 5.2.4 – VALUE CHAIN FOR THE GATEWAY OAKS IV PROJECT .................................. 55
FIGURE 5.2.5 – PROJECT ORGANIZATION CHART FOR JOHNSON RANCH HEADQUARTERS .... 58
FIGURE 5.2.6 – VALUE CHAIN FOR JOHNSON RANCH PROJECT ........................................... 58
FIGURE 5.2.7 – PROJECT ORGANIZATION CHART FOR ROSEVILLE CORPORATE CENTER ........ 59
FIGURE 5.2.8 – VALUE CHAIN FOR THE ROSEVILLE PROJECT ............................................... 60
FIGURE 5.2.9 – TIMELINE OF DEVELOPMENT AND USE OF THE STMF ............................... 61
FIGURE 5.3.1 - ISOMETRIC VIEW OF BEAM-COLUMN CONNECTION (STONE 1995) .................. 62
FIGURE 5.3.2 - CROSS-SECTION OF BEAM-COLUMN CONNECTION (STONE 1995) .................. 63
FIGURE 5.3.3 - PROJECT ORGANIZATION CHART FOR ROOSEVELT FIELD MALL GARAGES .... 65
FIGURE 5.3.4 - VALUE CHAIN FOR ROOSEVELT FIELD MALL GARAGES ............................ 65
FIGURE 5.3.5 - TIMELINE OF DEVELOPMENT AND USE OF II HYBRID FRAME ..................... 66
FIGURE 5.3.6 - PROJECT ORGANIZATION CHART FOR EUGENE GARAGE ....................... 67
FIGURE 5.3.7 - VALUE CHAIN FOR EUGENE GARAGE ......................................................... 67
FIGURE 5.3.8 - TIMELINE OF EUGENE GARAGE PROJECT .................................................. 69
FIGURE 5.4.1 - DYWIDAG DUCTILE CONNECTOR HARDWARE (NAKAKI 1994) ...................... 70
FIGURE 5.4.2 - ISOMETRIC VIEW OF A DUCTILE CONNECTOR (ENGLEKIRK 1995) .................. 71
FIGURE 5.4.3 - PROJECT ORGANIZATION CHART FOR WILTERN CENTER GARAGE ........ 74
FIGURE 5.4.4 - VALUE CHAIN FOR WILTERN CENTER GARAGE ......................................... 74
FIGURE 5.4.5 - TIMELINE OF DEVELOPMENT AND USE OF DPCF ...................................... 75
FIGURE 5.5.1 - STEPS INVOLVED IN CONVENTIONAL CIP CONCRETE SLURRY WALL CONSTRUCTION (ALLEN 1990) ................................................................. 77
FIGURE 5.5.2 - END VIEW OF A TYPICAL PANEL ................................................................ 78
FIGURE 5.5.3 - PROJECT ORGANIZATION CHART FOR OLD COLONY LINE PROJECT .......... 80
FIGURE 5.5.4 - VALUE CHAIN FOR OLD COLONY LINE PROJECT ....................................... 80
FIGURE 5.5.5 - TIMELINE FOR OLD COLONY LINE PROJECT ............................................ 81
FIGURE 5.5.6 - PROJECT ORGANIZATION CHART FOR SEAPORT HOTEL PROJECT ........... 82
FIGURE 5.5.7 - VALUE CHAIN FOR SEAPORT HOTEL PROJECT .......................................... 83
FIGURE 5.5.8 - TIMELINE FOR SEAPORT HOTEL PROJECT .................................................. 85
FIGURE 5.5.9 - PROJECT ORGANIZATION CHART FOR PILOT HOUSE .............................. 86
FIGURE 5.5.10 - VALUE CHAIN FOR PILOT HOUSE ............................................................... 86
FIGURE 5.5.11 - TIMELINE FOR PILOT HOUSE .................................................................... 88
FIGURE 5.6.1 - PROJECT ORGANIZATION CHART FOR DOW JONES GARAGE ................. 91
FIGURE 5.6.2 - VALUE CHAIN FOR DOW JONES GARAGE PROJECT .................................. 92
FIGURE 5.6.3 - PROJECT ORGANIZATION CHART FOR TUFTS HEALTH PLAN GARAGE .... 94
FIGURE 5.6.4 - VALUE CHAIN FOR TUFTS HEALTH PLAN GARAGE PROJECT .................. 94
TABLE OF TABLES

TABLE 4.1 - ENGINEERING AND CONSTRUCTION PERIODICALS .......................................................... 37
TABLE 4.2 - CONSTRUCTION PROJECTS VISITED ........................................................................ 38
TABLE 4.3 - LIST OF CONTACTS FOR CASE STUDIES ................................................................. 42
TABLE 6.1 – CONTRACT TYPE DATA SUMMARY ........................................................................... 125
TABLE 6.3 – LEVEL OF INNOVATION SPECIFIC INVESTMENT IN CO-SPECIALIZED ASSETS ....... 127
TABLE 6.4 – SOURCES OF INNOVATIONS ...................................................................................... 131
TABLE 6.5 – REUSE OF INNOVATIONS ......................................................................................... 132
TABLE 6.6 – STAGE OF PROJECT FOR COMMITMENT TO INNOVATION .................................... 133
TABLE 6.7 – AMOUNT OF PREVIOUS EXPERIENCE BETWEEN PROJECT TEAM MEMBERS ........ 135
TABLE 6.8 – OWNER’S OBJECTIVES FOR PROJECTS ................................................................. 136
TABLE 6.9 – EXPECTED BENEFITS OF INNOVATIONS ................................................................. 137
TABLE 6.10 – NUMBER OF INNOVATIONS OF EACH TYPE WITH RESPECT TO POSITION IN THE VALUE CHAIN ........................................................................................................... 138
TABLE 6.11 – PROJECT DELIVERY SYSTEM VERSUS INNOVATION SOURCE ......................... 142
TABLE 6.12 – INNOVATION SOURCE VERSUS EXPECTED BENEFIT OF INNOVATION ................ 142
TABLE 6.13 – INVESTMENT IN CO-SPECIALIZED ASSETS VERSUS INNOVATION CONTRACT .... 143
TABLE 6.14 – PROJECT TEAM CHANGES IN REUSE VERSUS INVESTMENT IN CO-SPECIALIZED ASSETS .... 143
TABLE 6.15 – PROJECT DELIVERY SYSTEM VERSUS PROJECT STAGE FOR COMMITMENT TO INNOVATION .................................................................................................................. 144
TABLE 6.16 – PROJECT CONTRACT VERSUS EXPECTED BENEFIT OF INNOVATION ............... 145
TABLE 6.17 – COMPARISON OF CASE STUDY AND LARGE SAMPLE DATA .................................. 146
1. INTRODUCTION

1.1. Problem statement

It is increasingly recognized that the development of many innovations typically requires collaboration across disciplines because an innovation in one area will often necessitate changes in other areas. In the construction industry, this is an important point because built facilities are composed of many individual components that must work together as a system for the facility to function properly. The problem is complicated even more by the way in which construction projects are designed and built. Due to their complexity, built facilities are typically divided into components along functional and/or physical lines. Then, a different firm typically designs each of these components, and subsequently other firms are responsible for the construction of each component. Thus, the problem is not merely one of cross-disciplinary collaboration within a vertically integrated firm, but one of inter-firm collaboration over the life of a project.

In construction, each facility consists of multiple systems. For example, in a typical office building, the major systems are the structural system, the enclosure system, and the services (which include the plumbing, air conditioning, heating, conveyance, fire protection, and electrical systems), and the interior finish system.

Thus, an innovation in the structural system may in turn require modifications to be made in the design and construction of the enclosure and other systems. The firm introducing the innovation must then negotiate with the other project team members to ensure compatibility among the components. In addition, if the innovation occurs during the design of a particular system, the designer must communicate its concept to the firm that will construct it.

Firm boundaries and other factors can affect the success of this negotiation process. For example, inter-firm cooperation is inhibited by the standard project delivery system used in the construction industry. In this system, known as design-bid-build, the design and construction functions are completely separated, as depicted by Figure 1.1. For example, consider a real estate developer that wants to build a downtown office building. Using the standard delivery system, the developer first hires an architect to be in charge of the design of the building and its systems. The architect typically hires consultants to do portions of this work, including a structural engineer for the structural design, a mechanical engineer to design the heating, ventilation, air conditioning and electrical systems, and perhaps an interior designer or landscape architect. After the design is completed, the owner hires a general contractor to be in charge of the construction phase of the project. The general contractor may perform some of the work itself, but it will typically hire a number of subcontractors to perform parts of the specialty work, including a concrete subcontractor, a steel erection subcontractor and so on. These subcontractors in turn may hire sub-
subcontractors to perform some of the work for them. In addition, there are also suppliers of labor, materials and equipment. Overall, there can be dozens of firms involved on a project with each party specialized in a particular task.

![Figure 1.1 - Separation of design and construction functions in design-bid-build](image)

Since the design process is complete before contractors are brought into the project, it can be difficult for contractors to introduce innovations. One reason is that incorporating innovations after the design is completed often requires redesign, which adds cost and time to the project. In addition, because the design and construction functions are so distinctly separated both in time and in organization, it is often difficult to negotiate the distribution of the impacts and associated costs and benefits of innovations. Also, in this delivery system, contractors are typically selected based on cost and signed to lump sum contracts, so they can face significant financial risk when introducing innovations.

1.2. Research objectives

The goal of this research is to gain an understanding of the factors that influence inter-firm collaboration in the development and implementation of construction innovations. Analysis of a sample of in-depth cases of construction innovation specifically focuses on the interactions among firms for a project over time. It is hoped that this knowledge will enhance our understanding of the process of innovation development and implementation in the construction industry in particular, and in other industries in general, specifically in fields where the design and realization of complex systems involves multiple firms. Owners can use this information to organize projects to implement innovations successfully, and construction and other companies can use it to improve their strategies regarding innovation.

1.3. Research significance

This research is important for several reasons. For one, it investigates the factors that influence inter-firm collaboration in the development and implementation of innovations, a combination that has
not previously been explored. This area of study is quite new and not fully developed. As the literature review in the following chapter shows, there have been several studies in recent years regarding factors that influence collaborative product development both at the inter-firm and intra-firm cross-functional levels. However, very few of these studies focused on innovative product development in particular. In addition, none of these studies dealt with the construction industry; most focused on the information technology sector. This area of study has come about largely due to recent trends in manufacturing as firms have decided to pursue product development projects through collaborative ventures with other specialized firms. However, in the construction industry, projects have been pursued in this fashion for decades. On the other hand, the standard model of product development in manufacturing had been a sequential process that was conducted in-house.

Thus, this research is also important because, as it shows how inter-firm collaboration for innovation occurs in construction, it can yield important information for the manufacturing industry as well as that industry moves toward a decentralized model of product development. In addition, this research can benefit the construction industry by adding to our understanding of the factors that affect the process of innovation.

1.4. Thesis organization

Chapter 2 contains a review of relevant literature in several areas of study. Among these fields are the principle-agent relationship and multi-agent theories, mechanisms of cross-functional collaboration, and inter-firm innovation. In addition, some research specific to innovation in the construction industry is described.

Chapter 3 explains the theoretical framework for this research, which consists of a set of variables that affect inter-firm collaboration on innovative construction projects. Measures for each variable are also presented in this chapter.

Chapter 4 outlines the methodology of this research, which is empirical, consisting of in-depth studies of ten innovations as well as a less detailed analysis of a larger set of innovations. Included in this chapter is an explanation of how the innovations were identified and how ten of them were selected for in-depth analysis. The methodology of the case study analysis is also presented in this chapter.

Chapter 5 contains ten detailed case studies of structural innovations. In addition, it contains a review of the innovations in the large data sample of 30 structural innovations. In Chapter 6, the innovations are analyzed with respect to the variables presented in Chapter 3. The findings are compared and contrasted with the theories presented in Chapter 2.
Chapter 7 contains the conclusions of this research. The analysis of Chapter 6 is summarized and the major points are stressed in terms of their implications for collaborative innovation in the construction and manufacturing industries. In addition, recommendations are given for future research.

Finally, there are three appendices. Appendices A and B contain explanations of the contracts and delivery systems used in construction, respectively. Appendix C contains the data for the ten case study innovations and the 30 innovations of the large sample in tabular form.
2 LITERATURE REVIEW

To understand the subject of inter-firm collaboration for innovation in the construction industry, there are several important areas of management and economics to consider. In recent years, researchers have turned their attention to the problem of inter-firm collaboration and have attempted to elicit the important issues. This chapter introduces those issues that have particular relevance to the construction industry. The first section discusses the theories of principal-agent and team relationships and how they relate to the construction industry. The second section reviews the literature concerning mechanisms that foster inter-firm collaboration. The third section consists of a review of the literature regarding inter-firm collaboration in the case of innovation specifically. This is a relatively new field of research, so very little has been published on the subject. Finally, the fourth part presents some relevant theory in the study of innovation in the construction industry.

2.1 Principal-Agent and Team Theory

In construction, as in many industries today, projects are completed through the combined and simultaneous effort of many functionally distinct firms. These firms each occupy a position in the value chain for the project, and the communication patterns between them create a structure that we will refer to as the inter-firm network. This section presents research conducted in agency theory, an area of study that examines these networks.

As described by Eisenhardt (1989), agency theory refers to situations “in which one party (the principal) delegates work to another (the agent).” This relationship is based on the contract between the two parties. The two problems central to agency theory are as follows:

1. The goals of the principal and its agent may not be aligned. This is a major concern when the principal finds it difficult or expensive to verify the agent’s actions.

2. Risk sharing is also a problem because, when the two parties have different attitudes toward risk, they will prefer different actions (Eisenhardt 1989).

Thus, the principal’s task is to design a contract that effectively deals with both problems. First, it must effectively drive the agent to act in the interests of the principal, especially when the principal cannot verify the agent’s performance. In that case, the agent may act out of self-interest and thus shirk its duties as described in the contract. Researchers have labeled this as the moral hazard in the principal-agent relationship. Second, the contract must efficiently allocate risk between the two parties. The owner must realize that the agent will charge a higher cost to cover the risks imposed upon him through the contract, particularly when the agent is highly risk-averse (Holmstrom and Milgrom 1991). The owner
must therefore weigh this added cost against what it would cost itself to assume that risk. If risk is allocated appropriately, then the principal's and the agent's goals will be aligned.

There are two general classes of contracts to consider – outcome-oriented and behavior-oriented. The former refers to contracts that include incentives such as commissions to motivate the agent to complete its task to achieve a specified outcome. The latter include contracts that pay salaries based on how the agent completes its task. Behavior-oriented contracts are best suited to situations in which the owner can adequately monitor the agent's performance to ensure that it is in line with the owner's expectations. Often, this will require some investment on the part of the owner into information systems to be used to monitor the agent.

Outcome-oriented contracts transfer risk from the owner to the agent while behavior-oriented contracts do the opposite. When the outcome is more uncertain (e.g., due to external factors such as government policies and economic climate), the cost of shifting the risk to the agent in an outcome-based contract increases. The selection of contract type, therefore, depends on the principal's and agent's respective attitudes toward risk and on the outcome uncertainty of the project. Another variable is the goal conflict between the two parties. In some cases, such as when the principal and agent have a good working relationship, the agent may be more inclined to act selflessly in order to preserve this relationship in hope of future contracts (Eccles 1981). In such instances, a behavior-based contract may be selected even if the principal cannot monitor the agent well.

There are two other issues to consider in the selection of contract type. The first is the programmability of the task, meaning the degree to which the agent's behavior can be specified in advance. Behavior-based contracts are best suited to tasks that are highly programmable. The other issue is the measurability of the outcome. When the outcome is easily measured, outcome-based contracts are better (Eisenhardt 1989).

Aside from the behavior- and outcome-based classes, there is also a third type of contract to consider, the incomplete contract. This contract type applies in cases in which the principal is unable to measure both the agent's actions and the outcome. Thus, the owner is faced with a problem that cannot be solved by using either the behavior- or outcome-based contract.

Many researchers have done studies using agency variables, such as task programmability, information systems and outcome uncertainty, to compare the efficiency of the two contract types in different situations. For example, Anderson (1985) found that the difficulty in accurately measuring outcomes by sales agents favored behavior-based contracts. Eisenhardt (1989) found support for agency theory in studies of salespeople in retailing. Overall, many research projects using such diverse methods
as questionnaires, interviews and laboratory experiments have found support for principal-agent theory (Eisenhardt 1989).

2.1.1 Contracts in Construction

Principal-agent theory is especially relevant in the case of construction because owners typically pursue projects by hiring several agents. These agents may include an architect and several engineers to perform the design work, and a general contractor and several specialty subcontractors to complete the construction. These agents subsequently hire consultants and subcontractors as well. Thus, construction projects have a complicated, multi-tiered principal-agent situation in which there are many principal-agent relationships at different levels, each with their own complications due to goal conflict and risk. Principal-agent theory is also useful in analyzing the distribution of risk, and consequently the appropriation of costs and benefits, on a project.

The two general classes of contracts in construction are lump sum and reimbursable (See Appendix A). The former is an outcome-based contract in which the owner pays the contractor a fixed sum of money to perform the work stipulated in the project plans and specifications. Because it is an outcome-based contract, the agent (the contractor) assumes the risks stemming from the uncertainty of the project. The owner minimizes its financial risks on the project because its costs are known from the start of construction. However, lump sum projects often wind up going over budget due to change orders issued by the contractor to cover missing design information or unforeseen site conditions. Thus, owners must understand that lump sum contracts are not foolproof.

The reimbursable contracts used in construction include cost plus a fixed or variable fee. Under these contracts, the owner pays the contractor for all costs incurred to complete the project. Thus, the owner assumes much of the risks. As is true of behavior-based contracts, the principal must be able to closely monitor the agent’s progress in order to ensure that the agent is working in the principal’s best interests.

The guaranteed maximum price contract (GMP) is a hybrid of the lump sum and reimbursable contract types. In this contract, the contractor is reimbursed for all of its costs, including labor, materials, and project overhead. The contractor is also paid a fee for company overhead and profit. The owner pays the contractor until the GMP value is reached and the contractor covers all costs thereafter. In some cases, the contract includes an incentive clause in which the contractor and owner share any savings if the project is completed for less than the GMP. With this type of contract, the owner must verify the actions of the contractor just as with any reimbursable contract. However, the contractor still assumes some risk because a GMP contract is similar to a lump sum contract with a cost cap.
In construction, the incomplete contract situation is very common. One reason is that it is difficult for owners to verify the outcome of the project in terms of quality and durability because constructed facilities are very complex and involve the integration of many systems. Thus, in the completed project, most of the work is hidden and cannot be readily inspected to verify that it conforms to the owner’s wishes. In addition, most owners do not have the expertise or staff necessary to monitor the behavior of their contractors. This is further complicated by the unique nature of each project.

2.1.2 Multi-task, Multi-agent Situations

In his research, Itoh (1991) studied situations in which there are multiple agents involved in a project. He defined two general cases of the multi-agent situation; either the principal wants unambiguous division of labor or it wants teamwork among the agents. The former is analogous to the DBB delivery system in construction, in which the principal has divided the work among specialized agents, and given the agents no incentive to help one another. Itoh refers to this as the specialized task structure. To induce teamwork, Itoh says that the principal must design the agents’ wage structures so that they depend on the outcomes of the other agents’ tasks. Itoh warns of several pitfalls that the owner must consider when deciding whether to go with a specialized task structure or to foster teamwork. One problem is that the principal can be hurt by the moral hazard problem that can lead to collusion among the agents. In addition, there is also the risk of free riding by an agent; that is, an agent could respond to outside help by decreasing its effort in its own task. This contracting scheme also leads to a form of the Prisoner’s Dilemma, in which agents must decide whether to help each other and how to respond to the other’s actions (Axelrod 1984).

Holmstrom and Milgrom (1991) focused on the issues of incentive contracts, asset ownership and job design in their study of multitask principal-agent situations. Their work deals with cases in which the principal has several different tasks for its agents to perform and/or an agent’s task is multidimensional. An example of the latter is when a worker is responsible for producing a large amount of high quality services. Multitask principal-agent situations are similar to incomplete contracting situations in that the principal may not be able to monitor either the agent’s behavior or the outcome. The authors argued that incentive schemes only serve to focus the agent’s attention on one dimension of its tasks. For example, if it was paid an incentive for volume of work completed, the agent would tend to ignore quality.

Holmstrom and Milgrom (1991) pointed out that the principal could use job design to avoid such conflicts. In other words, the principal should try to separate each dimension into different tasks to be completed by multiple agents. In this way, each task could be made one-dimensional and either outcome- or behavior-based contracts could be used successfully. When this is not possible, the authors argue that
the decision to use incentives for one dimension of an agent’s task must be based on the principal’s ability to monitor the other dimensions of the agent’s task.

2.1.3 Organizational Structure/Delivery Mechanisms in Construction

Owners have traditionally turned to the design-bid-build (DBB) project delivery system. This delivery approach involves the selection of designers based on their perceived design competence. The designers often include an architect, structural engineer, mechanical engineer, electrical engineer, and specialty system designers (e.g., security and communications). The designers complete their work and return it to the owner in the form of plans and specifications. The owner then solicits bids from general contractors based on these documents and typically hires the lowest bidder to a lump sum contract. The general contractor then hires subcontractors to complete specialty work. During the construction phase, the architect acts as the owner’s agent. Thus, the owner deals with the incomplete contract situation in two ways. One, there is the outcome-based contract with the general contractor. Second, the owner uses the architect to monitor the contractors’ actions and report to it any irregularity or nonconformance. Likewise, the general contractor is expected to report any errors or omissions by the architect to the owner. Thus, the contractor and the architect are pitted against one another to protect the owner’s interests.

This delivery system is successful in some cases. However, it can lead to problems because at times, it can be so adversarial that it eliminates the opportunity for cooperation among the project participants. Other delivery mechanisms have been adopted to address these shortcomings. These include design/build, construction management and design/build/operate/transfer (See Appendix B for an explanation of these delivery systems).

This study is very pertinent to the construction industry. Commercial construction projects are multidimensional at two levels. One, there are many tasks to complete; for instance, there is excavation, plumbing installation, and concrete pouring, to name a few. In addition, each of these tasks has multiple dimensions. For example, the concrete subcontractor must not only pour the concrete; it must do quality work so that the structure has the strength and durability that the owner desires.

In the traditional DBB delivery system, owners separate design tasks among several agents. However, as discussed above, they hire a single agent, the general contractor, to complete the many tasks involved in the construction phase because the owners typically do not have the expertise or staff to coordinate the work of many separate subcontractors. Even if they did contract with each subcontractor directly, the owner would not be able to separate each task into single dimensions; that is, the act of
pouring concrete is inseparable from the maintenance of quality in concrete construction. Thus, owners typically hire outside firms to do quality assurance during the construction phase.

Eisenhardt (1989) gave several recommendations for the application of principal-agent theory that support its use in the context of the construction industry. One suggestion was to use it in cases in which there are contracting problems, that is, there is goal conflict between principals and agents, outcome uncertainty is great, or there exist unprogrammed or team-oriented behaviors that are difficult for the principal to monitor and evaluate. All three of these problems exist in the construction industry. Goal conflict arises due to the individual profit motives of the principals and agents. In addition, outcome uncertainty is high in construction, due to the unpredictable fluctuations in material and labor costs and their availability, the influence of labor unions, the weather and other environmental factors, and the complexity of the facility. In addition, since each construction project is unique and a large team of agents is used to complete them, it would be impossible to program all of their tasks.

2.2 Mechanisms of inter-firm collaboration

Several researchers have tried to identify mechanisms of inter-firm collaboration using a variety of methods, such as interviews, surveys and case studies. The concept behind this research is to identify individual factors that promote cooperation among disparate agents in situations that would otherwise be non-cooperative. Although most of the inter-firm research has involved studies of specific industries other than construction, it is still relevant to this research. Also, a major difference from this body of research and this research is that none of the authors have addressed inter-firm collaboration in the case of innovation in particular.

Pinto et al. (1993) conducted a study involving a three stage model of projects, consisting of antecedent factors, the implementation stage and project outcomes. They investigated the roles of four antecedent factors, including superordinate goals, accessibility, physical proximity, and formalized rules and procedures. Superordinate goals were defined as “goals that are urgent and compelling for all groups involved but whose attainment requires the resources and efforts of more than one group.” The second factor refers to the accessibility of the project team members to one another. The third factor is similar, but specifically refers to the actual physical distance between project team members. The researchers broke the fourth factor into rules and procedures at the organizational and project levels. These factors were chosen partially because they are under the control of the project team. In addition, the latter three factors were viewed as proxies for organizational factors that are related to interactions with others.

The researchers looked at two types of project outcomes, including measurable task outcomes and psychosocial outcomes. The former refers to traditional project success measures, such as achievement of
performance goals or project schedules. The latter refers to how project participants feel about the project and other team members after the project. By looking at these outcomes, the researchers were able to assess the relative importance of the four antecedent factors in fostering project team cross-functional cooperation.

The researchers studied projects from a sample of hospitals in three states. The projects were intra-firm, but are relevant to the current study because they did involve teams consisting of persons from several functional areas. They found that superordinate goals can greatly enhance cooperation across disciplines; they can reduce conflict among project team members and inspire them to cooperate. In addition, they were also found to improve task outcomes.

The researchers also found that project-level rules and procedures helped foster cooperation in cases in which project team members were allowed some autonomy to conduct the project without the constraints of organizational rules and procedures. They noted that these rules and procedures are especially important on innovative projects or projects with very complex organizational structures. Thus, the authors argued that projects should be considered on an individual basis to make sure that the rules governing them facilitate cooperation. The concept is that rules and procedures can be used to link disparate specialized agents within the project.

The researchers found a somewhat weaker relationship between physical proximity and cooperation. Finally, they found little evidence for the importance of accessibility in fostering cooperation.

Another study looked at the cultural effects of individualism and collectivism on the achievement of cooperation on projects (Chen et al. 1998). The goal of this research was to develop a culturally-contingent model of cooperation by bringing together research from the social sciences and organizational behavior. It attempted to draw links between culture and cooperation and to show its implications for organizational behavior. The researchers addressed the following cooperation mechanisms:

- Superordinate goals
- Group identity
- Trust
- Accountability
- Communication
- Reward structure and incentives

This research was based on the inherent differences between individualists and collectivists. They represent essentially opposite ends of the cooperation spectrum; the former tend to be competitive, while the latter are more cooperative by nature. Chen explains the relationships between each cultural form and the six mechanisms. Although the current research does not specifically address cultural issues,
Chen’s work is relevant because it provides an in-depth discussion of the two extreme situations. In this way, it provides a starting point from which to understand cooperation on projects.

A study of integration in construction projects also addressed mechanisms of cooperation (Nam and Tatum 1992). The researchers were concerned with the disintegration inherent in construction; the design and construction functions are contractually and organizationally separated. The authors investigated ten construction innovations and found four non-contractual mechanisms of cooperation, including the following:

- Owner’s leadership
- Long-term relationships
- Integration champions
- Professionalism

It is important to point out that this research focused on non-contractual mechanisms, meaning informal means of attaining integration. For example, they did not address the role of new delivery systems, such as design/build, that formally achieve integration on construction projects.

The definition of owner’s leadership, as used in Nam and Tatum’s research, is similar to the superordinate goals referred to by Pinto (1993) and Chen (1998). In addition, long-term relationships are similar to trust, as cited by Chen. Nam and Tatum found that all four of the mechanisms listed above were effective at integrating construction projects and creating a cooperative project environment.

Another study attempted to find what were referred to as success factors for collaborative product development (Bruce et al. 1995). It contained an investigation of the information and communication technology (ICT) sectors in the UK. The approach of this research was to send questionnaires to suppliers of ICT products to study their experiences in collaborative product development ventures. One of the questions concerned what the suppliers felt were the determinants of successful collaborations. Success was found to be related to the even distribution of benefits among the project team members. In addition, a high level of inter-firm interaction was cited by many respondents. Mutual trust among participants was also found to be important.

A study of seven collaborative projects in the semiconductor industry addressed managerial approaches (Chiesa and Manzini 1998). The authors found several failure factors for collaboration. Some of these factors are similar to the mechanisms discussed above, such as lack of trust among partners, lack of communication, and lack of project rules. These failure factors can be interpreted as the opposite of cooperation mechanisms.
A survey of manufacturers in the information technology industry in the United Kingdom also showed that people view trust as an important element in collaborative business relationships (Littler et al. 1998).

Studies of game theory and the Prisoner’s Dilemma have also theorized and empirically shown that project team members are more likely to cooperate if they have mutual trust developed through a long working relationship (Axelrod 1984). The concept is that when two parties have a long-term relationship, they can anticipate how the other will react in subsequent situations. Thus, if one party thinks that the other will not be selfish, then they will be more likely to cooperate with them.

One study looked at formal and informal means of communication in cross-functional cooperation in hospital program development projects (Pinto and Pinto 1990). The study consisted of surveys of 72 project teams and found that teams with higher levels of cooperation had more cases of informal communication and were more successful overall. The study also noted that the nature of the project itself can dictate how important project team communication is. The need for communication among agents may also be imposed by the principal’s organization of the project. For example, it is unlikely that the agents’ tasks are all unrelated; inevitably, there a number of tasks will be linked and these links will have to be considered by these agents.

2.3 Inter-firm Collaboration for Innovation

In recent years, several researchers have recognized a trend in industry toward inter-firm collaboration for innovation. Firms have turned to collaboration to develop new products in order to leverage their resources and reduce their risk exposure. The latter point is especially relevant given the heightened uncertainty of innovative projects. Companies in a variety of industries have begun to collaborate with others during every stage of the product development process, from research and development to distribution (Powell et al. 1996). Inter-firm development has been especially prevalent in the case of projects that require inputs from a variety of technical disciplines. By creating what can be referred to as a virtual organization, firms are able to reap the benefits of the innovation without exposing themselves to the difficulties of vertical integration. These virtual organizations are often assembled temporarily for a particular project and they typically involve the combined efforts of several organizations that are functionally and geographically separate. Thus, the problems inherent in vertical integration are replaced with the difficulties involved in facilitating collaboration among these firms and in sharing information, risk, costs and benefits over organizational boundaries.

Millar et al. (1997) noticed this trend in industry and attempted to develop a framework that other researchers could use to study it. Their definition is very comprehensive and is as follows:
“Trans-organizational innovation involves generating new knowledge out of knowledge inputs which are distributed across disciplines and organizations which may be geographically dispersed.”

Their framework focuses on the links between the core concepts of products, the context in which they are conceived, and the management of the project.

Chiesa and Manzini (1998) attempted to use an empirical study of inter-firm collaborations in the technology sector to elicit effective practices for the management of such relationships. They surveyed people with experience in such projects, and found the most commonly cited failure factors, which included the lack of communication, leadership, and alliance rules. Then they developed a set of guidelines for the management of inter-firm collaborations.

Chesbrough and Teece (1996) attempted to rationalize the decision-making process used by companies who are deciding how to organize for innovative product development. They felt that too many people had touted virtual organizations as the best alternative. The authors pointed out that the project organization should be tailored to meet the specific characteristics of the product being developed and the capabilities of the involved firms. The main variables to consider are the type of innovation and whether the capabilities needed to develop it exist outside the firm or must be created. In addition, the authors point out that a company often has little ability to coordinate the activities of its partners in a virtual organization, and that it is more difficult to fairly distribute the costs and benefits of the project in a virtual organization. This is complicated by the fact that the firms involved are likely to act out of self-interest; they will attempt to get the most benefit at the expense of the others. Thus, in a virtual organization, one sacrifices a degree of control while reaping the benefits of flexibility.

Bidault et al. (1998) examined cooperation among buyers and suppliers for product innovation. Their focus was on the practice of Early Supplier Involvement, in which companies involve their suppliers early in the innovation development process. Using this practice, Japanese automobile manufacturers have developed strong bonds with their suppliers, and thus they have benefited from the expertise of the suppliers. This early association is in direct contrast with the buyer-supplier relationship in the US, which is typically competitively driven, such as by emphasis on low cost production.

A study of hospitals by Goes and Park (1997) showed that cooperative relationships among separate peer firms enhances innovative processes in organizations. They found that, through various types of interorganizational links, firms mutually benefited from each other’s knowledge and resources and were more likely to develop and adopt innovative services and technologies in the network of their peers.
Powell et al. (1996) argue that “when the knowledge base of an industry is both complex and expanding and the sources of expertise are widely dispersed, the locus of innovation will be found in networks of learning, rather than in individual firms.” This is because a single firm in such an industry would be unable to compete due to the high level of risk, and the varied and extensive knowledge required. Specifically, the researchers looked at the biotechnology industry and found that firms developed innovations by creating links with other firms in the value chain (e.g. peers and suppliers) to form a network.

Smith et al. (1991) studied research collaborations between small and large firms in the UK electronics sector. Through case studies, the authors found the common motives and problems of firms involved in such relationships. The researchers found that corporate cultures often conflict in collaborative arrangements because the cultures of some corporations have ingrained attitudes against collaboration, especially with smaller firms.

2.4 Innovation in Construction

2.4.1 Classification of Innovations

For the purposes of this research, innovation is defined as any non-trivial improvement or change to a product, process, or system that is actually implemented and that is novel to the company that develops or uses it.

Researchers have attempted to classify innovations by type based upon how they differ from the state of the art (Henderson and Clark 1990). Figure 2.1 shows a framework for classifying innovations. An incremental innovation entails a small change or improvement to a component while reinforcing the core concepts of a system and leaving the links between the concepts and components unchanged. Incremental innovations can be developed and implemented using currently available knowledge and experience. Due to these characteristics, the impacts of incremental innovations are predictable and very limited (Slaughter 1998). An example would be the use of a new crane with greater load capacity to lift construction elements.
A modular innovation involves a significant change to a single core concept of a component that does not change the linkages between the concepts and components of a system. Thus, it is possible for a specialized firm to develop a modular innovation in-house without the help of other specialties (Slaughter 1998). Likewise, the implementation of a modular innovation requires little coordination with the parties that are responsible for the other components of the system. An example of this type of innovation in construction is the dogbone, which is a steel beam that is specially shaped to dissipate seismic energy (Iwankiw and Carter 1996). The connection design and beam cross-section of the dogbone are major conceptual shifts from conventional steel frame design.

An architectural innovation is a small change to a single component that also changes the linkages between the concepts and components of the system (Henderson and Clark 1990). Such innovations require coordination with the parties responsible for the other components so that the components can work together with the innovation. An example of this type of innovation in the construction industry is the top/down construction method for the construction of buildings with multiple basement levels. In this method, the first step is to drive the piles that support the superstructure into the ground. Then, the superstructure is erected as the basement is excavated and the basement level floors are constructed. Thus, construction proceeds up and down simultaneously (Becker 1986). In the conventional method, the basement and superstructure would be constructed sequentially.

A radical innovation changes the core concepts and the linkages between the concepts and components of a system. Thus, radical innovations have the implications of both modular and architectural innovations. A recent example of a radical innovation in construction is the application of fiber reinforced plastics as structural members. These materials have been used in several short-span bridges and constitute a significant change from conventional steel and concrete construction. One, their
structural properties are different, which means that designers must use different analysis and design methods than they would with steel or concrete members. In addition, there are several changes in terms of their construction. The most apparent is that the plastic members are much lighter than conventional members, meaning that they can be constructed more safely and with simpler equipment. Perhaps the biggest change is that the plastic members cannot be joined using conventional methods. New connection methods had to be developed specifically for these materials.

However, the model shown above and others like it were typically developed from the perspective of manufacturing innovations. Slaughter (1998) adapted these definitions to the specific case of the construction industry, pointing out the essential differences between manufacturing and construction. Slaughter also added a fifth classification, system innovation. This refers to innovations that involve the “integration of multiple independent innovations which must work together to perform new functions” or improve the facility’s overall performance. An example from the construction industry is the SMART System for Automated Building Assembly. It is a self-elevating assembly factory for high-rise building construction that employs technical and logistical innovations. The structural components are specially designed and configured to allow for this construction method. Automated welding robots are used to make the steel frame connections (NOVA literature 1994).

Classifying innovations in this way is helpful to this research because it provides a way to elicit the relationships of innovations to inter-firm collaboration and the competencies of firms. It also enables one to compare seemingly disparate innovations based on their implications for inter-firm collaboration.

2.4.2 Who Innovates

Several studies have shown which firms innovate in construction and what types of innovations they generate. Many expect that innovation in construction can be spurred by government and industry investment in research and development. In fact, Japanese construction firms have been able to develop many significant innovations through their in-house research and development efforts. In Japan, construction firms invest much more than their American counterparts (Kangari and Miyatake 1997). To fill this gap, the US government, through organizations such as the National Institute of Standards and Technology and the National Science Foundation, has attempted to develop innovations for the construction industry. However, Slaughter (1993) found that many innovations in the residential construction industry were developed in the field, rather than by manufacturers or research laboratories, as some would expect. In addition, other researchers have found similar results for other segments of the construction industry (Johnson and Tatum 1993).
This is particularly relevant to this study because it focuses on innovations associated with the structural system of buildings. Researchers into the sources of construction innovation have until now concentrated on identifying single companies as sources of innovations. This study, however, will show that innovation development in construction is often not so clear cut; it often comes about through inter-firm cooperation. This is especially true of structural innovations for two reasons. One, they often require varied areas of expertise. In addition, because they typically affect other components of the building, the company implementing the innovation must negotiate with the other project team members to make the innovation compatible.

2.4.3 Implementation and Diffusion of Innovations

In studying the implementation and diffusion of innovations, one important issue is what capabilities are necessary to use the innovation. As explained above in Section 2.4.1, the characteristics of the innovation can determine the answer to this question. For example, the implementation of a radical innovation may require a set of skills that cannot be found within a single firm. Thus, this issue has important impacts on the ease with which an innovation can diffuse to different firms. In addition, it affects a firm's make or buy decision process. This issue was addressed by Cross (1983), who investigated the importance of the role of skilled labor in the diffusion of innovations.
3. THEORETICAL FRAMEWORK

This chapter contains the theoretical framework for this research. It is organized along the lines of the three theory areas just described in Chapter 2. A set of variables and corresponding measures has been assembled with which to test these theories in the context of the construction industry.

Developing this framework has been perhaps the most challenging aspect of this research. The first step was to come up with a list of project variables related to each theory area. The next step was to find ways to measure the states of these variables for the case studies. The goal was to assemble a framework that would allow us to conduct a comparable analysis of each case study in order to come up with conclusions regarding the factors that influence inter-firm collaboration on innovative construction projects. The following subsections address each of the variables studied and explain how those variables were measured.

3.1. Theory Area #1: Principal Agent and Team Theory

3.1.1. Variable #1: Distribution of benefits, costs and risks

The first variable addressed in the framework is the distribution of benefits, costs and risks among the project team members. Three measures are used to study this variable, including contractual relationships and organizational structure, delivery mechanism, and transaction cost. For the first measure, the contractual relationships of the project team members, data regarding contractual forms were developed for each project. To study this measure, information was obtained not only for the contract between the project owner and its contractor, but also for the parties directly involved in the implementation of the innovations. This was important because, in many of the case studies, subcontractors either introduced or directly implemented the innovations. Thus, information on owner/contractor contracts would have been insufficient. A contract is the formal mechanism for allocating costs, benefits and risk on a construction project. It spells out in clear language exactly what tasks each party is required to perform and how they will be compensated. The common contract types used in construction were discussed in Chapter 2, and are lump sum (competitive and negotiated award), guaranteed maximum price, and cost plus fee.

Another measure of this variable is the delivery system. Again, this analysis was conducted at both the project level and the innovation level. The project delivery system describes the owner’s method for procuring its facility. However, for several of the case studies, this was insufficient to describe exactly how the innovations were delivered. Thus, the innovation delivery system was also studied. This describes how the design and construction of the innovation itself took place. Organizations charts were
put together for each project to depict the formal relationships between the project team members. A sample organization chart for a project using the design-bid-build delivery system is shown below (Figure 3.1).

![Organization chart for design-bid-build](image)

Figure 3.1 - Organization chart for design-bid-build

The third measure of this variable is transaction cost. Only those transaction costs specifically related to the innovations were studied. Two types of transaction costs were considered. The first is information cost, which refers to the cost of the transfer of information between parties. For example, there is a cost associated with the transfer of shop drawings between the structural steel fabricator and the structural designer. The second is the cost of physical assets, such as special equipment or tools developed specifically for the implementation of an innovation. Changes in these transaction costs in the case of reuse were also considered. For example, if two firms are involved in the re-use of an innovation, they may invest in information systems to lower their transaction costs. In this way, they may actually be able to increase their net benefits.

Overall, our goal with this set of data was to see if there is a relationship between the formal distribution of costs, benefits and risks and inter-firm collaboration on innovative construction projects.

**Summary of measures:**

- Contract relationships
- Delivery Mechanisms
- Transaction costs
3.2. Theory Area #2: Mechanisms of Inter-firm Collaboration

3.2.1. Variable #1: Project Value Chain

This variable shows how information and value-added activities contribute to projects. The first measure of this variable is the value chain as it changes during the project and in reuse. Diagrams of the value chain were developed for each project. They are similar to the organization charts discussed above, but they provide more information because they show links between all firms that exchange information or services, not just formal contractual links among major parties. The value chain is a powerful tool because it can show informal relationships within the project team as well. Analysis of the changes in the project value chains also shows which party holds decision-making power at different stages of a project. For example, for a design-bid-build project, the value chain includes only the owner and its designers during the design phase. Contractors and subcontractors do not enter the picture until after the bidding phase. The changes in the value chains in reuse show which parties repeat and which do not. This analysis of change allows one to question the role of each firm in the implementation of the innovations.

Another measure used is the project timeline. This shows the general sequence of events in the development and implementation of an innovation. An important part of this measure is that it shows at which stage of the project a commitment was made to use the innovation.

The intent is to use the timelines and value chain information to show the dynamics of the composition of the project team. This set of data is useful because it shows how and when the parties involved were able to communicate with each other. This data also shows which party holds decision-making power during the project. The timing of commitment is important because it can limit the amount of time available to the project team to collaborate on the implementation of the innovation.

For example, in the case of a DBB project, the contractor does not enter the picture until the construction stage. This may be important if the innovation to be used on that project affects his work. In such a situation, the contractor may find the innovation difficult because it had no input in the development and design of the innovation. Alternatively, in a DB project, the designer and contractor are partners, and it would be in their collective interest to collaborate on the implementation of the innovation. In such a case, it is likely that the DB entity would be able to work out any coordination problems in the earliest stages of the project, a situation that would be impossible with DBB. Thus, the source of the innovation must also be considered in the analysis of these measures.

Thus, the goal with this set of data was to see if there is a link between the nature of and opportunities for informal communication and inter-firm collaboration on innovative construction projects.
Summary of measures:

- Value chain changes
- Timeline of events

3.2.2. Variable #2: Bond

The next variable in the framework is the bond between project team members. The measures of this variable include the reputation of the firms, the level of trust among firms and the length of the relationship between firms. Interviews with project participants were used to obtain a qualitative measure of bond. The factors explored were previous work with the other project team members and the nature of their previous business relationship. For example, some firms had worked together on previous projects, but had not developed much of a trusting relationship because they had always worked at arm’s length, without much direct contact. On the other hand, some firms responded that they had a developed trust for another firm through their business relationship. The reputation of a firm is also directly related to this issue. For example, a firm may be more likely to trust another firm if the second firm has a strong reputation of skill and excellent work. With this data, we hoped to gain an understanding of the bond between the project team members and to see whether this promotes inter-firm cooperation.

Summary of measures:

- Trust
- Length of relationship
- Reputation

3.2.3. Variable #3: Team Protocol

Qualitative data of the measures of this variable was gathered through interviews with project participants. One measure of this variable is the role of the lead firm. Typically, owners are not very sophisticated in terms of construction. Thus, they tend to use one member of the project team as their main agent. In design-bid-build, the architect assumes this role. They not only provide design services, but they also serve as the intermediary between the owner and the other design consultants and the general contractor. For example, the architect is in charge of approving payment requisitions from the general contractor. In other cases, the owner may hire a representative or an agency construction manager to buttress its construction expertise. Whoever this party is, they have credibility in the owner’s eyes,
thus the owner will follow its recommendations. This party typically plays a key role in approving innovations introduced by other project team members.

Another measure of this variable is a comparison of firm rules versus team rules, as studied by Pinto et. al. (1993). This analysis elicits important information regarding the behavior of individual employees of different firms when they are working together as a team on a project.

Summary of Measures:
- Role of lead firm
- Firm versus project team rules

3.2.4. **Variable #4: Objectives**

This variable was discussed in the previous chapter and has been studied by several researchers (Pinto et. al. 1993, Chen et. al. 1998, Nam & Tatum 1992). The measure of this variable is the superordinate goals of a project, meaning the owner’s principle objective for the project that directs the work of the project team. The project superordinate goals are also compared to the expected benefits from the innovation.

Summary of Measures:
- Superordinate goals

3.1. **Theory Area #3: Inter-firm Innovation**

3.3.1. **Variable #1: Nature of the Innovation**

To measure the nature of the innovation, the innovations were classified according to the models discussed in Chapter 2 (Slaughter 1998; Henderson & Clark 1990; Afuah & Bahram 1995). The innovations were analyzed to ascertain how they differed from standard practice in terms of concepts and relationships among components. This analysis was conducted from the perspective of each member of the project team, including suppliers, subcontractors, general contractors, designers and owners. A focus of this analysis was to identify the project team members most affected by the use of the innovation and consequently, the firms most likely to coordinate their work. In addition, this analysis identified the necessary competencies to develop and implement the innovation, which also provided information on the types of firms needed to collaborate on the innovation’s development.
The strategies of the firms with respect to the innovation were also analyzed. More specifically, firms’ attitudes with respect to flexibility and change in the development of the innovations were studied. The firms involved in developing the innovations were divided into two categories: construction industry firms (contractors, designers and such) and manufacturers. The latter refers to companies that mass-produce standardized products. These two types of firms are inherently different in their approach toward product development. The hypothesis is that construction firms develop innovations that are more easily adaptable to different situations while manufacturers will not be as proactive in developing products that are as flexible. In general, construction firms are used to developing products on a one-off basis and they expect to make variations to their products in order to make them work on different projects.

For example, a contractor may come up with an innovative formwork system for concrete placement, but they will design the system so that it is flexible enough to work in different situations. The contractor will do this because it knows that every construction project is different and therefore a standardized product will not work in all cases. On the other hand, most manufacturers are not used to this situation, so they tend to produce standardized products with little inherent flexibility. Thus, by categorizing the firms involved in the case studies, it can be shown how this difference between industries can affect the level of inter-firm cooperation achieved. Again, the source of the innovation must also be considered in the analysis of these measures. It is very useful in understanding the role of core competencies and strategies in innovation development and implementation.

**Summary of measures:**

- Classification of innovation from different perspectives
- Core competencies and strategies

### 3.3.2. Variable #2: Appropriation of Innovation Benefits

To measure this variable, the internal and external distribution of the benefits from the innovation were considered. This issue is related the research conducted by Chesbrough and Teece (1996) into the relationship between organizational form and innovation development and use. Thus, the measures of this variable are directly related to the delivery mechanism. For example, on some projects, a single firm performed the design and construction of the innovative system, thereby internalizing the benefits of the innovation.

**Summary of measures:**

- Internal versus external distribution of innovation benefits
3.3.3. Variable #3: Sharing of Competencies

The final variable addressed through this framework is sharing between firms, as discussed in Chapter 2 (Goes and Park 1997, Lynn et. al. 1997, Millar et. al. 1997, Powell et. al. 1996). To measure this variable, sharing was studied at two levels, among peers and along the value chain. Qualitative data concerning this measure was collected through interviews with project participants. The goal is to understand the direction of inter-firm cooperation for innovation in construction. The question is whether or not firms cooperate with firms at other levels of the value chain in developing and implementing innovations.

Summary of measures:

- Sharing among peers
- Sharing along the value chain
4. METHODOLOGY

The purpose of this research is to determine the effects of various factors on inter-firm collaboration in the development and implementation of innovations in the construction industry. It involves an extensive review of the literature concerning relevant theory areas in management science. These theories are tested through an empirical study of innovations in construction.

4.1. Literature Review

One aspect of this research was to review the relevant literature regarding aspects of management science, such as innovation, product development, principle-agent theory, inter-firm collaboration, and inter-firm innovation. These strands of theory are discussed in Chapter 2. Simultaneously, in order to find innovations to study, an extensive review was made of engineering and construction trade journals (Table 4.1).

| American Concrete Institute Structural Journal |
| American Society of Civil Engineers Conference Proceedings |
| ASCE Journal of Construction Engineering and Management |
| Civil Engineering |
| Civil Engineering Research Foundation Literature |
| Engineering News-Record |
| Modern Steel Construction |
| Prestressed Concrete Institute Journal |
| Tunneling and Underground Space Technology |

Table 4.1 - Engineering and construction periodicals

Additional data for this research was obtained through personal site visits to construction projects in the Boston metropolitan area (Table 4.2). The intent of these visits was to provide a first-hand look at standard practices in the construction industry, as well as implementations of innovations.
<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>Type</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logan Airport West Garage</td>
<td>Boston, MA</td>
<td>New parking structure</td>
<td>3100 spaces</td>
</tr>
<tr>
<td>Tufts Health Plan Garage</td>
<td>Watertown, MA</td>
<td>New parking structure</td>
<td>1400 spaces</td>
</tr>
<tr>
<td>Logan Airport Hilton</td>
<td>Boston, MA</td>
<td>New hotel</td>
<td>410,000 square feet</td>
</tr>
<tr>
<td>Seaport Hotel</td>
<td>Boston, MA</td>
<td>New hotel</td>
<td>18 floors</td>
</tr>
<tr>
<td>Marriott Residences</td>
<td>Cambridge, MA</td>
<td>New extended-stay hotel</td>
<td>300,000 square feet</td>
</tr>
<tr>
<td>Maxwell Dworkin Building</td>
<td>Cambridge, MA</td>
<td>New classroom and laboratory facility</td>
<td>100,000 square feet</td>
</tr>
<tr>
<td>Harvard Business School Executive Education Building</td>
<td>Boston, MA</td>
<td>New extended-stay residence</td>
<td>95,000 square feet</td>
</tr>
<tr>
<td>Eight Cambridge Center</td>
<td>Cambridge, MA</td>
<td>New office building</td>
<td>8 floors</td>
</tr>
<tr>
<td>Polaroid Building</td>
<td>Cambridge, MA</td>
<td>Office building renovation</td>
<td>45,000 square feet</td>
</tr>
<tr>
<td>University Park</td>
<td>Cambridge, MA</td>
<td>New complex of office buildings, parking structures and a hotel</td>
<td>Six buildings</td>
</tr>
</tbody>
</table>

Table 4.2 - Construction projects visited

4.2. Innovation Data Sample

The site visits and the review of the engineering and construction trade journals generated a heterogeneous set of innovations. Innovations for all building systems (i.e. structural, exterior enclosure, services (mechanical, electrical, and plumbing), and interior finish), types of construction (buildings, roads, etc.), project sizes, and geographic locations were included in the original sample. To obtain a more homogenous set of case studies, a selection mechanism was developed to increase the comparability of the cases and reduce the variance from multiple different project attributes.

The steps in the case study selection process were as follows:

1. Construction projects using innovations of any sort were considered.

2. These projects were limited by type to commercial construction, which includes apartment buildings, educational facilities, hotels, parking structures, and arenas. This excludes residential construction, infrastructure work and heavy civil construction. This decision was made for two reasons. First, it was the author’s main area of interest and expertise. Second, throughout the course of this study, this segment of the construction market was very active.
in the Boston metropolitan area, which enabled the author to make many site visits to learn
first-hand about construction practices.

3. Innovations were then limited to changes affecting the structural system, which includes
substructure (foundation) and superstructure. This decision to focus on structural system
innovations eliminated innovations in other building systems, such as plumbing, fire
protection and HVAC systems and other non-structural components. Also excluded were
construction management innovations, such as the use of information technology to transfer
information on projects. This decision was made for two reasons. First, the author had
experience in structural design of buildings, which made it easier to understand the
engineering and construction implications of the innovations. Second, it was expected that
structural system innovations would likely affect other building components.

4. All projects that were completed more than five years ago (pre-1993) were discarded. It was
anticipated that project participants would not be able to recall these projects with enough
detail to provide verifiable, reliable, and accurate data for detailed case studies.

5. The final step was to eliminate those innovations that do not change the links to other
components or subsystems, since it was anticipated that such innovations would not
contribute much to the exploration of inter-firm collaboration.

Case studies were subsequently developed for ten of the remaining innovations. Those
innovations that met the first three selection criteria were retained to serve as a larger sample to compare
to the smaller sample of in-depth case studies. The projects in the larger sample were not studied in as
much detail as the ten case studies were. The data from the larger sample act as a validation mechanism
for the results of the case studies.

Figure 4.1 depicts the methodology for the case studies. The unit of analysis is the innovation
itself as implemented in each project. The intent is to study how the collaboration variables change from
project to project, and how this affects inter-firm collaboration. These variables are discussed in Chapter
3 and include formal organizational factors, such as contracts and delivery systems, as well as informal
factors, such as bond, objectives, and team dynamics.
4.3. Validation of Data

As mentioned above, the case studies were developed through personal interviews with multiple project participants. Table 4.3 contains the names and affiliations of each person interviewed for this research. A review of the table shows that there is a good distribution of firm types, including designers, general contractors and subcontractors. This variety of sources made the case study data more complete and provided a check on the responses of each participant. On the other hand, if only one participant on a project was interviewed, its response would be questionable. By interviewing a project team member from another firm, one is able to validate the information given by the first person.

One might argue that interviews do not provide an accurate portrayal of projects and that the data is not useful because it does not lead to quantitative results. However, the goal of this research was not to develop a complete model of the factors that influence collaboration on innovative construction projects. This subject is simply too new; the objective is to begin the development of theories in this area of study.

In construction, the innovation development and implementation process is complex and dynamic. Thus, a relatively small sample of detailed case studies is appropriate because it allows one to investigate the multitude of variables that effect the collaboration process. This approach is particularly effective because, since this subject is so new, the variables are as yet undefined.

In any empirical study, one must pay particular attention to the representativeness of the data sample. From that perspective, the findings of this study may not apply to innovations in other building systems. This is because the structural system has some characteristics that make it much different than other systems. For example, there are important safety and health issues that must be considered when implementing structural innovations. These issues are of less concern in other systems, such as the mechanical system.
The representativeness of this sample with respect to structural innovations is helped by the fact that the projects studied involve several types of construction, including steel frame, cast-in-place concrete, and precast concrete. In addition, the projects are located in many areas, which minimizes the effect of location-specific factors.

With respect to other industries, the representativeness of this study is limited to industries in which the development of complex products is conducted through the combined effort of several specialized firms.
<table>
<thead>
<tr>
<th>Contact Name</th>
<th>Company</th>
<th>Location</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>David Lenie, Proj. Mgr.</td>
<td>TAMS Engineers</td>
<td>Boston, MA</td>
<td>Architect/Engineer</td>
</tr>
<tr>
<td>George Jenkins, superintendent</td>
<td>Tishman Construction</td>
<td>Boston, MA</td>
<td>Construction Manager</td>
</tr>
<tr>
<td>Joel Chase, Proj. Mgr.</td>
<td>Tishman Construction</td>
<td>Boston, MA</td>
<td>Construction Manager</td>
</tr>
<tr>
<td>Paul Tuttobenne</td>
<td>Taylor Devices</td>
<td>N. Tonawanda, NY</td>
<td>Damper supplier</td>
</tr>
<tr>
<td>Dave Nilson, VP</td>
<td>Kennedy &amp; Rossi</td>
<td>Lexington, MA</td>
<td>General contractor</td>
</tr>
<tr>
<td>Donald Fligg, superintendent</td>
<td>Kennedy &amp; Rossi</td>
<td>Lexington, MA</td>
<td>General contractor</td>
</tr>
<tr>
<td>Anthony Fidanos, superintendent</td>
<td>Morse Diesel</td>
<td>Boston, MA</td>
<td>General contractor</td>
</tr>
<tr>
<td>Charles Favazzo, superintendent</td>
<td>Morse Diesel</td>
<td>Boston, MA</td>
<td>General contractor</td>
</tr>
<tr>
<td>James Heighton, Proj. Mgr.</td>
<td>Morse Diesel</td>
<td>Boston, MA</td>
<td>General contractor</td>
</tr>
<tr>
<td>Maury Curran, Proj. Mgr.</td>
<td>VRH Construction</td>
<td>New York, NY</td>
<td>General contractor</td>
</tr>
<tr>
<td>Dave Seagren, Chief Engineer</td>
<td>Charles Pankow Builders</td>
<td>Altadena, CA</td>
<td>General contractor</td>
</tr>
<tr>
<td>William Mullin</td>
<td>Huber Hunt &amp; Nichols</td>
<td>Indianapolis, IN</td>
<td>General contractor</td>
</tr>
<tr>
<td>David Downey, Proj. Mgr.</td>
<td>Earl Construction</td>
<td>Sacramento, CA</td>
<td>General contractor</td>
</tr>
<tr>
<td>Dave Page, Proj. Mgr.</td>
<td>Turner Construction</td>
<td>Boston, MA</td>
<td>General contractor</td>
</tr>
<tr>
<td>Mike Egan, Proj. Mgr.</td>
<td>Massachusetts Bay Transportation Authority</td>
<td>Boston, MA</td>
<td>Owner</td>
</tr>
<tr>
<td>Gordon Collins</td>
<td>Rubb Building Systems</td>
<td>Sanford, ME</td>
<td>Roof subcontractor</td>
</tr>
<tr>
<td>Wesley Terry</td>
<td>Birdair, Inc.</td>
<td>Amherst, NY</td>
<td>Roof subcontractor</td>
</tr>
<tr>
<td>Alan Shalders, Chief Engineer</td>
<td>Universal Builders Supply</td>
<td>Mt. Vernon, NY</td>
<td>Scaffolding subcontractor</td>
</tr>
<tr>
<td>Robert Abramson, Pres.</td>
<td>Interstate Iron Works</td>
<td>Whitehouse, NJ</td>
<td>Steel subcontractor</td>
</tr>
<tr>
<td>John Mayo, Pres.</td>
<td>JD2 Steel</td>
<td>Auburn, CA</td>
<td>Steel subcontractor</td>
</tr>
<tr>
<td>Ahmad Rahimian, VP</td>
<td>Cantor Seinuk Group</td>
<td>New York, NY</td>
<td>Structural designer</td>
</tr>
<tr>
<td>Enrique Martinez Romero, Pres.</td>
<td>EMR Engineers</td>
<td>Mexico City, Mexico</td>
<td>Structural designer</td>
</tr>
<tr>
<td>Michael Jollife, Pres.</td>
<td>Zaldastani Associates</td>
<td>Boston, MA</td>
<td>Structural designer</td>
</tr>
<tr>
<td>Suresh Babu</td>
<td>Weidlinger Associates</td>
<td>Cambridge, MA</td>
<td>Structural designer</td>
</tr>
<tr>
<td>Mohammed Hidar</td>
<td>Weidlinger Associates</td>
<td>Cambridge, MA</td>
<td>Structural designer</td>
</tr>
<tr>
<td>Minhaj Kirmani, VP</td>
<td>Weidlinger Associates</td>
<td>Cambridge, MA</td>
<td>Structural designer</td>
</tr>
<tr>
<td>Gary Cook, Proj. Mgr.</td>
<td>Walker Parking Consultants</td>
<td>Chicago, IL</td>
<td>Structural designer</td>
</tr>
<tr>
<td>Gilbert Peterson</td>
<td>Cole/Yee/Schubert</td>
<td>Sacramento, CA</td>
<td>Structural designer</td>
</tr>
</tbody>
</table>

Table 4.3 - List of contacts for case studies
5. CASE STUDIES

This chapter contains ten case studies of innovations related to the structural system of buildings. These ten innovations are studied over 18 implementations total. The case study write-ups present data regarding the variables discussed above in Chapter 3.

5.1. Trio Structural System

5.1.1. Brief description

In the design of buildings, one must consider the effects of wind and seismic activity specific to the site. For areas of high seismic activity, such as the Pacific Rim and around the Mediterranean Sea, the bulk of the design effort must be devoted to this issue. The typical solutions to this problem are the use of concrete shear walls, steel moment-resisting frames, diagonal steel bracing, or some combination thereof. Over the years, structural engineers have learned more about the effects of earthquakes on structures and how different structural systems behave. The risks are high in terms of structural damage, property damage, discontinued use of the building and even loss of life.

A new solution has come about in recent years to tackle this problem. It is the fluid viscous damper. Below is a cross-sectional view of one of these dampers, showing the piston configuration and the silicone fluid (Figure 5.1.1). Figure 5.1.2 shows a damper installed in a steel framed building. A fluid viscous damper acts like a shock absorber; as a force is applied to it, it dissipates energy by regulating the flow of the fluid through small orifices in the head of the piston. Since their first use in commercial construction in 1994, fluid viscous dampers have been used in several projects, including seismic retrofits and new construction of bridges and buildings (Taylor Devices product literature).

![Cross-section of a fluid viscous damper](image)

Figure 5.1.1 - Cross-section of a fluid viscous damper (Constantinou and Symans 1993)
By dissipating part of the seismic energy, the dampers reduce the amount of force applied to the structure, thereby reducing the amount of material needed. Thus, the damped structure can survive a more intense earthquake with less damage more efficiently than an undamped structure (Rasmussen 1997). The supplemental damping reduces the stress and deflection in the structure. The initial cost premium for the dampers is more than offset by the savings in material and repair costs in the future (Rasmussen 1997).

This case study addresses the Trio Structural System, a structural steel framing system that uses a combination of moment-resisting connections, shear walls and fluid viscous dampers to create a structural system for tall buildings in earthquake-prone areas. This innovation can be classified differently depending on one’s perspective. First, for the owner, it is essentially a modular innovation because it constitutes a change only to the structural component of the building as a whole. For the architect, it is also an architectural innovation. From their perspective, they see major changes in the structure that must be considered in their architectural design, but the use of the dampers does not cause any major changes to other components, such as the mechanical systems or the exterior enclosure.

In contrast, the structural design is a system innovation to structural engineers because it introduces a new approach to the overall design for dynamic loads through the use of damping devices and the configuration of adjacent structural members and the overall structural frame. For the general contractor, the steel fabricator, and the steel erector that installs the dampers, this is an incremental innovation. The only considerations for these parties are that the frame must be erected with tight tolerances and that the dampers must be treated and installed carefully to ensure that they function as intended. These are relatively minor changes to standard practices for these parties and do not require the
firms to develop any new competencies. Finally, this innovation has no effect on the damper supplier because they can use their standard dampers that they have already developed for other applications.

5.1.2. **Innovation development and use**

5.1.2.1. **Development**

The concepts behind fluid viscous dampers date back to the late 19\textsuperscript{th} century but were fully developed during the Cold War era for military and government aerospace applications. In 1955, a company called Taylor Devices was founded to provide fluid viscous dampers to the US government. With the end of the Cold War, the government declassified the technology, and Taylor began to seek other markets. In 1991, they teamed up with the National Center for Earthquake Engineering Research (NCEER) at the State University of New York at Buffalo to conduct research and testing of fluid viscous dampers for seismic energy dissipation in buildings. In the next few years, they did many shake-table tests and published several papers detailing the applicability of the dampers for this purpose (Winters 1998).

The Trio system was actually developed by an outside engineering firm, the Cantor Seinuk Group (CSG), with no direct association with either Taylor or SUNY Buffalo. A partner at CSG, Ahmad Rahimian, developed the system during the design phase of the Chapultepec Tower project, as described below. However, this design innovation built heavily upon the development and testing of the dampers done by Taylor and SUNY Buffalo, which only demonstrated that it was feasible to use the Taylor fluid viscous dampers to dissipate seismic energy. However, Taylor did not have the competencies necessary to do the actual implementation in a structure. They needed an engineer with experience in earthquake engineering of structures to work with them to incorporate their product into an actual project.

5.1.2.2. **Use - Chapultepec Tower, Mexico City, Mexico**

Chapultepec Tower is a Class AAA mixed-use tower currently under construction in Mexico City. The building consists of four sub-grade parking levels and 53 floors, with a total of 1.6 million square feet of floor space. Construction is expected to span a 30 month period at a cost of over US$150 million. It is the largest application of these dampers to date in commercial construction. It is the first application of the Trio Structural System to date.

5.1.2.2.1. **Search process**

In 1994, CSG began working on its conceptual design for the Chapultepec Tower. The principal in charge of the project for CSG was Dr. Ahmad Rahimian, P.E., an engineer with nearly 20 years of
experience in the design of tall buildings subjected to high wind and seismic loads. At the start of the project, the owner, ICA Reichmann, established a key performance requirement, that the building continue to be fully functional after a serious seismic event. Thus, the engineer worked under a performance-based specification, with the expected performance exceeding the current acceptable levels prescribed by the building codes. These codes only require that structures not collapse and kill their occupants in a major seismic event (Rahimian 1998). This is interesting because the codes are moving toward performance-based design in the near future.

To achieve this high level of performance required a new design approach, since it is simply not economically efficient to design a tall building to survive a major earthquake with minimal damage using a conventional undamped steel or concrete structural system. It would require massive beams and columns that would greatly reduce the usable floor space. Thus, using the codes, buildings are designed with the understanding that they may sustain a great deal of structural and non-structural damage during this type of earthquake. However, building owners have found that the repair costs after a major event can be excessive, and, in many cases, it has proven cheaper to simply tear down the damaged building and build a new one (Taylor product literature).

Therefore, the owner's objective posed a major challenge for the structural engineer. In addition, Dr. Rahimian realized that the Mexican building codes are much more demanding than U.S. codes in terms of certain design parameters, such as overturning moment and allowable displacement. Thus, the structural designer realized that he would have to add supplemental damping to the structure (Rahimian 1998). CSG created graphs of the differences in the code requirements to convince the owner that an undamped structure would be too costly and inefficient, while the graphs also showed that added damping would make the owner's goals achievable.

Dr. Rahimian then looked at the damping technologies available at the time, which included Taylor fluid viscous dampers, the ADAS system and viscoelastic plate dampers from 3M Corporation. The ADAS system is a hysteretic type of damper consisting of specially shaped steel members that are designed to dissipate energy through cyclical deformations. The 3M damper consists of a special polymer material bonded to steel plates. The plates overlap and the polymer dissipates energy as the plates slide over one another (Constantinou and Symans 1992).

The 3M damper was ruled out right away because it does not behave as efficiently as the other two types of dampers. CSG then did schematic design studies of the Taylor and ADAS devices. The ADAS dampers were not selected because they conflicted with the architectural design of the building, since the ADAS units must be installed at the vertex of chevron bracing but, in this case, the architect would only allow such bracing in the core of the building. If placed in the perimeter walls of the building, the chevrons would have cut across the windows, a feature that would have reduced the value of the
building to potential tenants. However, if the dampers were only allowed in the core, they would not provide enough damping to limit overall building damage. In addition, the ADAS dampers sustain damage and must be replaced after an earthquake. The Taylor dampers, on the other hand, do not need to be repaired after an earthquake, and they have a patented seal that has been proven in decades of use to prevent the silicone fluid from leaking. In addition, the Taylor dampers are made of stainless steel, so they do not require maintenance. In fact, Taylor Devices actually contends that the dampers will outlive the building that they are installed in (Taylor product literature).

Armed with the studies of the dampers and graphs depicting the stringency of the code requirements, Dr. Rahimian was able to convince the owner to go with the Taylor dampers. During the design development phase of the project, Dr. Rahimian studied over 25 different configurations of the Taylor dampers; he varied their number, orientation and output characteristics. What made this process even more daunting was the fact that there were no building code requirements in existence for structural design using these dampers. Overall, he took three months to study the various damping systems in different structural configurations until he was able to prove to the owner that the supplemental damping system should be used. This negotiation process was also made easier by the fact that the owner, Reichmann International, had worked with CSG in the past on a large commercial development project in London and trusted their judgement and ability (Rahimian 1998).

The result of the design development was the Trio Structural System, which employs the dampers as diagonal members to provide supplemental damping to a complicated structural system that employs a steel truss core and braced moment-resisting frames along the perimeter (Rahimian and Romero 1998). Taylor Devices was at first skeptical of the system because it was such a departure from other applications (Rahimian 1998). Other engineers had used the dampers as single diagonals in a steel frame or horizontally to control the movement of base isolated structures. In this design, however, Dr. Rahimian created a system that would optimize the performance of the dampers by increasing the differential velocity of the dampers as the building deflects under lateral wind and seismic loads. This increases efficiency because the amount of energy dissipated by a damper is a function of the differential velocity between its ends.

During the early part of the detailed design phase, the project was put on hold after the Mexican peso lost nearly 40% of its value during the first two months of 1995. Work resumed in the spring of 1997, after the economy strengthened and ICA/Reichmann decided that economic conditions were positive.

Overall, the development and implementation of this innovation required a range of competencies. First, there was the damping technology, originally developed by Taylor Devices. In addition to the decades of work done by Taylor prior to this project, the company also helped Dr.
Rahimian during the design phase of this project by providing him with test data on the performance characteristics of the range of dampers that they manufacture. CSG had the other important competency, which was Dr. Rahimian’s expertise in structural dynamics and engineering of tall buildings under wind and seismic loads. In addition, CSG’s local Mexican engineering partner on the project, Enrique Martinez Romero, added his competencies in supplemental damping for buildings and Mexican code provisions.

5.1.2.2.2. Project organization

The organization chart for this project is depicted below.

![Organization Chart](image)

**Figure 5.1.3 - Project organization chart for Chapultepec Tower**

The project is being led by a 50/50 joint venture between Empresas ICA, Mexico’s largest engineering, procurement and construction firm, and Reichmann International, a real estate developer. ICA, as a construction company separate from the joint venture, holds a guaranteed maximum price contract with ICA/Reichmann for the construction of the project. Thus, they have a dual role. First, they act as the construction management arm of the joint venture owner entity. Second, they act as the builder for the construction phase. The delivery system used is most like construction management. The GMP contract fits well because the project was fast-tracked, meaning that construction progressed as the design was completed. With the GMP contract, ICA had room in their price to cover any uncertainties in the design at the time of the contract signing.

The design team is headed by Zeidler Roberts, an architecture firm responsible for the conceptual design of the project. Adamson Associates is the project architect, which performs the detailed design work and coordinates the work of the engineers. Cantor Seinuk Group is the structural engineer, in partnership with Enrique Martinez Romero of Mexico. CSG’s contract was a negotiated fixed fee for
services and they were chosen based on their capabilities, which is typical of structural design, and were therefore fully compensated for their extensive conceptual design studies of the damping systems.

The diagram below depicts the overall value chain for this project.

![Value chain for Chapultepec Tower](image)

As is apparent from the discussion thus far, this value chain changed as the project developed. The engineers, architects and construction manager were involved from the start of the project, and the other parties were brought in later. Taylor was brought in by CSG during the conceptual design phase, but they only became a formal member of the project team during detailed design. The structural steel fabricator/erector became part of the project after the completion of the superstructure design through a competitive bidding process. As shown by the dashed oval, CSG and Taylor were the two firms most involved in implementing this innovation in this project.

This dynamic assembly of firms had several implications. The most important one is that the construction manager, ICA, as contractor and co-owner, was able to control progress throughout the project. ICA served as the intermediary between the project team members and the owner. In addition, it held coordination meetings at various stages of the design process to coordinate the work of the various consultants. It was also able to perform cost estimates during design as well as order materials early so that construction could proceed efficiently.

5.1.2.2.3. Coordination process

The main coordination issue caused by the use of this innovation arose between CSG and the other design consultants, because the large number of diagonal members and diagonally-oriented dampers often conflicted with service runs or architectural elements. For the latter, the architect wanted to make sure that the diagonals in the perimeter walls were architecturally pleasing. In fact, Zeidler Roberts worked with CSG to modify their designs so that the large x-shaped diagonal bracing system in each façade was expressed in the architectural design. In addition, the diagonal member orientations in some cases had to be modified slightly to allow for doorways and openings in walls. Adamson and CSG held
coordination meetings toward the end of the design phase to address these issues. Adamson also brought the mechanical engineer to coordinate their design with CSG, and ICA was involved in these meetings, in order to avoid conflicts during the construction phase.

An important issue to address is the negotiation process that took place between CSG and Taylor during the detailed design phase. Although Taylor Devices had put a lot of effort into studying the potential for its dampers in earthquake-resistant buildings, it did not modify its products specifically for building applications. For Chapultepec Tower, it simply provided the same unit that it had developed for a military submarine project years earlier. The only change it made in the damper design was to the orifice size, which changes the response characteristics of the damper. This is a very minor change that they make regularly. It also did not have any structural engineers on staff to aid outside engineers in using its products in buildings, which limits the amount of specific assistance that they can provide. More importantly, it severely limits their understanding of construction and how their product could be adapted to better suit the building design and construction industry.

5.1.2.2.4. Appropriation of costs/benefits

In this case, the owner benefited because it got a high-performance building that has more value for tenants than other buildings because it was designed to remain serviceable even after an extreme earthquake. This performance level mitigates the risk for potential tenants in locating in a seismic region like Mexico City, and potentially gives tenants a competitive advantage over other firms located in buildings that do not perform as well. This is especially important because this will be the first Class AAA office building in Mexico City.

The structural engineer should benefit because it used the dampers in such an innovative way. This should lead to an improved reputation for the firm and Dr. Rahimian, as an individual. It also gives them a competitive advantage over other structural designers in the tall building market. In addition, they strengthened their relationship with Reichmann International. Also, the added costs to CSG related to the specialty design of this system were completely recovered on this project.

Taylor Devices benefited from this project as well. Not only did it get their dampers used in a high-seismic area, but Chapultepec Tower is also the most extensive application of the dampers to date. This project and its visibility enhance Taylor Device’s reputation, and instill confidence in potential users to implement the dampers in extreme situations.

Below is a summary timeline for this project. This chart adds a couple of important points concerning the use phase of the building. Mexico City’s building code requires that buildings be instrumented for monitoring. CSG plans to use this data to assess the performance of the structural system with respect to the predictions of their model. They will receive free field data, which are
measurements that show the motion of earthquakes, in addition to motion data from the building's ground floor, top floor and several points in between. Taylor Devices provides a 35 year warranty on the dampers to the owner.

<table>
<thead>
<tr>
<th>Conceptual design phase</th>
<th>Owner selects architect and issues high performance objective to structural engineer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CSG studies available damping technologies with respect to project requirements and performs conceptual analyses over 3 months. Taylor Devices is brought into the project.</td>
</tr>
<tr>
<td></td>
<td>CSG convinces owner of the advantages of supplemental damping over an undamped structure. Owner OK's use of Taylor Dampers.</td>
</tr>
<tr>
<td>Design development</td>
<td>CSG studies over 25 different damped designs and comes up with the Trio system</td>
</tr>
<tr>
<td>Detailed design phase</td>
<td>Work is stopped for 2 years due to currency crisis. ICA and Adamson hold meetings to coordinate the work of the design consultants. Contract documents are created.</td>
</tr>
<tr>
<td>Bidding &amp; Construction phase</td>
<td>Damper installation begins</td>
</tr>
<tr>
<td>Use</td>
<td>Building performance is monitored continually. Warranty period for dampers.</td>
</tr>
</tbody>
</table>

Figure 5.1.5 - Timeline for the Chapultepec Tower project
5.2. Special Truss Moment-Resisting Frame (STMF)

5.2.1. Brief description

The effects of wind and seismic activity specific to the site are critical in the design of building structures. The loads from these effects can be significant and thus they complicate the design effort. The typical solutions to this problem are the use of concrete shear walls, steel or concrete moment-resisting frames, diagonal bracing, vertical trusses, or some combination thereof. However, recent earthquakes such as Northridge (1994) and Loma Prieta (1989) have exposed deficiencies in accepted design solutions. The Northridge quake alone caused an estimated $12.5 billion in property damage (Rosenbaum 1995). Owners have come to realize the potential lost revenue due to disruption of use and the high cost of repair resulting from earthquake damage to their buildings. Structural engineers face the challenge of designing a reliable structure while minimizing repair costs and controlling construction cost and duration.

![Image of a Special Truss with text: Figure 5.2.1 – Close-up view of a Special Truss; the thinner diagonals yield during an earthquake (Rosenbaum 1998)]

The STMF consists of steel trusses joined by simple connections. The trusses are typically 3 to 3 1/2 feet deep and are built up from steel angles and small I-sections in the fabrication shop. Open web joists are used as floor beams to carry gravity loads. The trusses contain several diagonals that are designed to yield during a seismic event (Figure 5.2.1). In this way, energy is dissipated and the amount of energy transferred to the structure is reduced. Thus, the yielding diagonals act much like the fluid viscous dampers used in the Trio Structural System (See Section 5.1). By sacrificing a few members, damage to the superstructure and non-structural elements is reduced. The yielded diagonals are accessible for repair or replacement above the hung ceilings of the building.
The STMF holds several benefits over conventional steel systems. For one, there is no need for the full penetration welds of moment connections in steel frames. These connections are costly, time-consuming and many of them failed in the Northridge quake. The STMF requires only single pass fillet welds and bolted connections (Figure 5.2.2). There is also material savings because an open web steel joist typically weighs about 20% less than a wideflange beam capable of carrying the same gravity load. The reduced weight of the structure decreases the burden on the foundation, leading to even more savings. In addition, the fabrication cost for open web joists is 20% less than that for wideflange beams. Altogether, this translates into savings of roughly $5 per square foot. In addition, since the structure can be erected much faster, the owner saves on financing costs and is able to occupy the building earlier. A very important benefit of the system is that it has a lot of ductility, which means that it will dissipate seismic energy through yielding without failing. This translates into reduced damage to nonstructural elements.

Figure 5.2.2 – Comparison of connection types (JD2 product literature)

The STMF is an incremental innovation for owners because it changes only the performance characteristics of the structure during an earthquake. It is also incremental for architects because the use of the deep truss girders and open web joists for floor beams is only a minor change from their perspective over a conventional steel frame structure. However, its impact on structural designers is far greater. From their perspective, it is a system innovation, because it combines a novel analysis and design technique with the use of a new type of structural member, the Special Truss. It is an architectural innovation for general contractors because they must coordinate the installation of the building services
with the configuration of the structural framing. The services, such as the heating and air conditioning ducts, must be installed through the gaps in the open web joists and the Special Trusses. Finally, from the steel erector’s perspective, this is an incremental innovation because the construction sequence and connection types are not unique.

5.2.2. **Innovation Development and Use**

5.2.2.1. **Gateway Oaks IV, Sacramento, California**

This four-story, 84,000 square-foot office building was completed in 1998 at a cost of approximately $5.5 million (Rosenbaum 1998). It marked the first application of an STMF.

5.2.2.1.1. Search process and development

In 1994, Nucor Steel paid over $1 million to the University of Michigan to do a study to determine the possibilities of a yielding truss frame. Their motive was to increase the market available for the open web joists and trusses that they manufactured in their Vulcraft subsidiary. Professor Subhash Goel of Michigan did theoretical studies and testing and finally developed design guidelines for the STMF. His most important contribution, however, was that he pushed for an amendment to the Uniform Building Code to allow for yielding moment-resisting steel trusses. The amendment was published in 1996. In addition, Professor Goel publicized the STMF concept in lectures to groups such as the Structural Engineers Association of California.

The Gateway Oaks IV office building in Sacramento, California was the first application of the STMF concept. In the initial design meeting for the project, the construction manager, Earl Construction, asked JD2, the structural steel fabricator and erector, if they had any ideas about how to reduce the cost of the job. JD2 remembered a project they had done in the mid-1980’s in which they had used moment-resisting trusses. They approached Vulcraft, the manufacturer of these trusses and Vulcraft showed them the University of Michigan studies. Vulcraft, however, did not want to take on the liability of designing the entire structure. They only fabricate open web joists and trusses. JD2 was impressed with the study and proposed bringing Cole/Yee/Schubert in to do the structural engineering. JD2 had working relationships for several years with both Vulcraft and Cole/Yee/Schubert and they knew that they had the capabilities in earthquake engineering and plastic analysis to design the yielding elements. The engineer actually used a performance based analysis procedure on this project. This method is the state of the art in structural engineering.

In terms of the search process, JD2 was the main search agent in question. They went into the second phase of the search process (previous partners) to find a solution to the problem posed to them by Earl Construction. They used Vulcraft and Cole/Yee/Schubert to solve their problem. However, it is
important to note that this happened only after Vulcraft had gone to the third phase of the search process (engineering and construction industry) when they approached the University of Michigan to develop the concepts behind the STMF.

5.2.2.1.2. Project organization

This project was completed using a construction manager at risk under a negotiated GMP contract. The organization chart and value chain for this project are shown below (Figures 5.2.3 and 5.2.4).

![Organization Chart](image)

**Figure 5.2.3** – Project organization chart for Gateway Oaks

![Value Chain](image)

**Figure 5.2.4** – Value chain for the Gateway Oaks IV project

The owner had two construction managers compete with each other based on cost for this project. The owner only gave them a site plan and schematic drawings. As discussed above, the Earl Construction approached JD2 for their ideas for the structure. Then, JD2 approached Vulcraft and the innovation was
proposed. Based on the low cost of the system, the owner approved the idea, hired Earl Construction and
the structural engineer was brought into the project. The structural engineer designed the overall steel
superstructure, including the yielding trusses. For the gravity load-carrying open web joists, they only
had to provide a load per linear foot to Vulcraft because they have standard designs for different levels of
load. JD2 is known as a steel fabricator and erector, but they are actually more like a construction
manager for structural steel. They contract other companies to do the actual fabrication and erection.
Their role is only to serve as the manager of the process. Their main task during design is to work with
the structural engineer to create the shop drawings. During construction, they manage the procurement of
the steel members and the erection process.

The owner only held contracts with the architect, civil engineer, and construction manager. Earl
Construction held the subcontractors as well as the mechanical engineer and the structural engineer.
Thus, the project was partially Design Build.

5.2.2.1.3. Coordination issues and negotiation process

The main coordination issues caused by the use of the STMF involved the design and
construction of the services (plumbing, fire protection, HVAC and electricity) and the design, fabrication
and erection of the structural steel.

Due to the delivery system used, Earl Construction was in an excellent position to coordinate the
services. They had direct contractual relationships with designer of these systems and the subcontractors
responsible for installing them. The challenge was that they had to coordinate the structural and
mechanical designs so that the services could be run through the openings in the trusses and joists. In a
conventional steel structure composed of wideflange beams, the services run between beams, under them,
or through holes in the beam webs. In this case, all of the horizontal service runs had to be installed
through the joist and truss openings. This required careful attention by Earl Construction to the
mechanical system design to make sure that they would fit in the structure.

Coordination of the steel superstructure was more difficult. Earl Construction held the contract
with Cole/Yee/Schubert as the engineer of record but they were first contracted to JD2 to design the
yielding trusses. As a steel management company, it is in JD2's interest to improve the delivery system
for design, fabrication and erection of structural steel. They acted as the intermediary between the
engineer and the fabricator to get the joists and trusses made correctly. They also had to manage the
delivery of the materials to the site to make the erection process more efficient.
5.2.2.1.4. Appropriation of costs/benefits

The owner received several benefits from the use of this system. For one, it saved roughly two months in the construction schedule. This saved them about $2 per square foot in financing costs. In addition, this time savings enabled them to generate revenue sooner. In addition, the use of the steel joists enabled them to efficiently span a longer distance than they could have with wideflange beams. This meant that the tenant space was more open which means that they can charge a premium for the building. Column-free space is very important to office space tenants. The owner also benefits because the structure will perform well in a seismic event. Damage will be less and therefore downtime and repair costs will be lower.

Earl Construction also benefited from the innovation because its low cost was the reason why they were awarded the job in the first place. JD2 and Vulcraft also benefited because they brought the idea into the project. However, Vulcraft was unwilling to do any of the engineering of the structure, so they only benefited from the sale of the joists and girders. The benefits thus had to be shared with the structural engineer who took the liability of designing the structure.

5.2.2.2. Johnson Ranch Corporate Headquarters, California

This two-story, 60,000 square-foot office building was the second application of the STMF.

5.2.2.2.1. Search process and development

In this project, the owner was again Spiiker Properties and they wanted to use the system again because it went so well on the Gateway Oaks IV project. Thus, the search process was short; it only went as far as the known solutions of the project team members.

5.2.2.2.2. Project organization

This project was also completed using a construction manager at risk working under a negotiated GMP contract. The organization chart and value chain for this project are shown below (Figures 5.2.5 and 5.2.6).
The only change in this project was that a new architect was used. In addition, Earl Construction did not have to compete for the contract; Spieker Properties awarded Earl the project at the start.

5.2.2.2.3. Coordination issues and negotiation process

The coordination issues were the same. However, the team members took steps to improve the coordination process for the steel superstructure. Earl Construction became more involved in coordinating the communication between the structural engineer and JD2. Electronic mail connections were set up between Cole/Yee/Schubert and JD2 to speed up the transfer of shop drawings. JD2 also helped more in the design process. They developed standard details for beam to column connections while the structural engineer designed the yielding portion of the trusses. With these improvements, they were able to minimize the lead-time for the structural steel delivery. From the moment that they engineer starts designing, they need only 18 weeks until the steel reaches the site. In a normal project using a design bid build delivery system, there is usually a 30-week lead-time for structural steel.
5.2.2.2.4. Appropriation of costs/benefits

The appropriation of costs and benefits on this project was the same as it was on the previous project.

5.2.2.3. Roseville Corporate Center, California

This project involves the construction of a three-story, 120,000 square-foot office building. Construction began in August, 1998 and is expected to finish in late 1999. It is the third application of the STMF to date.

5.2.2.3.1. Search process and development

The owner in this case was again Spieker Properties and again they decided from the start to use the STMF. Thus, the search process only went to the team members’ known solutions.

5.2.2.3.2. Project organization

This project was also completed using a construction manager at risk working under a negotiated GMP contract. The organization chart and value chain for this project are shown below (Figure 5.2.7 and 5.2.8).

![Project organization chart for Roseville Corporate Center](image-url)

Figure 5.2.7 – Project organization chart for Roseville Corporate Center
The project team members used here are the same as they were on the first project.

5.2.2.3.3. Coordination issues and negotiation process

Again, the coordination issues were the same as on the other projects. The team members have said that they continually try to improve the efficiency of the communication process for the design, fabrication and erection of the steel superstructure.

5.2.2.3.4. Appropriation of benefits/costs

No change except that the original architect was involved. However, the architect plays no role in the coordination required to implement the STMF. Thus, they appropriate none of the benefits of its use and it does not cost them anything.
The order of events was similar for all three projects discussed. The figure below depicts the typical timeline of events, including the pre-project development of the STMF.

<table>
<thead>
<tr>
<th>Pre-project development</th>
<th>1994 - Nucor Steel hires University of Michigan to develop a yielding truss frame.</th>
<th>Prof. Goel of UM develops design guidelines for the STMF and pushes for an amendment to the building code to allow for yielding moment-resisting steel trusses.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>JD2 works with Cole/Yee/Schubert to design and detail the superstructure</td>
<td>The shop drawing review process is conducted electronically</td>
</tr>
<tr>
<td>Construction</td>
<td>The superstructure is erected and the building completed</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.2.9 – Timeline of development and use of the STMF
5.3. Hybrid Moment-Resisting Precast Concrete Frame

5.3.1. Brief description

This innovation is a precast concrete moment-resisting frame system that incorporates a novel configuration of connecting elements to improve the performance of the structure under wind and seismic loads. As shown in Figure 5.6.1, the beam to column connection system consists of two main elements. The first is the post-tensioned (PT) cable that runs through the duct at the centerline of the beam. This cable runs continuously through all of the beams in the frame through holes in the columns that line up with the ducts in the beams. The PT cable pulls the beams against the columns, thereby creating enough friction to withstand the shear forces developed from gravity loads in the structure. Another benefit of the PT cables is that they provide force to re-center the joint after an earthquake. Thus, there is essentially no residual drift (Stone et. al. 1995). With other systems, large earthquakes would result in some amount of residual drift that would have to be repaired.

![Figure 5.3.1 – Isometric view of beam-column connection (Stone 1995)](image)

The other element of this system is the mild steel reinforcement. These bars are installed by laying them in the beam trough and subsequently sliding them through the end of the beam, the column and into the beam on the opposite side. These bars are then fixed in place with nuts. The bars are installed in the upper and lower part of the beams and provide tension capacity for the connection to withstand the flexural loads that result from wind and seismic forces. Figure 5.6.2 shows a cross-section of the overall connection assembly. It is called a hybrid frame because it incorporates both PT cables and mild steel bars in its connections (Stone et. al. 1995).
This innovation is an alternative to conventional cast-in-place (CIP) concrete structures. Its benefits over CIP construction come mainly from the economies of precast concrete construction, such as speed of erection and improved quality control. It also performs better under extreme earthquake conditions than traditional precast concrete frames. The hybrid frame sustains very little damage in its beams and columns because the mild steel bars are designed to yield. Since the mild steel bars dissipate energy by yielding, the rest of the structure is subjected to smaller earthquake loads.

From the owner’s perspective, this is an incremental innovation because, while it improves the cost and performance of the facility, it does not change usage characteristics. From the structural engineer’s perspective, it is a system innovation because it changes the nature of the beam to column connections and requires innovative processes to install all the components. The use of mild steel bars and PT cables changes the way in which an engineer analyzes and designs frames. For the erector of the frame, this is an architectural innovation because it changes the construction sequence. Since the PT cable runs through all of the beams in a particular frame, the erector must temporarily support the beams while the PT cable is fed through the ducts and tensioned. Thus, the innovation dictates the construction sequence. In addition, it is innovative because the steel reinforcing bars are installed in the field through holes in the members. This is not typical of precast concrete construction.

5.3.2. **Innovation development and use**

5.3.2.1. **Development**

The development of this system was sparked by a 1987 initiative by the National Institute of Standards and Technology (NIST) to develop designs for economical precast concrete moment-resisting
beam to column connections suitable for seismic regions. NIST began the Precast Seismic Structural Systems (PRESS) program to meet this goal. This system was one of several new systems developed as part of this program.

A consortium of several types of organizations is responsible for the development of the hybrid system. Charles Pankow Builders, a construction company based in California, led the development of the hybrid frame, providing constructibility expertise. Funding was also provided by NIST, the Precast/Prestressed Concrete Institute (PCI) and the Precast/Prestressed Concrete Manufacturers Association of California (PCMAC). Robert Englekirk Engineers (Los Angeles), the American Concrete Institute and other members of industry also supported the development work. Englekirk provided the bulk of the structural analysis and design input for this project. Members of academia contributed their knowledge of earthquake engineering and concrete behavior.

Tests of alternative designs of the hybrid frame were conducted from 1992 to 1994 at both NIST and the University of Washington. These tests showed that the hybrid frame could perform at least as well as a conventional CIP concrete frame under seismic loads. Based on the test results, the system was accepted by the Uniform Building Code in March 1996. The code does not allow for precast concrete moment-resisting frames unless they are proven to be equivalent to CIP frames. The system won a Civil Engineering Research Foundation award in 1996 for innovation (Civil Engineering 1996).

5.3.2.2. **Use - Roosevelt Field Mall Parking Garages, Long Island, New York**

This set of three parking structures was completed in 1996 and marked the first application of the hybrid system. The garages service a large shopping mall.

5.3.2.2.1. **Search process**

The search process in this case was irrelevant because Charles Pankow Builders had already developed the system and was looking for a project to use it on. They approached the owner with the system in their proposal for the project.

5.3.2.2.2. **Project organization**

The project delivery system was design/build, with Charles Pankow Builders signed to a lump sum contract. The architect was HNA and the structural designer was Thornton Tomasetti, with some assistance from Robert Englekirk Engineers. The organization chart and value chain for this project are shown in Figures 5.6.3 and 5.6.4, respectively. Pankow performed all of the work itself, with the exclusion of the mechanical, electrical and plumbing systems (MEP).
5.3.2.2.3. Negotiation process

The negotiations necessary for the implementation of this innovation were limited mainly because Pankow performed much of the work related to the innovation itself. However, there were some unforeseen complications. One problem was that Pankow encountered some sequencing issues during the project because they had never built one of these structures before. Sequencing is especially important for this system because the innovation dictates the erection sequence, as discussed above.

This implementation was simplified by the fact that the seismic requirements in New York State are not very stringent. Thus, the structure did not require many frames incorporating the novel components. Dave Seagren, of Pankow, says that this system is not applicable to all situations (Seagren 1998). For example, for buildings that require many intersecting frames, this system would not be ideal because it would be difficult and inefficient to design the reinforcement at the intersections of the frames. The beams would have to intersect at different levels to prevent the PT cables and mild steel bars from
crossing. Fortunately, for many projects, a smaller number of moment-resisting frames placed in parallel are sufficient. In such cases, intersections can be avoided.

5.3.2.2.4. Appropriation of costs/benefits

The owner benefited because the structure has better performance characteristics than a conventional CIP concrete structure or precast concrete structure. In addition, the owner also received the benefits of precast construction, including quick erection and better quality control. Pankow and the other project team members benefited because they gained experience with the system. Pankow also benefited because they got the system out on the market, which provides them with a competitive advantage, offering a unique structural system with improved performance and decreased time.

Figure 5.6.7 below contains a summary timeline for the development and implementation of this innovation.

<table>
<thead>
<tr>
<th>Research &amp; development phase</th>
<th>NIST initiates PRESS program. Pankow leads development of hybrid frame with the aid of engineers from Englekirk and other industry organizations.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hybrid frame is tested at NIST and the Univ. of Washington. UBC approves system.</td>
</tr>
<tr>
<td>Bidding phase</td>
<td>Owner issues RFP for design build services</td>
</tr>
<tr>
<td></td>
<td>Pankow proposes hybrid frame system</td>
</tr>
<tr>
<td>Detailed design phase</td>
<td>Thornton Tomasetti completes design of system. Pankow coordinates this design with the precaster.</td>
</tr>
<tr>
<td>Construction phase</td>
<td>Hybrid frame erected</td>
</tr>
</tbody>
</table>

Figure 5.3.5 - Timeline of development and use of Hybrid Frame

5.3.2.3. Use - Eugene Parking Garage, Eugene Oregon

This parking structure, built for the city of Eugene, was the second application of the hybrid frame. It contains approximately 400 parking spaces.
5.3.2.3.1. Search process

As was the case with the previous project, the search process was irrelevant because Pankow was looking for a project to implement the system on. They approached the owner with the system in their proposal for the project.

5.3.2.3.2. Project organization

The project delivery system for this project was design/build, with Charles Pankow Builders signed to a lump sum contract. Pankow hired Robert Englekirk Engineers as the lead structural designer and HNA Architects as the architect. Figures 5.6.5 and 5.6.6 show the project organization chart and value chain, respectively. As on the previous project, Pankow performed all of the work itself, with the exclusion of the mechanical, electrical and plumbing systems (MEP).

![Project organization chart for Eugene Garage](image1)

![Value chain for Eugene Garage](image2)

5.3.2.3.3. Negotiation process

As on the previous project, the negotiations necessary for the implementation of this innovation were limited primarily because Pankow performed much of the work related to the innovation itself. One
benefit of this system is that it does not limit the architectural design of the facades; it can accommodate virtually any exterior treatment. In fact, on this project, the precast spandrels were actually cast with a design that was expressed in the exterior of the structure. Thus, additional architectural spandrel elements were unnecessary.

In addition, the seismic requirements of this project complicated the design process. Englekirk found it difficult to detail the precast concrete members due to the high degree of rebar congestion. In addition, Englekirk had to devise a way to create a moment-resisting connection at the bases of the columns. This issue had not been addressed during the pre-project development program; they had only concentrated on the beam to column connection. Englekirk decided to use a grade beam to create this connection. Dave Seagren, of Pankow, said that this solution will most likely change from project to project depending on project requirements (Seagren 1998). The nature of this connection does not affect the performance of the beam to column connections, so engineers are free to use whatever type of connection to the substructure which they feel comfortable.

5.3.2.3.4. Appropriation of costs/benefits

As on the previous project, the owner benefited because the structure has better performance characteristics than a conventional CIP concrete structure. In addition, the owner also received the benefits of precast construction, including quick erection and better quality control. Pankow and the other project team members benefited because they gained experience with the system. Pankow also benefited because they were able to implement the system in an area with high seismic requirements. In addition, Pankow learned about how to implement this system in high-seismic areas. For example, Pankow used a new connection system between the superstructure and the foundation. With this project, they positioned themselves well to market the system for high-rise construction (Dave Seagren 1998). Pankow also improved their competitive advantage; they can now offer a seismic frame with improved performance and construction time.

Since this project was completed in 1998, two office building projects have entered the design phase using the hybrid frame. The two parking garage projects proved the feasibility of the system and enabled Pankow and Englekirk to work out some complications. They are now marketing the system heavily in the high-rise construction segment.
Figure 5.3.8 contains a summary timeline for the Eugene parking structure project.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bidding phase</td>
<td>Owner issues RFP for design build services</td>
</tr>
<tr>
<td></td>
<td>Pankow proposes hybrid frame system</td>
</tr>
<tr>
<td>Detailed design phase</td>
<td>Englekirk completes design of system. Pankow coordinates this with the</td>
</tr>
<tr>
<td></td>
<td>precaster.</td>
</tr>
<tr>
<td>Construction phase</td>
<td>Hybrid frame erected</td>
</tr>
</tbody>
</table>

Figure 5.3.8 - Timeline of Eugene garage project
5.4. Ductile Precast Concrete Frame

5.4.1. Brief description

This system is similar to the Hybrid Frame discussed in the previous section. Both systems involve innovative connection systems for moment-resisting precast concrete frames. In the Ductile Precast Concrete Frame (DPCF), precast concrete beams are bolted to precast concrete columns, creating a moment-resistant frame that is quick and simple to construct. The members are bolted together using a unique connection developed for this system, called the Dywidag Ductile Connector (DDC), which is a button headed rod made from very high quality steel. The ductile connectors are cast into the columns of the superstructure and footings of the substructure, and the structure is then bolted together in the field.

The entire DDC assembly is depicted in Figure 5.10.1. The ductile rod is threaded to receive the bolt. The connector plate has two sets of holes in it. One set is threaded to receive the high strength reinforcing bars, called Threadbars®, which were developed for and are unique to this system. These bars are the reinforcement in the beams. They are threaded into the connector plate, and the assembly is precast into the beam. The second set of holes in the connector plate is used for the high strength bolts. Once the beam is lifted into place against the column, these bolts are inserted through the connector plate and threaded into the ductile rods, providing the connection between the beam and column. The rod portion of the DDC is designed so that it yields during an earthquake, while the other portions of the connector are designed to remain in the elastic range (i.e. to respond to the forces without failure of the components). Thus, the rod acts like a capacitor, yielding while protecting the beam and column from damage from the earthquake (Nakaki et. al. 1994). Figure 5.10.2 shows an isometric view of the connection.

![Diagram of Ductile Precast Concrete Frame](image-url)

Figure 5.4.1 - Dywidag Ductile Connector hardware (Nakaki 1994)
This system is an alternative to monolithic cast-in-place (CIP) concrete construction and standard precast concrete frames. The DPCF has several advantages over CIP concrete structures both in terms of construction and performance. It has all of the benefits of precast concrete construction, which include improved quality control and ease and speed of erection. In addition, the ductile link reduces the amount of earthquake energy and resultant damage to the beams, columns, and non-structural elements. DPCF structures can actually survive major earthquakes while sustaining only minor damage. The ductile rods are the only elements that are damaged extensively. In a CIP frame or shear wall structure, the structural elements themselves sustain damage, necessitating extensive repair work after a major event.

With respect to classification, this is an incremental innovation for owners because it does not change the configuration or usage of the facility, it only improves its cost and performance. For structural engineers, it is a system innovation, because it requires the use of new reinforcing and connection elements for precast elements, including the DDC, threadbars and bolts. This innovation changes how the structure is analyzed and designed. From the erector’s perspective, this is a modular innovation because it only changes how the members are connected, while using a standard erection sequence. For precast concrete manufacturers, this is an incremental innovation because it only requires them to cast new elements into the concrete.

5.4.2. Innovation development and use

5.4.2.1. Development

Prescriptive code requirements in the US have prevented structural designers from using precast concrete in creative ways in seismic regions. The Uniform Building Code does not allow precast concrete
moment-resisting frames, unless they are proven to perform better than CIP structures. Thus, designers who want to use precast concrete have been forced to use mixed construction or monolithic emulation. In the former, precast concrete is used to carry gravity loads only, while cast-in-place concrete shear walls or frames carry the lateral loads. However, this mixing of construction techniques reduces the efficiencies present in precast concrete construction. The total cost of a mixed system may actually exceed that of a single construction system.

In monolithic emulation, the precast concrete frame is designed so that yielding occurs in the beam, away from the beam to column connection. This area of yielding is referred to as the plastic hinge, because it yields under extreme loads, causing damage to the beam. This type of construction is inefficient because it requires other trades, such as welding, grouting, or cast-in-place concrete work, in addition to the precast concrete crew. Thus, the speed of precast concrete construction is wasted (Nakaki et al. 1994).

In response to this problem, the Precast/Prestressed Concrete Institute (PCI) and the National Science Foundation co-sponsored the Precast Seismic Structural Systems program (PRESS). One project within this program involved the development and testing of the DPCF. Begun in 1992, the objectives of this project were to develop a high performance precast concrete frame that could be fabricated and erected using standard practices and equipment. For example, the developers made sure that the system could be fabricated using rectangular forms, thereby eliminating the need for specialized investment in formwork. In addition, the developers kept in mind that the system had to allow for typical construction tolerances (Englekirk 1996).

The development of the DPCF was initiated by Englekirk and Nakaki Incorporated (ENI), a Los Angeles-based firm that was created specifically to develop new structural systems. Dywidag Systems International manufactured the ductile rods and connection assemblies. The system was tested in April 1993 at the University of California at San Diego. This test was funded by ENI. Soon after, the International Conference of Building Officials approved the implementation of the DPCF. The approval was based on the fact that the tests of the DPCF showed that it could outperform cast-in-place concrete frames as described by UBC (Nakaki et al. 1994).

5.4.2.2. Use – Wiltern Center Garage, Los Angeles, CA

Completed in 1996, this four-story, 160,000 square foot parking structure cost $3.6 million (Englekirk 1996). It is the first application of a DPCF. It should be noted that the DPCF is not limited to this type of structure. In fact, it was originally developed for high-rise building construction.
5.4.2.2.1. Search process

In late 1994, the Ratkovitch Company, a developer, approached a structural design firm, Robert Englekirk Consulting Structural Engineers, with plans for a parking structure in the urban downtown of Los Angeles. They also retained Greg Petroff as their architect. The developer's primary goal was to ensure the safety of the users of the facility in the event of an earthquake. They felt that this was important due to the urban location of the structure and the fact that it would be in use 24 hours per day. Another goal was to minimize the cost of the structure and to speed its completion. The latter goal was important because the developer had to rent parking space nearby during construction.

The designers produced conceptual plans for the facility and turned them over to Turner Construction Company, the construction manager. Based on these plans, Turner put together a preliminary budget and schedule for the project. The designers then worked together to come up with alternatives for the structural system, with Turner assessing the impact of each system on the budget and schedule. They only investigated cast-in-place systems until Spancrete, a precast concrete manufacturer and erector, proposed two precast schemes. One of these schemes was the DPCF. Spancrete was brought into the project because of its reputation for quality and service (Englekirk 1996).

5.4.2.2.2. Project organization

The project delivery system was construction management at risk, with Turner Construction signed to a GMP contract. Spancrete manufactured the precast concrete elements and erected them in the field. Dywidag Systems International supplied the DDC. Figures 5.10.3 and 5.10.4 show the project organization chart and value chain, respectively.

The value chain diagram shows how Turner, Englekirk and Spancrete were heavily involved in the implementation of this innovation. Spancrete initiated the idea and fabricated and erected the elements. Englekirk performed the design work, including the detailing of the connections. Turner estimated the cost of the system and compared it to the other structural alternatives.
5.4.2.2.3. Negotiation process

During this project, all firms took part in the negotiation process. Robert Englekirk, the CEO of Englekirk and Nakaki, attributed the success of the project to the “close collaboration between the owner/developer and the design and construction teams.” One difficult part of the implementation of this innovation was that there was no historical data upon which Turner could base its cost estimate. They had to work closely with Spancrete to identify every aspect of the system for cost purposes (Englekirk 1996).

5.4.2.2.4. Appropriation of costs/benefits

The Ratkovitch Company, the owner, benefited from the use of this innovation in several ways, the most prominent of which was cost (Englekirk 1996). This system cost less than all of the cast-in-
place alternatives and the other precast system. Most of the savings came from the fact that the erection process for it was significantly shorter than that of the CIP systems. In addition, the integrated delivery system used allowed Spancrete to begin production of the precast concrete members before the design was fully completed. Ratkovitch not only was able to realize earnings from the facility sooner, but they were also able to rent temporary parking for a shorter time. Another benefit to them is that the system will perform better than CIP systems during earthquakes. CIP frames typically experience significant concrete cracking and spalling that must subsequently be repaired. A DPCF does not undergo significant cracking (Englekirk 1995). The project team members benefited from their contracts and from the experience that they gained with the system. Englekirk entered a new market with a proprietary system and Spancrete got a new system (and sub-market) in which to supply precast concrete components.

Figure 5.10.5 below contains a timeline of the development and use of the DPCF.

<table>
<thead>
<tr>
<th>Research &amp; development phase</th>
<th>NIST initiates PRESS program. ENI leads development of DPCF with the help of Dywidag Systems and other industry organizations. DPCF is tested at UCSD. UBC approves system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual design phase</td>
<td>Owner retains a design team and construction manager and sets cost and performance goals for the project. They study various CIP concrete structural alternatives. Spancrete proposes the DPCF and it is selected based on construction speed, cost and performance.</td>
</tr>
<tr>
<td>Detailed design phase</td>
<td>Englekirk engineers the structure.</td>
</tr>
<tr>
<td>Construction phase</td>
<td>DPCF erected</td>
</tr>
</tbody>
</table>

Figure 5.4.5 - Timeline of development and use of DPCF
5.5. Precast Concrete Slurry Wall

5.5.1. Brief description

Many urban commercial construction projects include basements several floors below grade. Constructing these sub-grade walls is a very difficult task due to the uncertain nature of the ground conditions. The presence of voids, a high water table, large boulders and other obstacles can make this a very lengthy process. These walls must not only be strong enough to support the surrounding soil and groundwater, but they must also be watertight. The latter is especially important when the site is close to a body of water or a high water table.

The common method for foundations is to construct a cast in place (CIP) concrete slurry wall. This technique has been used since the 1940s and can be found worldwide (Sanchez 1998). A prime example is the Central Artery project currently underway in Boston. This project involves the construction of very long slurry walls to create the sidewalls of a new underground highway (Doebler & Brown, Construction Congress V).

Figure 5.5.1 depicts the steps involved in the CIP concrete slurry wall method. The first step (A, B in Figure 5.5.1) involves the use of a clamshell bucket suspended from a cable attached to a specially modified crane. The clamshell is used to dig a trench down to bedrock. Shallow concrete guide walls are constructed first to ensure the accuracy of the excavation. As the clamshell brings up soil, a slurry of bentonite clay and water is pumped into the trench. This mixture prevents the trench from collapsing and also prevents water infiltration into the site because bentonite clay expands in the presence of water. This technique is efficient because the slurry is reusable. Once the trench is complete, steel members and reinforcing cages are lowered into place (Figure 5.5.1, part C). Then, concrete is poured into the trench by the tremie method to form the walls (Figure 5.5.1, part D). The concrete is poured into the bottom of the trench via a tube. Simultaneously, the displaced slurry is pumped out. Once all of the walls have been poured and have cured, the inner area is excavated incrementally and the walls are supported to prevent them from collapsing inward (Figure 5.5.1, part E). In the completed building, the basement level floor slabs help prevent the walls from collapsing inward.
The Precast Concrete Slurry Wall innovation is an alternative to the conventional CIP concrete slurry wall method. It starts out exactly the same as the conventional method in that a trench is dug and filled with bentonite slurry. The two methods diverge once the trench is completed. In the new technique, large precast/prestressed concrete panels are lowered by a crane into the trench and placed side by side to form the walls. The panels are typically nine feet wide and they run the full depth of the basement. This depth depends on the building, but the panel length is actually limited by the capacity of the crane. The maximum feasible length is about 65 feet (Sanchez 1998). The panels typically extend below the bottom level of the basement, giving them a back-span to help counteract the lateral earth and water pressures.

Before the panels are put in place, a layer of concrete is poured in the bottom of the trench one foot above the bottom of the panel to provide a footing. The panels are then lowered into the trench and hung off of concrete guidewalls along the rim of the trench to hold them in place. Since the trench is several inches wider than the panel, spacer blocks are placed on both faces of the panels to center them in the trench. These steps ensure that the panels are aligned vertically and horizontally. Adjacent panels are connected to one another across a tongue and groove joint by a steel key. A cement/bentonite grout is poured into the joint keyway and on both sides of the panels. Thus, the joints are sealed, blocking the infiltration of water into the basement. The figure below shows an end view of a typical panel (Figure 5.5.2).
This innovation has several benefits over the traditional method. For one, it uses much less concrete. This is due to the fact that the precast panels are prestressed and made of higher strength concrete. Thus, they are typically 21 inches thick, while CIP walls are typically 36 inches thick. Second, the precast panels are made with tight quality controls, which gives them much better crack control. Third, the precast walls give the basement a clean interior finish that the CIP slurry walls cannot provide. Inevitably, there are voids and irregularities in the inner face of the trench, which get filled with concrete when the walls are poured in the traditional method. Once the basement is excavated, these voids give the walls an unpleasant finish. Often, a concrete block wall is built up to cover it or the walls are smoothed manually, where both methods are costly and time-consuming. In addition, the CIP method requires the use of more reinforcing steel (Greg Sanchez 1998; Suresh Babu 1998; Kirmani & Babu, Building to Last).

To a project owner, this is a modular innovation because it constitutes a major improvement to a single component of a building through the use of a new construction method. For structural designers, this is also a modular innovation because it requires the engineer to change its design method for structural diaphragm walls. With this system, a designer must consider issues dealing with prestressing, precast fabrication, and integrity of the joints. To general contractors, this is an architectural innovation because it follows a different construction sequence than the traditional CIP concrete system. It is a system innovation for the foundation subcontractor, because it requires them to use a different method of construction in addition to the issues regarding the sealing of the joints between the panels.

5.5.2. **Innovation development and use**

5.5.2.1. **Development**

This case study addresses the precast slurry wall system developed by Trevi Icos, a foundation subcontractor based in Italy with operations in Boston, Massachusetts. Icos was originally exposed to the
concept in Europe and developed its own version for the applications discussed in this section. With the concept in mind, Icos fully developed the details of its system for the first application as described below.

5.5.2.2. Use - Old Colony Rail Line, Kingston, MA

5.5.2.2.1. Search process

This project involved the construction of a 1000-foot retaining wall along a railroad bed adjacent to a highway as well as the construction of two sidewalls for a rail tunnel under a highway. The tunnel was constructed by the cut and cover method with a CIP concrete roof atop the precast sidewalls. Trevi Icos bid this project with the precast slurry wall concept from the start. However, before Icos could even bid it, it had to develop their concept further. Icos’ first step was to solicit bids from several precast concrete manufacturers, including Northeast Concrete Products. Northeast has a lot of experience in producing large, heavy precast concrete sections for heavy civil construction, so this system fit their capabilities very well. Thus, Northeast was the lowest bidder and was chosen by Icos.

With this bid, Icos was able to win the Colony Rail contract. However, it still needed to finalize the details of the system. Icos did not have the expertise to do so, however, so it hired Weidlinger Associates Incorporated, a structural engineering firm, to do this work. The three firms worked together during the design process. Icos made sure that the panels could be handled and erected easily in the field and Northeast made sure that they could be cast efficiently in their plant. Weidlinger provided its skill in prestressed concrete design.

5.5.2.2.2. Project organization

This project was conducted using the design-bid-build delivery system with a general contractor hired to a lump sum contract. This procurement strategy is required of all public projects in the Commonwealth of Massachusetts. The figures below depict the organization chart and value chain for this project, respectively (Figures 5.5.3 and 5.5.4).
The value chain depicted above went through many changes during the course of the project. Since the owner used the design-bid-build delivery system, only the MBTA, the architect and engineer were involved during the design phase. The other participants did not become formally involved in the project until after the bidding phase. Icos issued a bid to the GC based on its prices from Northeast and Weidlinger. Essentially, this delivery system completely separates the design and construction functions from each other. However, in this case there was some redesign.

5.5.2.2.3. Effects on other components and negotiation process

Due to the nature of the project, there was little negotiation required in order to implement the precast slurry wall system. However, important negotiations did occur between Icos, Weidlinger and Northeast. These companies were the primary problem solvers and they are circled in the figure above.
5.5.2.2.4. Appropriation of costs/benefits

On this project, Icos received the benefits of the innovation directly in the form of its contract payment from the general contractor. It then passed some of these benefits along to Northeast and Weidlinger in return for their services. None of these parties could have implemented the innovation alone because they simply do not have the range of capabilities and expertise necessary.

Below is a summary timeline for this project.

<table>
<thead>
<tr>
<th>Design phase</th>
<th>MBTA selects architect/engineer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design is completed using CIP concrete slurry walls</td>
</tr>
<tr>
<td>Bidding phase</td>
<td>Icos solicits bids from precasters and Weidlinger for engineering</td>
</tr>
<tr>
<td></td>
<td>Icos submits bid with precast system</td>
</tr>
<tr>
<td></td>
<td>GC wins job with Icos’s bid</td>
</tr>
<tr>
<td>Construction phase</td>
<td>Weidlinger performs detailed design of precast system</td>
</tr>
<tr>
<td></td>
<td>Panels are installed successfully</td>
</tr>
</tbody>
</table>

Figure 5.5.5 - Timeline for Old Colony Line project

5.5.2.3. Use - Seaport Hotel, Boston, MA

5.5.2.3.1. Search process

The Seaport Hotel was the first building that was constructed with this innovative system. It contains three sub-grade parking levels underneath an 18-story hotel above ground. In the case of the Seaport Hotel, the search process and development progressed differently than it had on the Colony Line project. Weidlinger was selected by the architect to be the structural engineer at the start of the design phase. However, they followed the standard method and designed the structure with a CIP concrete slurry wall. Their design was complicated by the fact that the hotel is located very close to the harbor. This
means that the water table is high, salt water corrosion of rebar must be prevented and tidal forces must be resisted.

When the general contractor, Morse Diesel, solicited bids for the foundation work, several subcontractors, including Icos, responded. Icos was the low bidder, but they also included the precast system as an alternate. Morse Diesel’s policy is to interview the three lowest bidders along with the owner to review the scope and make sure that their bids were complete (Heighton 1998). The two other subcontractors interviewed could not offer the precast system. The owner was initially reluctant to take the risk of being the first to use this system on a building project, but Icos convinced them of its credibility by showing them the rail project and Northeast’s precast plant. The owner was convinced and decided to use the system because they were getting more value for a lower cost, specifically because the system provided them with a smooth interior finish that is necessary for a parking garage.

At this point, Icos again hired Weidlinger to do the design work for the precast slurry wall panels. This is an important point; although they were already contracted to the owner for the building’s design, Weidlinger was paid by Icos to design the precast panels. This design cost had to be included in Icos’ bid for the work. Thus, it posed no extra direct cost to the owner. Also, Icos did not solicit bids from precast concrete manufacturers; they simply negotiated a contract with Northeast.

5.5.2.3.2. Project organization

The organization chart and value chain for this project are shown below.

![Project organization chart](image)

Figure 5.5.6 - Project organization chart for Seaport Hotel project
Figure 5.5.7 - Value chain for Seaport Hotel project

This project was completed using the design-bid-build delivery system with Morse Diesel hired as a general contractor to a low bid GMP contract. As in the Old Colony Rail Line project, Trevi Icos, Weidlinger Associates, and Northeast were involved.

As is normal in construction, the value chain pictured above fluctuated over the course of this project. The changes in the value chain were similar to those that occurred on the Old Colony Line project, however, the difference was that the engineer involved in the design phase was also the engineer used by Icos to perform the slurry wall redesign. Thus, there was a link between the main design phase and the redesign work that took place after the GC was selected.

5.5.2.3.3. Effects on other components and negotiation process

There are two types of coordination issues that arose on this project. First, there was the coordination between Icos, Weidlinger and Northeast for the design, manufacture and erection of the precast panels. Icos held coordination meetings with engineers and project managers from Northeast and Weidlinger to develop the design and to finalize the shop drawings. Because the two firms were directly contracted to them, Icos had the authority to make them work together to solve their problems. Icos also had to ensure that these negotiations did not threaten their budget. This process was made easier by the fact that Icos had working relationships with both firms dating back before the Old Colony Rail Line project. In addition, the principle in charge of this project for Weidlinger seeks to help subcontractors as often as he can. He feels that this is a good way to make projects successful and also to implement innovations. He says that Weidlinger has a developed a reputation for this and as result, subcontractors often approach them with their ideas for innovations, seeking their design expertise (Minhash Kirmani 1998).

Second, there was the coordination of the innovation with the other components of the structure. The panels had to be designed to accommodate openings for utility supply from the street. In addition,
they had to be designed with enough capacity and precision to support the garage floor slabs and superstructure columns that rested on top of the panels. These design requirements did not exist on the Colony Line project; they were specific to the Seaport Hotel project. Thus, Weidlinger had to modify the system to fit a new use. These coordination activities were the responsibility of Morse Diesel. They had to check all of the shop drawings to make sure that there were no conflicts. Weidlinger also played a role in coordinating the garage floor slab elevations with the precast panels. This task was complicated by the fact that the floor slabs are slanted in some areas to provide ramps in the garage. A notch is cast into the panels so that the slabs can be keyed into them. Reinforcing steel dowels are used to connect the two elements. Since Weidlinger was the engineer of the structure and the panels, they were able to coordinate this. Had separate engineers been used, this process would have been more difficult (Heighton 1998). It is important to note that Morse Diesel felt that the coordination work would have been less disruptive if the walls had been designed as precast from the start. In that case, any incompatibilities could have been sorted out during the design development stage rather than after the designs were already complete.

5.5.2.3.4. Appropriation of costs/benefits

The owner benefited on this project because they received a higher quality product for less cost than the conventional system. However, there were some difficulties: several joints between adjacent panels leaked and had to be re-grouted. This marked an additional monetary and reputation cost to Icos, as well as an aggravation cost to the owner. However, CIP concrete slurry walls are also prone to leakage, especially when located near water as in this case.

Icos benefited because they were able to get their system out into the market. They have expanded their range of services, improved their reputation as innovators and differentiated themselves from their competition. It should also be noted that they may not have gotten the project if another subcontractor had been able to offer the precast system. In addition, just as on the Old Colony Rail Line project, Icos chose to share the benefits with Northeast Concrete and Weidlinger. The three firms were able to mutually benefit from sharing their complementary assets. By using Weidlinger, Icos avoided the added cost and liability of adding in-house engineering design capabilities. Icos could have used another precast manufacturer or engineer; perhaps for a lower cost. However, they realize that there is a learning curve involved in innovation and that using the same firms again would be more efficient (Bill Wieners 1998).
Below is a summary timeline for this project.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design phase</td>
<td>Owner selects architect</td>
</tr>
<tr>
<td></td>
<td>Design is completed by Weidlinger, using CIP concrete slurry walls</td>
</tr>
<tr>
<td>Bidding phase</td>
<td>Icos negotiates prices with Northeast and Weidlinger</td>
</tr>
<tr>
<td></td>
<td>Icos submits bid with precast system</td>
</tr>
<tr>
<td></td>
<td>Morse Diesel wins job with Icos’s bid</td>
</tr>
<tr>
<td>Construction phase</td>
<td>Weidlinger performs detailed design of precast system, modifying their previous</td>
</tr>
<tr>
<td></td>
<td>design and coordinating this with the rest of the structural design. Morse Diesel</td>
</tr>
<tr>
<td></td>
<td>checks shop drawings to ensure that all designs are compatible</td>
</tr>
<tr>
<td></td>
<td>Panels installed successfully</td>
</tr>
</tbody>
</table>

Figure 5.5.8 - Timeline for Seaport Hotel project

5.5.2.4. Use - Pilot House, Boston, MA

5.5.2.4.1. Search process

This project involved the construction of an addition to an existing building located on a wharf in Boston Harbor. The new structure contained three sub-grade parking levels at a total depth of 33 feet. The precast system became a part of this project through a different pathway. The owner’s representative heard about the Seaport Hotel project and persuaded the owner to consider Icos’s precast slurry wall system. The owner then had their construction manager ask Icos for a bid. The cost was actually higher than that of a CIP system, but the owner felt that the value added was worth the price premium.

5.5.2.4.2. Project organization

The organization chart and value chain for this project are shown below (Figures 5.5.9 and 5.5.10).
The evolution of the value chain for this project is distinctly different from that of the two previous projects. The owner initially retained an architect and representative to do planning and schematic design work. The owner then sent out a Request for Proposals that included conceptual drawings and rough details of the building configuration. Several firms responded and three were chosen to interview for the contract. Turner Construction Company won with a proposal that actually included the use of a conventional CIP system and a top/down construction sequence. They were hired as a construction manager at risk under a negotiated GMP contract. During the preconstruction phase of the project, they reviewed the designs as they were being developed, providing constructibility advice, budget information and value engineering ideas. This entire phase lasted about four months. It was during this time that the owner asked them to contact Icos about the precast system. Overall, the major difference it
his case was that Turner was involved not only in the construction of this building, but also in its design. Thus, they were able to ensure that the designs of the various components of the project were complete and compatible, thereby making the construction process smoother.

5.5.2.4.3. Effects on other components and negotiation process

The same coordination issues were present on this project. However, because Turner was involved during the design development phase, they were able to ensure that the designs were all coordinated so that construction could proceed smoothly. Dave Page, Turner’s project manager for this job, said that “in the design-bid-build delivery system, incomplete documents can hurt the construction process because they can lead to change orders and conflicts. When a construction manager is used, these difficulties can be avoided.” He felt that this was important to the successful implementation of the precast system on this project. Mr. Page referred to the organization used as a “team approach.” He also said that Weidlinger did a good job of coordinating the design of the panels with that of the rest of the structure (Dave Page 1998). However, just as in the Seaport Hotel, the precast slurry wall system developed leaks at several joints which had to be regROUTed.

5.5.2.4.4. Appropriation of costs/benefits

The appropriation of benefits on this job was similar to the Seaport Hotel project. Again, Weidlinger was contracted to lcos for the panel design work. However, Icos charged more for the precast system than they did on the Seaport Hotel project. This was partly because they had under-priced it on the Seaport job to get it out into the market. It was also due to the fact that on the Seaport job they saw that unforeseen complications in the joints can raise the cost of the system. In addition, they feel that they can charge a premium for the system because of its advantages over the conventional system (Heighton 1998).
Below is a summary timeline for this project.

<table>
<thead>
<tr>
<th>Conceptual design phase</th>
<th>Owner selects architect and representative to assist with construction advice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design is completed by Weidlinger, using CIP concrete slurry walls</td>
</tr>
<tr>
<td>Bidding phase</td>
<td>Owner issues RFP for construction management at risk</td>
</tr>
<tr>
<td></td>
<td>Turner wins project with CIP slurry wall system and top/down construction schedule</td>
</tr>
<tr>
<td>Detailed design phase</td>
<td>Owner has Turner get bid from Icos on precast system</td>
</tr>
<tr>
<td></td>
<td>Icos awarded contract and hires Weidlinger to perform design of panels</td>
</tr>
<tr>
<td></td>
<td>Weidlinger performs design of panels, coordinating with rest of structural design. Turner monitors design development phase to ensure complete and compatible documents</td>
</tr>
<tr>
<td>Construction phase</td>
<td>Panels installed successfully</td>
</tr>
</tbody>
</table>

Figure 5.5.11 - Timeline for Pilot House project
5.6. Hybrid Parking System

5.6.1. Brief description

Traditionally, parking structures have been constructed of steel reinforced cast-in-place (CIP) or precast prestressed concrete. These structures typically consist of large concrete columns supporting post-tensioned concrete slabs. This innovation, the hybrid system for parking structures, constitutes a major conceptual shift from this design paradigm. It replaces CIP concrete with steel beams and columns and precast concrete double tees to create parking garages that have several distinct advantages over CIP concrete designs.

The steel columns are actually paired wide-flange sections joined by welded steel plates approximately every five feet. They are set so that the main axis of each column pair is perpendicular to the axis of the overall line of columns. A pair of steel girders connects each column in each pair at every floor. The precast concrete double tee beams are then attached to these girders. With this superstructure in place, practically any type of façade construction can be used, including brick, precast concrete or stone panels.

This system has several advantages over traditional CIP concrete designs. First, it has the advantages of precast concrete construction, which include durability, quality control and ease of erection. The double tee beams can be erected quickly and easily in the field, even during inclement weather. In CIP concrete construction on the other hand, all of the forming, pouring and curing must take place in the field, subjecting the project to quality control and weather-related problems. Also, the design of the steel structure makes it self-supporting during erection, so there is no need for temporary shoring. In the direction of the overall column line, the structure is supported by the frame action of the beam and column system. In the transverse direction, it is supported by the paired columns, which act like a ladder frame cantilevering from the ground. In addition, because the system is modular, it can be readily adapted to different bay sizes, floor heights and circulation patterns.

There are other advantages as well. In CIP concrete garages, there are typically concrete shear walls to provide for lateral stability. The hybrid system eliminates these, thereby opening up the space visually to allow for a sense of security and improved circulation of people and air. In addition, the precast double tees can be placed more accurately to ensure proper floor pitch for drainage. This is important because salt water puddles in garages can corrode the steel components of the structure.
5.6.2. **Innovation development and use**

5.6.2.1. **Development**

The hybrid system for parking structures was developed by Zaldastani Associates, a structural engineering firm based in Boston, Massachusetts. They developed the concept over several years, starting in the 1960’s with the design of the Central Parking Garage at Logan Airport in Boston. This was the first time that they used precast concrete decking, although the columns were of CIP concrete. Later, they renovated Harvard Stadium, replacing the seating with precast concrete members. On this project, they concentrated on detailing of the connections in order to prevent corrosion of the steel support structure. The first hybrid parking structure was built soon after that in Cambridge, Massachusetts. The system has been refined and improved with each application since (Jollife 1998).

From an owner’s perspective, this is an incremental innovation. This is because a hybrid parking garage functions like any other garage, except that it is cheaper and has some quality and circulation improvements. For Zaldastani, it is a modular innovation, because it overturns a core concept of garage design, the use of CIP concrete. From the perspective of a general contractor, it is an architectural innovation, because it changes the relationships between various components of a typical parking garage. For one, the contractor must coordinate the simultaneous delivery and erection of both steel and precast concrete elements, rather than just CIP concrete construction. This is difficult due to the different fabrication times and delivery schedules required for the steel and precast members and the different trades involved. In addition, the contractor has to coordinate the installation of mechanical systems, such as fire protection pipes and lighting conduits. In a hybrid structure, these elements run vertically through the area between paired columns and horizontally along the underside of the double tees.

5.6.2.2. **Use - Dow Jones Garage, Princeton, New Jersey**

This facility, completed in 1997 has a capacity of 700 cars and was built in conjunction with an office building for the Dow Jones Corporation. The entire project, from design through construction lasted only four months.

5.6.2.2.1. **Search process**

The story behind how this innovation came to be implemented on this project is quite interesting. Interstate Iron Works Corporation, a structural steel fabricator and erector from New Jersey won the steel contract for the office building at the site. At that point, they heard that the owner was soliciting bids for design-build services for a parking garage on the site. The owner provided bidders with conceptual
drawings for the garage, including elevations, a building plan and circulation patterns. Interstate immediately contacted Zaldastani, and the two firms worked together to complete a preliminary design and bid the project. Interstate had already worked with Zaldastani on the construction of another hybrid garage for Lucent Technologies, so they knew of its potential. Before accepting Interstate’s proposal, Dow Jones had their construction manager, Bovis Construction, review it. With Bovis’s approval, and the benefit of the low cost of the system, Dow Jones Corporation accepted Interstate’s proposal.

As partners on this project, Zaldastani and Interstate shared their competencies in structural design and steel fabrication and erection, respectively. Interstate also acted as the general contractor on the project, managing subcontractors for the foundation construction and the mechanical systems installation.

5.6.2.2.2. Project organization

The project organization chart is shown in the figure below (Figure 5.6.1). The owner contracted on a lump sum basis with Interstate for design-build services. Interstate paid Zaldastani a fee for the design of the garage. Interstate then subcontracted with a local precast concrete manufacturer for the fabrication of the precast concrete double tees. It also subcontracted for the design and installation of the mechanical systems and other items of work, such as the foundation and façade. Bovis Construction was the construction manager for the overall program, including both the office and garage projects.

![Project organization chart for Dow Jones Garage](image)

The value chain for this project is shown below (Figure 5.6.2). It is quite simple from the owner’s perspective because Interstate provides them with a single point of contact for design and construction. For the implementation of the innovation itself, the main collaborating partners were Interstate, the precaster and Zaldastani, as shown by the dashed circle. These firms pooled their competencies to make this implementation a success. Interstate provided overall construction.
management as well as fabrication and erection expertise to the project team. The precaster added their skill in precast concrete fabrication. Finally, Zaldastani brought in their skill in structural design and their knowledge of design issues specific to parking garages.

![Value chain for Dow Jones Garage project](image)

Figure 5.6.2 – Value chain for Dow Jones Garage project

5.6.2.2.3. Negotiation process

The main negotiations related to the implementation of this innovation took place between Zaldastani and Interstate. The two firms worked together to coordinate the details of the structure, especially the connections between the precast concrete elements and the steel members. This connection is not normally encountered in construction and, according to Zaldastani, many firms are not experienced in making this connection. To avoid complications related to this, Zaldastani attempts to fully detail these connections so that the contractor understands them before construction begins (Jollife 1998).

Zaldastani also attempts to avoid problems with the precast concrete elements. Since the hybrid system is modular, they are able to complete their design quickly, which allows them to order materials with long lead times sooner (Jollife 1998). This avoids delays due to delivery of materials during the construction phase.

5.6.2.2.4. Appropriation of costs/benefits

The owner reaped several benefits in this case, primarily in terms of cost savings due to the efficient use of materials in this system and the speed of delivery. Not only is the duration of the construction phase reduced through the use of modular elements, but the design phase was also expedited due to Zaldastani’s experience and the design-build delivery system.

Zaldastani and Interstate both benefited as well. For one, they became more experienced with the system, which brings them further up the learning curve. In addition, they only won the contract because they proposed this innovation. It should also be added that Interstate’s position on this project is unique
for them. Normally, they work as a subcontractor, so working in a lead, general contractor-type role on this project was a major shift for them. Bob Abramson, of Interstate, commented, “Precasters work with contractors and engineers in this type of partnering arrangement quite often and it is important for steel fabricators to start getting involved in these arrangements.”

5.6.2.3. Use - Tufts Health Plan Garage, Watertown, Massachusetts

This parking garage has a capacity of 1400 cars and was erected in just 38 days. Design work began in July, 1997 and construction was completed in January 1998. The garage was one component of a larger development project that also included the renovation of 290,000 square feet of office space and the construction of another 70,000 square feet of new office space.

5.6.2.3.1. Search process

In this case, Zaldastani teamed up with the construction manager for the office construction portion of the project and submitted a proposal to the developer. Thus, it was similar to what happened on the Dow Jones project. Another similarity is that the owner selected the system over a conventional one based on its low cost.

5.6.2.3.2. Project organization

This project was organized similar to the Dow Jones project. The developer was Prospectus Properties. They hired Kennedy and Rossi (KRI), a construction firm based in Lexington, Massachusetts, to provide construction management (at risk) services for the overall project. Prospectus had a separate architect and engineer for the office portion of the project, but Zaldastani was contracted to KRI for the engineering design of the garage. Thus, for the garage portion of the project they used the design-build delivery system, while the office work was done on a design-bid-build basis. Prospectus had a GMP contract with KRI. Zaldastani was paid a fee by KRI for their design services. KRI contracted with Northeast Concrete Products of Massachusetts for the fabrication of the precast concrete double tees. In addition, they had a subcontractor for the fabrication of the steel. Another subcontractor provided erection services for both the steel and precast members. The organization chart for the garage is shown in the figure below (Figure 5.6.3).
The value chain for this project is shown in the figure below (Figure 5.6.4). It shows that KRI had several interfaces to deal with. They subcontracted the work differently than Interstate did on the Dow Jones project. Interstate, as a steel fabricator and erector, was able to perform much of the work directly related to this innovation itself. KRI on the other hand, had to subcontract the fabrication and erection work separately.

5.6.2.3.3. Negotiation process

There were several coordination issues arising from the use of the hybrid system on this project. First, there was the coordination between Northeast Concrete and Zalastani. Zalastani claims that they are able to get precast concrete products for 20 to 25% less money than general contractors can because they fully describe the system in the drawings, which makes the precaster’s job much easier. Thus, precasters typically will not include the contingencies that they would include when they submit a price to a general contractor (Michael Jollife 1998). Zalastani also tracks precast concrete prices very closely,
which is important because these prices fluctuate widely. In this way, they are able to order materials at a lower cost.

KRI was confronted with several coordination problems during the construction process. For one, Zaldastani did not include the rainwater drain pipe hole locations in the shop drawings for the precast concrete beams. Thus, KRI had to drill these holes in the field at approximately four times what it would have cost to have the precaster include these holes during fabrication (Fligg 1998).

In addition, in Zaldastini’s drawings, the gap where the ends of the tees butted up against each other was one inch. However, due to small irregularities in the precasting and erection processes, this gap varied from less than one inch to as much as 2.5 inches. This gap has to be covered with a layer of concrete to prevent water from reaching the underlying steel structure. However, the concrete would have fallen through such large gaps. Realizing this, KRI approached Zaldastani for a solution. Zaldastani replied that they had seen this happen on other jobs, but that they did not know what other contractors had done to cover the gap. KRI devised their own solution consisting of a thin rubber sheet to bridge the gap and hold the concrete in place as it cured (Fligg 1998).

KRI faced its most difficult coordination issues in the delivery and erection of the structure. There was little on-site area for storage of materials, so the delivery of the precast and steel members had to be timed well with the progress of the erector. The work proceeded faster than KRI anticipated, so their delivery schedule fell behind, slowing the project down.

Dave Nilson of KRI commented that they were happy with the system due to its ease of erection and low cost. He said that this project was a good learning experience for them and that they know what to expect in the future. KRI and Zaldastani have now bid on two more garages since this one. Mr. Nilson say that he will be sure to address all coordination issues during the design phase on future projects to avoid delays during construction.

5.6.2.3.4. Appropriation of costs/benefits

Prospectus benefited from this innovation just as Dow Jones did in the previous case. They saved money and time and received a quality facility. KRI may be able to reap benefits from future projects as a result of the relationship that they developed with Zaldastani on this project. Zaldastani benefited from this project because they won the contract and received revenue from it.
In both projects, the events occurred in the same sequence and at similar stages of the project. This sequence is shown in the timeline below.

<table>
<thead>
<tr>
<th>Conceptual design phase</th>
<th>Owner selects architect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Architect develops conceptual design for the garage, including circulation patterns, elevations and overall dimensions</td>
</tr>
<tr>
<td>Bidding phase</td>
<td>Owner solicits bids for design-build services for the garage</td>
</tr>
<tr>
<td></td>
<td>Contractor contacts Zaldastani to put together a design and bid proposal. They bid and win.</td>
</tr>
<tr>
<td>Detailed design phase</td>
<td>Zaldastani completes their design.</td>
</tr>
<tr>
<td>Construction phase</td>
<td>Contractor completes construction of parking garage, using the hybrid system.</td>
</tr>
</tbody>
</table>

Figure 5.6.5 – Timeline of implementation of the Hybrid Parking System
5.7. Double Helical Ramp

5.7.1. Brief description

The Double Helical Ramp is an innovation that provides an alternative method of circulating cars within a parking structure. It consists of two intertwined helical ramps made of cast-in-place concrete. One ramp is for traffic going up and one is for traffic going down in the garage. The double helix is positioned adjacent to the garage so that one edge of it intersects with the floors of the parking structure. The photo below shows how a double helical ramp connects to a parking structure (Figure 5.7.1).

![Image](image-url)

Figure 5.7.1 – Example of a double helical ramp (ENR 1998)

Parking structure designers usually implement straight ramps within the floor area of garages for circulation. However, this practice has several drawbacks. One, it breaks up the floor plan of the garage, which presents engineering and construction challenges. The straight ramps also take up a large amount of floor area, which increases the total footprint of a structure.

The double helix can eliminate the need for these ramps, thereby leaving the floor slabs continuous and flat, which simplifies the engineering and construction of these floors and lowers their cost. In addition, because of its geometry, this innovation uses space more efficiently; the parking density is higher. This high density makes it suitable for tight sites and increases the economic performance of the facility. However, this innovation also has negative aspects. For one, it is expensive, with a cost of
approximately $300,000 for each 360-degree section. In addition, its geometry is very complex. The complex geometry makes it difficult to design, especially since it is typically post-tensioned. Fabricating the formwork used to cast the concrete is also difficult because the ramps are simultaneously slanted upwards, curved and pitched toward the center.

From an owner’s perspective, this is an incremental innovation because it only changes the efficiency of the garage without changing its function appreciably. For designers, it is a modular innovation because it changes the standard concept for circulation. For concrete subcontractors, the Double Helical Ramp is an architectural innovation because it requires a unique construction sequence. The ramps are typically built in a staggered fashion: 180-degree sections of each ramp are built and supported on top of each other during construction. For formwork subcontractors, it is an incremental innovation. A typical formwork contractor has experience in fabricating formwork for slanted or curved structures, so they often are able to build formwork for a double helix.

5.7.2. Innovation development and use

5.7.2.1. Development

Several engineers have designed this system over the years. This paper does not address the development of this innovation from the engineering perspective. Instead, this paper concentrates on the development work done by the contractors who attempt to implement this system. The following case studies show that formwork and concrete contractors must perform project-specific development work to build this type of structure.

5.7.2.2. Use - Logan Airport West Garage, Boston, Massachusetts

This seven-story garage, completed in September 1998, has a capacity of over 3000 cars. Its total cost was approximately $85 million. It was constructed to provide much needed parking facilities for Logan Airport in Boston.

5.7.2.2.1. Search process

The configuration of this parking garage is shown in the plan below (Figure 5.7.2). The helix was placed into a notched corner of the structure. Thus, the ramps are 90 degrees out of phase with each other. At each floor, both helical ramps are connected to the garage by short bridges, eliminating the need for straight ramps within the garage floor plan. Thus, the floor slabs could be totally flat.
5.7.2.2.2. Project organization

The owner in this case is the Massachusetts Port Authority (Massport). It used the design-bid-
bid-build delivery system for this project, as per state regulations. This project is one component of Logan
2000, a large modernization and expansion program that includes several construction projects at the
airport. Massport hired Tishman Construction for a fixed fee as the construction manager for all projects
within the Logan 2000 program. They hired TAMS Consultants to design the West Garage. After a
competitive bidding process, they awarded the construction contract to Modern Continental Construction.
Modern in turn hired Simons Construction to design and fabricate the concrete formwork and G & C
Concrete of New Hampshire to install the formwork. Modern performed the actual pouring of the
concrete. The figures below depict the project organization chart and the value chain.

Figure 5.7.3 – Project organization chart for Logan West Garage
5.7.2.2.3. Negotiation process

To implement this system on this project, a lot of negotiation was required. First, TAMS became involved during the bidding process in order to help the bidders understand the geometry of the system. They assembled a scale model of the structure and used it to illustrate how the double helical ramp fit in with the parking structure. This visualization tool was important because TAMS was the only project team member that had experience with this system (Lenie 1998).

During construction, there were negotiations as well. Simons fabricated special formwork specifically for this project and helped G & C when they began to install them. The subcontractors worked in a team with Modern Continental to make this implementation a success. According to George Jenkins, Tishman Construction’s superintendent on the site, “G & C Concrete is very progressive: they won’t back down from anything difficult.” The formwork was fabricated in four large sections that together formed a 180-degree section of one helical ramp. These pieces were re-used 28 times on this project; there were seven levels and two helixes. Thus, G & C was able to achieve economies of scale with the formwork; the initial cost of the formwork was spread out over many uses within one project (Lenie 1998).

5.7.2.2.4. Appropriation of costs/benefits

In terms of costs and benefits, the owner paid the cost premium to have a garage with an efficient ramp system. This was important to Massport because the site is very congested and they needed to maximize the capacity of the facility. TAMS was able to make use of their previous experience with double helical ramps. An interesting aspect of this project is that the formwork fabricated by Simons is essentially a fixed asset. Massport paid Simons to develop this asset, but Simons has ownership of them. Thus, they may be able to use them on a future project, as long as the geometry fits.
5.7.2.3. Use - Empress Casino Garage, Hammond, Indiana

This project involved the addition of a double helical ramp to an existing nine-story garage at a casino. Construction lasted eight months and provided much-needed access to this busy parking facility. The lower three floors of the garage are used for valet parking and will be accessed by the existing straight ramp system. The double helical ramp will be used for non-valet parking on the other floors.

Each helix connects with alternating floors of the structure. In other words, the upward helix starts at the first floor and intersects with odd-numbered floors of the structure. Likewise, the downward helix intersects with even-numbered floors. Thus, the straight, two-way ramps in the garage are still used. For example, to drive up to the sixth floor, one would take the upward helix from the first floor two times around to the fifth floor. Then, one would enter the garage and take a short ramp from the fifth to the sixth floor. Similarly, to exit from the seventh floor, one would take a short ramp, located within the garage, down to the sixth floor. Then, one would follow the downward helix twice around to the second floor. Finally, one would take a straight ramp inside the garage down to the first floor and out of the garage.

5.7.2.3.1. Search process

Walker Parking Consultants of Chicago was the designer on this project. They have a lot of experience with this system, having designed roughly 50 double helical ramps over the past 20 years. Thus, when the owner told them that they had access problems with their garage, they immediately suggested the double helix.

5.7.2.3.2. Project organization

The owner, Empress Casino, hired Walker as its designer based on their qualifications and paid them a fee for their services. After Walker completed their design, the contract documents were released for bid. The owner used the traditional design-bid-build delivery system. The general contractor, Superior Construction of Gary Indiana, was selected because it was the lowest bidder. Superior signed a lump sum contract with the owner. For the formwork, Superior solicited bids from three contractors and made its selection based on a combination of low cost and qualifications. The formwork subcontractor used Super Stud Frames, a commercially available modular formwork system and adapted them for use on the double helix. The Super Stud Frames are manufactured by EFCO. The project organization chart and value chain are depicted in the figures below.
Figure 5.7.5 – Project organization chart for Empress Casino Garage

Figure 5.7.6 – Value chain for the Empress Casino Garage project

5.7.2.3.3. Negotiation process

Unlike TAMS, Walker did not play a role in translating the design for the contractors, although none of them had ever built this type of ramp before. Walker did only what they are required to do under their contract: they designed the structure and completed the contract documents. They did not take any steps to explain the system to the contractors as TAMS had. Gary Cook of Walker commented, “We did not help the formwork or concrete subcontractors at all. We are not supposed to get involved in the contractor’s means and methods.” Thus, this project was very traditional; there was a strong division between the design and construction processes.

Mr. Cook made an important point that “The double helical ramp is difficult because it is like stick-built construction: you have to build small sections of formwork to create the curves. With a long beam, you can build and re-use larger sections of formwork.”
The formwork subcontractor had never done a double helical ramp before, but they had the competencies to submit a winning bid and complete this project because they had experience in forming slanted and curved structures for transportation projects.

5.7.2.3.4. Appropriation of costs/benefits

The owner benefited because they were able to add access to their parking facility without taking up much site area. Walker benefited from being awarded the contract and receiving a fee from the owner. The formwork subcontractor benefited because they were able to find a creative and economical solution for forming this structure. Unlike Simons on the Logan project, they did not spend as much effort on fabricating curved forms from scratch; instead they adapted a modular system to fit their needs.

Both projects had the same delivery system, so their timelines are similar. Below is a timeline that shows the order of events for both projects (Figure 5.7.7).

<table>
<thead>
<tr>
<th>Design phase</th>
<th>Owner selects designer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design completed</td>
</tr>
<tr>
<td>Bidding phase</td>
<td>General contractor selected based on low cost</td>
</tr>
<tr>
<td></td>
<td>Formwork fabricated and installed.</td>
</tr>
<tr>
<td></td>
<td>Concrete is cast</td>
</tr>
</tbody>
</table>

Figure 5.7.7 – Timeline of Empress Casino Garage project
5.8. Fabric Roof

5.8.1. Brief description

There are many alternatives available for the design of roofs for buildings. The concept chosen usually depends on the building type and aesthetic needs. For example, office building roofs are typically flat and constructed of steel beams and corrugated metal decking covered by a waterproof membrane. However, some buildings, such as arenas or large assembly halls, have very long spans, which make the standard system uneconomical. Concrete or steel domes and steel truss systems are common for these applications. Other more aesthetically driven designs may incorporate trusses to support glass to create an atrium space, or tensile fabric 'tents' to cover large open areas. Roof design concerns for all projects generally include aesthetic issues as well as the wind and snow loads specific to the site.

In recent years, there have been many applications of fabrics in roof designs. Some examples include major sports arenas such as the Carrier Dome in Syracuse, New York, the Denver International Airport in Colorado, and the Millenium Dome currently under construction in London. Fabrics are an excellent alternative to standard materials for some projects because of their low weight and translucency. They can also be formed into a variety of graceful and creative curved shapes. However, they tend to become discolored over time and they are not insulated. In some cases, they can be constructed in a double layer to provide a space for insulation, but this approach leaves them opaque. An even bigger concern is that the life span for the fabric is less than 25 years (Schiff 1998). The cost and disruption caused by reconstruction may be undesirable for some applications.

The fabrics come in a variety of types, with different strength, life span and translucency characteristics (Salvadori 1986). The strongest type is Teflon-coated glass fiber fabric, which is unfortunately very expensive. Typically, the fabric is supported by tensioned steel cables or a system of steel trusses. The fabric comes in sheets and must be stretched over the structural form and secured in place. If the fabric tears, it can be easily patched.

This case study investigates the development and application of an innovative fabric roof design. The system consists of a translucent, PVC-coated polyester fabric stretched over curved steel I-beams. The fabric comes in 56 inch wide rolls, which are welded together to form 16 foot wide sheets to span between the curved beams. It uses a patented connection mechanism developed specifically for tensioning and connecting the fabric to the curved beams. This system differs from the manufacturer's typical method to connect adjacent sheets of fabric. Normally, the fabric is pulled taut from its ends and the seams between adjacent sheets are laced together. However, in this case, the fabric sheets were tensioned along this seam at each curved beam. This connection was developed because the architect
wanted the fabric sheets to be separated by the curved beams, rather than have the sheets cover the beams completely.

Figure 5.8.1 – Isometric view of Fabric Roof support structure (Collins 1998)

Figure 5.8.2 – Isometric view of fabric tensioning system (Collins 1998)
From the owner's perspective, this is a modular innovation, because it changes only the characteristics of the roof. However, this innovation does constitute a major change in the concept behind roof design for the architect and structural designer. Normally, roofs are intended simply to support wind and snow loads and to keep water out of the building. However, this system changes that concept by making the roof translucent; the focus shifts from the roof's function to its appearance. It can be seen as an architectural innovation for the architect because it changes the aesthetic links of the roof to other systems, such as the lighting and exterior wall systems. To Rubb, this is a system innovation, because the roof consists of multiple innovations, including the architectural fabric, the curved members and the new patented connections. The set of individual innovations is integrated into a wholly new roof system. The materials and connection methods used are all different than those of the standard roof system.

5.8.2. **Innovation development and use**

5.8.2.1. **Development**

This innovation was developed by Rubb Building Systems, a manufacturer of tensioned fabric structures that can be relocated easily. It is a vertically integrated company; it provides a full scope of services including planning, design, fabrication, erection of structures and even site work and installation of mechanical systems. It also offers maintenance service during the life of the building. For the most part, it offers a set of standard designs that can be adapted to meet the size requirements of different projects. Typically, these fabric structures are used for aircraft hangars, warehouses and temporary shelters. The strength of Rubb's standard building systems is that they are modular and therefore, they are easy to manufacture and erect.

Rubb first developed this innovative fabric roof for an occupied building for the Temporary Powell Library building at UCLA, constructed in the early 1990s. UCLA needed a fast and cost-effective temporary structure to use while the Powell Library was undergoing a seismic upgrade. The architect, Hodgetts and Fung, chose Rubb because they wanted the aesthetic appearance of the translucent fabric. A system of aluminum ribs was used to support the fabric. Rubb developed its patented connection system of the tensioned fabric to the curved beams specifically for this project. The design won praise in the architecture community as an innovative use of architectural fabric (Collins 1998, Rubb product literature).

In terms of competencies, this innovation requires architectural design skill in addition to structural engineering expertise. In addition, it requires knowledge of the use of architectural fabrics, including how they can be installed and how they can be connected to the underlying structure.
5.8.2.2. Use - JFK Airport International Arrivals Building Temporary Domestic Baggage Claim Area, New York, New York

This building measures 70 feet by 96 feet and was intended to provide a temporary baggage handling area while a new terminal was constructed (Figure 5.8.3). The owner needed the project to be done quickly and for low cost. The overall cost of the project was roughly $3 million and it took approximately one year from design through construction, finishing in 1995. It is scheduled for demolition in late 1998, after the new terminal is completed.

Figure 5.8.3 – Fabric Roof installed at JFK Airport building

5.8.2.2.1. Search process

The owner, the Port Authority of New York and New Jersey, hired David Liebowitz Architects (DLA) to perform the conceptual design of the building. In its design for the building, DLA’s greatest concern was foundation work. They knew that there were extensive underground utilities on the site, but their exact locations could not be accurately determined. The principal in charge of the project for DLA, Michael Schiff, pointed out a similar situation a few years earlier at Newark Airport which ended in disaster as foundation workers driving a pile damaged a critical electrical supply line, cutting power for days. Fortunately, there were footings on the JFK site that had previously supported bus waiting area canopies. DLA sought to use these footings as much as possible in order to keep foundation work to a minimum, and to speed up the construction process (Schiff 1998).

DLA chose to use a fabric roof, which it hoped would prove more economical than a conventional insulated metal deck for the spans required. However, the company had no prior experience with this type of construction (Schiff 1998). The designer in charge investigated several fabric roof manufacturers, including Rubb and Birdair (Birdair fabricated and constructed the well-known fabric roof for the recently completed Denver International Airport). However, he found that Birdair’s system was expensive and did not fit the layout of the building very well, while Rubb’s system conveniently fit the regular geometry of the existing footings.
5.8.2.2.2. Project organization

The Port Authority hired DLA and Ysrael A. Seinuk (YAS), a structural engineering firm, to develop the conceptual design of the building. Based on this conceptual design, it issued a request for proposals from firms to provide design/build services for the project. Four teams bid on the project and the lowest bidder was selected. The winning team was a joint venture of TAMS Consultants, an engineering design firm, and VRH Construction, and it was hired to a lump sum contract. The joint venture was responsible for the detailed design and construction of the entire project. The organization chart and value chain for this project are shown below (Figures 5.8.4 and 5.8.5).

![Diagram of project organization chart for JFK Airport project]

**Figure 5.8.4 – Project organization chart for JFK Airport project**

Below is the value chain for this project (Figure 5.8.5).

![Diagram of value chain for JFK Airport project]

**Figure 5.8.5 – Value chain for JFK Airport project**

During the conceptual design phase, only DLA and YAS were involved in the project. Once their work was completed and a design/build team selected, they left the project. VRH TAMS was then
responsible for the rest of the work. The joint venture companies pooled their respective talents in construction and design to complete the work. The joint venture solicited bids from subcontractors, including fabric roof manufacturers, when it put together its proposal for the work. It selected Rubb for the design and fabrication of the roof system because it had a lower cost and more suitable geometry than Birdair’s system. A separate erection subcontractor was hired by Rubb to install the roof. Thus, the roof was essentially a small design/build contract within the overall project. The dashed oval indicates the firms that had to work together to make the implementation of this innovation successful.

In terms of relationships on this project, VRH and TAMS had worked together before, once as a joint venture. They are happy with how they supplement each other’s competencies and are looking for more opportunities to form joint ventures for design build projects (Curran 1998). Otherwise, there were no significant relationships among the project team members.

5.8.2.2.3. Negotiation process

The fact that the design was started by one set of firms and completed by the joint venture team led to coordination problems. Maury Curran, the project manager from VRH for this project, said that DLA attempted to influence the joint venture’s detailed design work, even though DLA had no contractual relationship with the joint venture (Curran 1998). VRH TAMS had to take the conceptual design, which is incomplete by nature, and develop it fully. Thus, they had to fill in the gaps in DLA’s work. For example, they had to figure out exactly how to route service runs. One of their solutions was to clamp the sprinkler pipes to the underside of the curved roof beams in order to make them less obtrusive.

There was also extensive negotiation work between Rubb and DLA, during the conceptual design phase, and VRH TAMS during the detailed design phase. In the first case, Rubb reviewed DLA’s concept for the roof design and made suggestions to make it easier to manufacture and install. Rubb showed DLA the connection system it had developed for the UCLA project and gave DLA information on the performance characteristics of the fabric, which dictates the spans achievable. During the detailed design phase, Rubb worked with VRH TAMS to finalize the details of how the roof would fit in with the other building components, such as the services and walls. During this phase, VRH TAMS was the integrator agent responsible for coordinating the design effort. Because they are in a joint venture for design and construction, they internalize most of the coordination of the design and construction work.

It is also important to point out that since Rubb is a vertically integrated firm, it eliminates some members from the value chain. For example, it has design and fabrication functions in-house. This organizational structure internalizes the interface between the design and fabricator. Rubb generates its own design and internally produces shop drawings and fabricates the system.
It is also important to comment on Rubb because it is involved in the construction industry, but it operates like a manufacturer. According to Gordon Collins of Rubb, the company’s main goal is to manufacture standardized relocatable fabric structures. Thus, the UCLA and JFK projects were a departure for Rubb because these projects required it to develop a new system with a different configuration of elements. Mr. Collins actually said that Rubb does not actively aim its marketing efforts at the occupied buildings market and that it sometimes turn down this type of work when potential clients approach it. This is interesting because while both UCLA and JFK were very successful projects, Rubb does not want to get heavily involved in this market. It seems to be exhibiting the typical mentality of manufacturers; they focus on the production of standardized products. On the UCLA and JFK projects, however, they had to work more like a construction firm; they had to specially modify their system to meet a specific situation.

5.8.2.2.4. Appropriation of costs/benefits

This innovation reduced the overall cost of this project because it is very light, which reduces the number and size of steel supports needed and the depth of foundation work. In addition, the project was completed quickly because the owner used a design/build team to fast track it. Thus, the owner reaped benefits due to the low cost and fast completion. Rubb benefited as well because they won the contract and made money. The conceptual design team appropriated few benefits from initiating the process, but the design/build joint venture appropriated the benefits from decreased cost, increased construction speed, and the aesthetics of the tensile fabric structure.
Below is a summary timeline for this project (Figure 5.8.6).

<table>
<thead>
<tr>
<th>Conceptual design phase</th>
<th>Owner selects DLA and YAS to do conceptual design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DLA develops a concept for a fabric roof and investigates suppliers</td>
</tr>
<tr>
<td>Bidding phase</td>
<td>Owner issues RFP for design build services</td>
</tr>
<tr>
<td></td>
<td>VRH TAMS wins project with Rubb as roof designer/fabricator</td>
</tr>
<tr>
<td>Detailed design phase</td>
<td>Rubb completes detailed design work on roof</td>
</tr>
<tr>
<td></td>
<td>TAMS finishes design of rest of building</td>
</tr>
<tr>
<td></td>
<td>VRH TAMS coordinates design effort</td>
</tr>
<tr>
<td>Construction phase</td>
<td>Fabric roof installed</td>
</tr>
</tbody>
</table>

Figure 5.8.6 – Timeline for JFK Airport project
5.9. Tension Braced Dome

5.9.1. Brief description

The concept for this design combines the best features of a tensegrity cable dome and a single-layer braced dome. In a tensegrity structure, a combination of steel cables and rigid members are used to create a very lightweight structure capable of spanning long distances efficiently (Salvadori 1986). An example of a single-layer braced dome is a thin reinforced concrete dome. Such structures have a simple load path. However, the Tension Braced Dome does not require the compression ring of a cable dome. The compression ring is located along the perimeter of a cable dome; all of the roof loads are transferred to it, putting the ring in compression. The Tension Braced Dome also has better buckling stability than a single-layer braced dome, which is an especially important consideration in Buffalo, where there is a lot of snow. Due to their small thickness, single-layer braced domes can buckle and collapse under extreme loads (Salvadori 1986). This is a very important consideration in the design of these structures.

5.9.2. Innovation development and use

5.9.2.1. Development

The tension braced dome was developed by Birdair, from Amherst, New York, a designer and erector of long-span roofs for structures such as arenas and airports. Birdair developed the concepts behind this innovation based on other long-span roofs that they had done. One of these projects was the Georgia Dome, which has a tensegrity roof that uses cables extensively. However, they finalized the details of the system during their design of the roof of the Marine Midland Arena, as discussed in the following section.

5.9.2.2. Use - Marine Midland Arena, Buffalo, New York

This arena, completed in the fall of 1996 at a cost of $85 million, seats over 20,000 people. The roof system is a combination of a tensegrity cable dome and a braced barrel dome and is patented by Birdair under the name Tension Braced Dome Structure. It marks the first use of the Tension Braced Dome. As shown in the plan view below (Figure 5.9.1), the roof consists of a half-domed portion at each end and a 36.6-meter long barrel-shaped center section. The ends have a plan radius of 51.8 meters and the overall roof plan measures 140.2 by 103.7 meters (Terry et. al. 1997).
5.9.2.2.1. Search process

Originally, the owner on this project hired Ellerbe Becket to provide architectural and engineering services, including the design of the building superstructure and roof. In the conceptual design phase, EB proposed a conventional one-way steel truss design for the roof. At this point, Birdair approached the construction manager, Huber Hunt and Nichols (HHN), with their tension braced dome concept. The two firms had worked together before on the construction of the Carrier Dome in nearby Syracuse years earlier. Birdair wanted the Marine Midland Arena contract because it was located nearby and was in their niche.

Birdair submitted their ideas to the owner and Ellerbe Becket through HHN as a value engineering proposal. HHN supported the idea because they found that it fit the architecture of the arena and their quick estimates showed that it would save money over EB’s design. EB approved of the concept as well. They also had worked with Birdair before. Birdair was accepted by the owner and became a subcontractor to HHN for the preliminary design and construction of the roof. The owner was mainly driven by cost on this project and that is why they chose to use Birdair’s design over the traditional design. EB remained as the architect and engineer for the remainder of the structure. They also performed the detailed design of the roof.

Bill Mullin of HHN said of the project, “all three firms felt comfortable with each other.” He also added, “three strangers showing up at the table would have been a lot tougher because they would not have felt so comfortable” (Mullin 1998).
In terms of competencies, Birdair and Ellerbe Becket overlapped in terms of their structural engineering abilities. EB served mainly to verify Birdair's design and to work out the details. In this way, it remained the engineer of record for the entire project. Birdair brought its expertise in the construction of long-span roof structures to the project.

For the owner, this was an incremental innovation because from their perspective it simply lowered the cost of the roof without changing its appearance or performance considerably. For the structural engineer that designs this structure, it is a modular innovation, because it involves a change in the concept of dome structures. This innovation is based on the idea of tensegrity, which is a conceptual shift from conventional designs that employ familiar truss systems. Tensegrity structures typically employ a system of tension carrying cables coupled with rigid members to create a lightweight, efficient structural system. Designing such structures requires an in-depth understanding of structural behavior and load patterns.

5.9.2.2.2. Project organization

The owner of the arena is the Buffalo Sabres. They hired Huber Hunt and Nichols (HHN) as a construction manager at risk with a GMP contract. The owner also hired Ellerbe Becket for architecture and engineering services. HHN also contracted with Birdair on a lump sum basis to provide design-build services for the roof. The overall project organization structure is shown in Figure 5.9.2.

![Diagram of project organization chart for Marine Midland Arena](image)

The overall value chain for this project is shown in Figure 5.9.3. Birdair was linked to Ellerbe Becket on the design of this structure and to Huber Hunt and Nichols on its construction. Birdair subcontracted for the fabrication of the steel members for the roof structure. The dashed circle is used to
highlight the fact that the main collaborating parties on this project were Birdair and Ellerbe Becket. Two factors made the implementation of this innovation successful. One, the owner committed to use the innovation early in the design phase. Second, HHN, as the construction manager, was involved in the project from the very beginning. This early commitment meant that HHN was able to work with Birdair and Ellerbe Becket throughout the design phase to coordinate their work, and allowed them to gain a full understanding of the design so that they could translate it more easily in the construction phase.

![Figure 5.9.3 - Value chain for Marine Midland Arena](image)

5.9.2.2.3. Negotiation process

Birdair initially wanted to use prestressed cables in portions of the roof, but they could not make it work, given the architecture of the arena and economic issues. One of the issues was that the unbalanced snow and rigging loads on the roof would have created local or even global instabilities by making some cables go slack. In addition, in cable dome construction, the cables must be prestressed using jacks, a process that takes more time and money than simply installing standard steel mill shapes. For the spans on this project, rigid members were more economical than prestressed cables. Birdair came across these issues as they developed their design for the roof and this is why they decided to use rigid members throughout the roof.

This design change had some other benefits besides savings in construction cost. Using rigid members considerably increased the stiffness of the structure, which meant that the lateral deflection and thrust from gravity loads decreased. The self-weight, wind, rain, and snow loads cause the roof to deflect both downward and laterally. The force component that causes the lateral deflection is referred to as thrust. This increased stiffness in turn eliminated the need for slide bearing connections, a ring beam and an expansion joint between the roof and the top of the superstructure columns. This was particularly beneficial in the case of the expansion joint, which is very costly.
Birdair used their in-house structural analysis and design software to complete the preliminary design of the roof. They developed the concept for the roof, finalized the configuration of the members, and then passed their work along to EB. Ellerbe Becket, as the engineer of record, was heavily involved in verifying Birdair's roof design. EB actually created another three-dimensional computer model of the roof using a commercial software package. They used this model to evaluate Birdair's design, size the members and finalize the details of the connections.

The two firms had worked together early in the design stage to develop the concepts for the connections. Since they completed the detailed design of the connections during the contract document phase, EB was able to avoid problems with the steel fabricator. In most cases, connections are detailed after the fabricator has been selected and the shop drawings are being completed. However, with a completed design such as this, EB anticipated that there would be a potential for problems with the fabricator. They avoided this situation by detailing the connections before a fabricator was even awarded the contract. Thus, the fabricator understood the roof configuration and details fully when they bid on the job.

EB also used their computer model to study the stability of the structure during erection. They evaluated the construction sequence to ensure that the temporary supports would provide enough stability to make the process safe. Much of the roof assembly work was actually done on the ground for efficiency and safety. The total construction duration for the roof structure, catwalks and metal deck was under 15 weeks (Terry et. al. 1997; Terry 1998; and Mullin 1998).

Another important issue related to coordination is that Ellerbe Becket completed the mechanical engineering design for the arena as well. This meant that they internalized the coordination between the mechanical systems design and the design of the roof. This was important due to the extensive and complicated lighting and HVAC systems that are supported by the roof.

Huber Hunt and Nichols was responsible for the coordination work during the construction phase. Their impression was that the implementation of the innovation went smoothly. Bill Mullin, their project manager said that “all arena and stadium projects are complicated and require a lot of coordination work because they are like a combination of heavy civil and commercial construction.”

Overall, most of the negotiations pertaining to this innovation took place between Birdair and Ellerbe Becket. Wesley Terry said that generally “coordination is really about relationships and personalities, not contracts.”
5.9.2.2.4. Appropriation of costs/benefits

Due to the structural efficiency of the tension braced dome, this project cost $500,000 to $600,000 less than it would have with a conventional long-span steel truss roof. The total cost of the roof structure and metal deck was $4.5 million. The tension braced dome uses less steel per square foot of floor area, which lowers the cost of the roof as well as the supporting walls and foundation. This is because the load on these elements from the roof itself is decreased. This savings was passed directly to the owner, without any sharing with the construction manager. Birdair obviously benefited; they only got the job because they introduced the innovation to the project. Not only did they get that contract, but they also have completed the design of two more tension braced domes with Ellerbe Becket for other owners. Thus, Ellerbe Becket benefited as well from the implementation of this innovation. Through their collaboration with Birdair on this project, they developed expertise in the design of these unique structures. The two firms are now able to pool their competencies and access to owners to win new contracts.

Figure 5.9.4 shows a timeline of the development of the Tension Braced Dome and its implementation on the Marine Midland Arena project.

<table>
<thead>
<tr>
<th>Conceptual design phase</th>
<th>Owner selects architect and construction manager</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ellerbe Becket develops conceptual design of arena, including a conventional one-way steel truss roof structure</td>
</tr>
<tr>
<td></td>
<td>HHN completes a cost estimate of the conceptual design</td>
</tr>
<tr>
<td></td>
<td>Birdair contacts HHN with their tension braced dome roof concept. HHN estimates its cost and brings it to the owner as a value engineering proposal. Owner accepts it due to low cost.</td>
</tr>
<tr>
<td>Design development</td>
<td>Birdair works with EB on roof configuration and concepts for connections.</td>
</tr>
<tr>
<td></td>
<td>Birdair completes a preliminary design of the roof and passes it on to EB.</td>
</tr>
<tr>
<td>Detailed design phase</td>
<td>EB completes the detailed design of the roof, including the connections.</td>
</tr>
<tr>
<td>Bidding &amp; Construction phase</td>
<td>A steel fabricator is selected for the roof. The steel is fabricated and Birdair performs the construction of the roof under the guidance of HHN.</td>
</tr>
</tbody>
</table>

Figure 5.9.4 - Timeline of development and use of the Tension Braced Dome
5.10. Moveable Arched Scaffold

5.10.1. Brief description

Scaffolding systems are an important element in the construction process and they come in a variety of forms, depending on the needs of the particular project. There are hanging platform scaffolds that can be lowered from the roof of a building to allow workers to access the outer walls of a building. More common is tower scaffolding, which typically consists of a steel or aluminum pipe structure built from the ground up alongside a building. In this case, workers may climb ladders or temporary staircases to get to the work platforms. These types of scaffolds are normally used for construction work on the walls of buildings, such as brickwork, painting, or window installation.

This case study concerns an innovative scaffolding system used on the rehabilitation of Grand Central Station in New York City. The scaffolding was used to provide work platforms for interior restoration of the walls and ceiling of the terminal (Rasmussen 1997). The system consisted of two 30-meter tall tower scaffolds that ran parallel to each other along opposite walls of the terminal. These structures supported work platforms that were used to access the walls. In addition, there was a 37.7 meter long by 9.1-meter wide arched scaffold that sat on top of the tower scaffolds that allowed workers to access the barrel-shaped ceiling of the terminal (Figure 5.7.1). The arch rested on rollers that ran along railroad-like tracks on top of the tower scaffolds. Thus, the arch could be moved along the tracks as work progressed on the ceiling. This was done manually by workers using pull cables and grip hoists.

Figure 5.10.1 – Moveable Arched Scaffold installed at Grand Central Terminal (Rasmussen 1997)
This system is innovative because it involves the use of a creative structural form, the arch, and the use of tracks to move a scaffold. A conventional design would have included similar tower scaffolds for the walls and suspended work platforms for the ceiling work. A scaffolding system that rested on the floor to reach the ceiling was not allowed because the terminal had to remain in operation.

5.10.2. **Innovation development and use**

5.10.2.1. **Development**

This innovation was developed specifically for the Grand Central Station renovation project, as discussed in the following section.

5.10.2.2. **Use - Grand Central Station Renovation, New York, New York**

When Grand Central Station in New York City was completed in 1913, 150,000 people came to see its underground rail yards and its enormous, 37.7 meter wide by 91.4 meter long terminal with its barrel-vault ceiling (Rasmussen 1997). The ‘sky ceiling,’ as it was called, was painted blue and had lights installed in it in the patterns of the constellations. Unfortunately, the station became seriously worn out with decades of heavy use and neglect. Urban grime covered the walls and the sky ceiling. In addition, there were leaks in the walls and roof, which left stains throughout the sky ceiling. In 1996, the owner, the Metropolitan Transportation Authority of New York (MTA), began an extensive renovation project. A large team of engineering and historic preservation consultants worked on the design phase. At a total cost of $197 million, the renovation work lasted two full years, with a formal re-dedication ceremony on October 1, 1998.

5.10.2.2.1. **Search process**

After the MTA’s consultants finished the design of the renovation project, they solicited bids from general contractors. One of the bidders was Bovis Construction, which intended to bid the work assuming that it would be able to perform work on the ceiling and in the attic space simultaneously. These tasks were the restoration of the sky ceiling and the upgrade of the heating, ventilation, and air conditioning (HVAC) system located in the attic. The original designers of the station included access holes in the ceiling that could be used to hang platforms from gusset plates on the roof trusses in the attic space. Unfortunately, Bovis found out that the roof trusses did not have enough reserve capacity to support workers and material for both tasks at once. According to Steve Sommer, VP of Bovis, doing the tasks in sequence would have practically doubled the construction schedule (Rasmussen 1997).
Bovis contacted Universal Builders Supply (UBS), a scaffolding design and installer to see if it could come up with a solution. UBS developed and proposed the moveable arch system, which would not put any load on the roof trusses, thereby allowing work to progress on both the restoration of the ceiling and the HVAC upgrade simultaneously. UBS had never designed a scaffold bridge that large before, let alone one that ran on tracks. It used only aluminum members in its design, which reduced the overall weight of the structure and made it easier to assemble and disassemble. UBS has a lot of experience in the design of aluminum scaffolds. In addition, it has a history of providing scaffolding for major historic preservation projects, such as the Statue of Liberty, Ellis Island and the Jefferson Memorial. Thus, Bovis bid the work with a faster construction schedule at a lower cost, both primary objectives of the owner.

In terms of innovation classification, from UBS's perspective, it is an architectural innovation. UBS changed the links between the components of scaffolding design; rather than having a fixed system, UBS made it moveable. For Bovis, this was an architectural change when considered in the context of the scheduling of the entire project. With this innovation, they were able to change the sequencing of the construction operations. The innovation essentially erased the relationship between the work in the attic and the renovation of the ceiling. For the owner, the innovation had little effect because it did not change the quality of the work performed, so it is an incremental innovation because it only reduced the schedule. For the trade workers who used the scaffold, it was also an incremental change. The work platforms that they used were built on top of the arch, so their access to the ceiling was unencumbered by any hanging members, as it would be with a platform hung from the ceiling. A flat platform was constructed over approximately the center half of the arch. The vaulted roof was shallow enough to be accessible from this flat platform. To reach the rest of the ceiling, shorter platforms were built atop the arch in a stepped configuration. Workers could easily climb ladders up each stepped platform section to the central flat platform. The platforms are visible in the photo of the scaffolding above (Figure 5.10.1).

5.10.2.2.2. Project organization

This was a public project, so it was pursued essentially through the design-bid-build delivery system. The owner, the MTA, hired Beyer Blinder Belle (BBB) to lead the design team and BBB, in turn, hired several design consultants for historic preservation and structural and mechanical engineering services. In addition, because it was so large and complex, the MTA also hired GCT Venture Incorporated, a joint venture of LaSalle Partners and Williams Jackson Ewing, to manage the project. After the design phase was completed, they solicited bids from general contractors. Bovis was hired under a lump sum contract. Their contract with UBS was negotiated and covered the design and
fabrication of the scaffold, as well as the cost to erect it and move it during the renovation process. This organization is shown in the chart below (Figure 5.10.2).

![Project organization chart for Grand Central Terminal restoration](image)

Figure 5.10.2 – Project organization chart for Grand Central Terminal restoration

The value chain for this project is shown in the figure below (Figure 5.10.3). In terms of its evolution over the course of the project, it started out with the MTA, GCT, BBB and the other design consultants during the design phase. Bovis contacted UBS during the bidding phase and both became formal members of the project team after Bovis was selected. UBS is essentially a design/build company for scaffolding systems; they design, fabricate and construct scaffolds.

![Value chain for Grand Central Terminal restoration](image)

Figure 5.10.3 – Value chain for Grand Central Terminal restoration

5.10.2.2.3. Negotiation process

In terms of negotiations in the implementation of this innovation, there was little. The major negotiations took place between UBS and Bovis during the bidding phase. Bovis asked them to come up
with a system that would allow both work items to proceed simultaneously and UBS developed this innovation.

There is an important point that should be made concerning this situation. Bovis took bids from a number of scaffolding companies, including UBS. So, when UBS gave Bovis its idea for the moveable arch, it was taking a risk. Bovis could have showed its idea to another scaffolding company in hopes of getting a lower price. Alan Shalders, of UBS, said that “You tend to earn your living by the generation of new ideas. You have to trust the GC not to divulge your ideas to others subcontractors. Likewise, the GC has to trust you not to give its ideas to other GC’s.” Thus, there is an important element of trust in this relationship.

There were also negotiations between UBS and the MTA, which wanted to be sure that the moveable arch was safe. This was important because the station was to remain in service during the renovation process. Engineers from the MTA reviewed UBS’s design and tested the arch after it was assembled. One night, while the station was closed down, the MTA put test weights on the arch up to its rated load capacity and rolled the arch down the length of the concourse. UBS then had the MTA go a step further; it doubled the test load and rolled the arch again. This test proved to the MTA that the arch and its support structure were safe.

5.10.2.2.4. Appropriation of costs/benefits

There were several benefits for the owner in this project. For one, the innovation shortened the project duration by six to eight months, by Alan Shalders’s estimation. This schedule savings also reduced the cost of the project for the owner. With its innovative system, UBS benefited by winning the contract. The innovation also enabled Bovis to win the contract. In addition, safety was increased by this innovation. Since it would cost too much to erect hanging platforms throughout the ceiling, Bovis had planned to build two smaller sections. As the work progressed, it had planned to leapfrog one section past the other to the next section of the ceiling. This type of work would be very dangerous at a height of 37 meters above the main concourse. In addition, the process of stripping and rebuilding the hanging platforms would have been very slow because it could only be done during the four-hour overnight station closure. The arched scaffold, on the other hand, provided a stable platform that could be moved easily. In addition, the arched scaffold made it easier to work because there were not any vertical hangers in the way. The owner, GC and the subcontractors who use the scaffolding shared these safety benefits.
Below is a summary timeline for this project.

<table>
<thead>
<tr>
<th>Design phase</th>
<th>Owner selects designer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design completed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bidding phase</th>
<th>Bovis asks UBS to develop a scaffold system. UBS develops the moveable arched scaffold, which allows work in attic and on ceiling to proceed simultaneously. Bovis wins job as a result.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UBS designs arch scaffold system.</td>
</tr>
<tr>
<td></td>
<td>MTA reviews design.</td>
</tr>
<tr>
<td></td>
<td>UBS erects scaffold and MTA tests its load capacity and mobility.</td>
</tr>
</tbody>
</table>

| Construction phase     | Workers use moveable arched scaffold system to complete renovation work of walls and ceiling. |

Figure 5.10.4 – Timeline of development and use of the Moveable Arched Scaffold
6. ANALYSIS

This chapter consists of an analysis of the case studies presented in the previous chapter. Appendix C contains tables of outcomes of the measures for each innovation case study.

6.1. Theory Area #1: Principal Agent and Team Theory

The theories regarding the principal-agent relationship and teams of agents contribute very much to this research. The main issues in agency theory are that the goals of the principal and its agent are not typically aligned and that the two parties may have different attitudes toward risk. Agency theory sets the groundwork concerning the relationship between the principal and its agents and explains how different contractual forms can be used to align the goals of the two parties and allocate risk effectively.

6.1.1. Variable #1: Distribution of benefits, costs and risks

Three measures were used for this variable. The first is contractual form; the contract data is analyzed with respect to agency theory. The second measure is the delivery mechanism, which provides important information regarding the relationships among project participants. Transaction costs were also studied to measure this variable. These include costs associated with information transactions and investment in physical assets.

6.1.1.1. Measure #1: Contracts

Contracts were considered at two levels, the project as a whole and the parties involved specifically related to the innovation. The project contract refers to the contract between the owner and the builder, whether it is a general contractor, construction manager or design/build joint venture. The nature of the project contract can yield information regarding the risks and incentives that the owner has given to the builder. However, for the purposes of this study, it is more important to investigate the nature of the contracts governing the behavior of the firms who are directly involved in the implementation of an innovation on a project. These contracts are referred to as the innovation contracts. For example, in the case of Chapultepec Tower, the innovation contracts include the contract between the owner and the structural designer as well as the one between the construction manager and the structural steel subcontractor. The project contract in this case is the contract between the owner, ICA/Reichmann, and the construction manager, ICA.

This method of analysis yields some interesting results, as shown in Table 6.1. For example, for Chapultepec Tower, the project contract between the owner and ICA was guaranteed maximum price
(GMP), but ICA’s contract with the steel subcontractor was lump sum. The other innovation contract, that between the owner and the structural designer, was fixed fee.

<table>
<thead>
<tr>
<th>Contract type</th>
<th>Project Contracts (# of projects)</th>
<th>Innovation Contracts (# of projects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMP</td>
<td>9 (7 negotiated, 2 competitively bid)</td>
<td>0</td>
</tr>
<tr>
<td>LS</td>
<td>8 (1 neg., 7 compet.)</td>
<td>17 (8 neg., 9 compet.)</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 6.1 – Contract type data summary

This table shows that there is a marked difference between the project contracts and the innovation contracts. Looking at the project contract data, there is an even split between GMP and lump sum contracts. However, all of the innovation contracts with contractors and subcontractors were lump sum. It is typical in construction for contractors to sign their subcontractors to lump sum contracts. In addition, all of the contracts between owners and designers were fixed fee, another typical result for the construction industry. These results emphasize the importance of collecting the correct data; if one were to research only the project contracts of innovative projects, the results would be misleading.

What do these results say about risk allocation on innovative projects? In chapter two, lump sum contracts were classified as outcome-based contracts. A contractor or subcontractor working under a lump sum contract assumes the financial risk from the uncertainty involved in its work. For contractors who hold a lump sum contract, signing subcontractors to lump sum contracts provides them with a way to pass along risk. This is important to note because there is typically a great deal of uncertainty in the implementation of innovations. Thus, one would predict that lump sum contracts would deter innovation. However, the results show that this is not true; innovation occurs in construction despite the widespread use of lump sum contracts.

The fixed fee contracts of the designers are similar to lump sum contracts in that they do not reimburse the designer for each cost incurred on the project. Instead, they are paid a percentage of the total project cost. Thus, this type of contract does not seem to give the designer an incentive to pursue innovative solutions. One would expect that they would reduce their uncertainty by following standard practice. However, four of these innovations originated from designers, although their contracts do not explicitly promote innovative activity as expected in the theory.

It should be noted, however, that although all 17 of the innovation contracts were lump sum, eight were negotiated rather than competitively bid. A negotiated lump sum contract has different implications than a competitively bid lump sum award. In the former case, the contractor shares the risk more than it
does in a competitive lump sum contract. Thus, one would expect that a negotiated lump sum contract would be more conducive to innovation. The results support this theory.

6.1.1.2. Measure #2: Delivery mechanisms

As in the contract analysis, data was gathered on the overall project delivery system as well as on the delivery system for the innovative system alone. This data is summarized in Table 6.2. For example, the project delivery system for the Seaport Hotel was design-bid-build. However, the delivery system for the precast concrete slurry wall was design/build; the foundation subcontractor contracted with an engineer and a precaster to provide the system to the general contractor. The delivery mechanism for the project can provide the general context in which an innovation is considered, but the delivery mechanism for the innovation is the degree of direct control and coordination between the design and the means to realize the design.

<table>
<thead>
<tr>
<th>Delivery System Type</th>
<th>Project Delivery Systems (# of projects)</th>
<th>Innovation Delivery Systems (# of projects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design-bid-build</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Construction management at risk</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Design/build</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 6.2 – Delivery mechanism data summary

The table shows that looking at overall project delivery systems alone does not give an accurate picture of how innovations are implemented. The delivery system types are listed in increasing order of integration of design and construction. In 12 out of the 17 cases, the innovation was implemented through design/build. The other four followed the traditional design-bid-build method. This is interesting because the 17 projects were almost evenly split in terms of their project delivery system. The results indicate that there is a correlation between innovative activity and the use of a cooperative delivery system for the innovation itself. The results also show that, if one were to look at only the overall project delivery systems, one would not see a meaningful relationship between the delivery system and the presence of innovative activity.

In some cases, both the design and construction functions were internalized in a single company. This was true for three projects: JFK Airport; Grand Central Station; and Marine Midland Arena. In each, a subcontractor was hired to provide both design and construction services. This internalization simplifies the project organization chart by eliminating the interfaces that would normally be present between a separate designer, fabricator and erector. By internalizing the implementation of their
innovations, these firms were able to hold a larger share of the benefits. However, at the same time, they also assumed more risk. Chesbrough and Teece (1996) addressed this issue. They pointed out that, as a company becomes more vertically integrated, its incentive to take risks decreases and its ability to settle conflicts and coordinate activities increases.

In the other nine design-build projects, the innovations were delivered by a temporary partnership of firms. For example, in all three applications of the Special Truss Moment-Resisting Frame, JD2, the structural steel fabricator and erector partnered with the structural designer to provide design and construction services to the construction manager. Likewise, on the Dow Jones Garage project, Interstate Iron Works partnered with Zaldastani Associates to provide design-build services. Interstate acted as the general contractor but also did the steel fabrication and erection itself. Zaldastani performed the structural design of the facility.

6.1.1.3. Measure #3: Transaction costs

For the purposes of this research, two types of transaction costs were studied. The first type is costs related to information transfer, such as the cost of passing design information from the structural engineer to the steel fabricator. The other type of transaction cost is the cost of developing physical assets, such as construction equipment. Only those transaction costs directly related to the innovation were studied. Table 6.3 contains a summary of the relative amount of investment made by project team members into developing co-specialized assets specific to the implementation of the innovations.

<table>
<thead>
<tr>
<th>Investment in Co-Specialized Assets</th>
<th># of Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>9</td>
</tr>
<tr>
<td>Some</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 6.3 – Level of innovation specific investment in co-specialized assets

One would expect that firms would only make these investments if they expected a sufficient return. For example, a firm would be likely to develop co-specialized assets for an innovation if they expected to be involved in several implementations of that innovation. However, as described in Chapter 2, the nature of the construction industry makes such situations atypical. For example, consider the subcontractor that fabricated the special formwork for the double helical ramp at Logan Airport. Since subcontractors do not take part in the design process, this company is not able to convince more owners to use this system in their garages. If they were able to exert this influence, this company would be more certain that they would be involved in future implementations of the system. Its chances for reuse are
also hurt by the fact that subcontractors are typically selected through the competitive bidding process. Therefore, even though the investment is not expected to be recouped over additional projects, design and construction firms did make innovation-specific investments in most of the projects studied.

There were other cases in which firms invested in physical assets specific to an innovation. For example, Rubb, the designer and fabricator of the Fabric Roof, also developed and manufactured connection hardware specifically for that system. Likewise, UBS, the company that designed and erected the Moveable Arched Scaffold, owns the scaffolding system. In addition, a special connection piece was developed and produced to be used in applications of the Ductile Precast Concrete Frame.

In only one case study, the Special Truss Moment-Resisting Frame, was there evidence of firms making an effort to reduce their information transaction costs for subsequent applications of an innovation. In this case, the structural steel fabricator and erector (JD2) the construction manager (Earl Construction) and the structural designer (Cole/Yee/Schubert) worked together on all three applications. Currently, no other firms or set of firms have used this structural system. JD2 actually markets the STMF exclusively and offers the system under the name ‘Tru-Frame,’ claiming that it “performs better than conventional steel frames and can be built cheaper and faster” (JD2 product literature).

The way this three-firm partnership worked on the three projects was as follows. The construction manager held a contract with the structural designer for structural design services. The CM also had a contract with the steel subcontractor for the fabrication and erection of the steel superstructure. The projects were fast-tracked, meaning that the construction phase began before the design was completed. The steel subcontractor and structural designer collaborated on the design; the steel subcontractor detailed the connections and the structural designer performed the analysis and design of the structure. They developed the shop drawings together as the design process progressed. Thus, they were able to order materials earlier, taking weeks off the construction schedule. In design-bid-build, the shop drawings are produced after the bid phase, and only then can materials be ordered.

JD2 produced the shop drawings used to fabricate the steel based on Cole’s design. Cole checked the shop drawings to make sure that they followed the design. This process is typically iterative. First Cole sent their design to JD2, who then created the shop drawings and returned them to Cole. Cole then checked the drawings and returned them to JD2 for revisions. JD2 made the changes and then resubmitted the drawings to Cole. This process of revision and checking continued until the drawings were complete.

In the first application of the STMF, JD2 and Cole realized that they could save time and money by communicating electronically. They invested in information technology so that they could send the
shop drawings back and forth over the Internet. This system was put in place on the second and third projects, decreasing the cost and time associated with the design process (Mayo 1998).

It was surprising not to find similar situations in the other case studies. However, possibilities do exist. For example, the subcontractor that fabricated the formwork for the Logan Airport Garage project could use it for future double helixes. If so, the cost to the owner for this service would decrease or the avoided cost for the subcontractor would increase, thereby raising the subcontractor’s profit and/or competitiveness. One may also speculate that other firms could use information technologies to lower their information transaction costs. However, such an investment would only be worthwhile if the firms could guarantee that they would work together in the future. Unfortunately, in construction, this guarantee of future teams is often difficult to ensure.

Even JD2 and Cole/Yee/Schubert worry that they may not always be able to work together on the STMF. John Mayo of JD2, said that the two firms have an excellent relationship that allows them to efficiently share their capabilities to implement the system (Mayo 1998). At this point, both firms have knowledge and expertise specific to the STMF that other companies simply do not have. Thus, they share an interest in preserving their partnership; if Cole were to split off and find another company to work with, JD2 would lose its hold on the market. However, at the same time, Cole would be hurt because there would be a higher cost associated with training a new steel subcontractor on the system. The reverse would also be true if JD2 were to work with another engineer on the STMF.

JD2 has found it difficult in some cases to preserve its relationship with Cole. Since the success of the STMF has become publicized, several interested property developers have approached JD2. However, some of these owners have balked at the idea of hiring Cole with JD2 because some already have a designer that they want to use. Thus, JD2 has begun to consider ways in which it can hold onto the STMF market even without Cole.

The precast slurry wall case also makes an important point regarding transaction costs. Trevi Icos constructs cast-in-place concrete slurry walls as well, so they already have trenching equipment that they can use to construct the precast system. In addition, they have the equipment necessary to work with slurry and grout. Therefore, they have not had to invest in specialized equipment to construct the precast system. This reduces the transaction cost associated with this innovation from the start.

This is an interesting fact that is true of all of the other cases as well: most of these innovations are simply novel combinations of standard construction materials and elements that can be built using existing competencies. These innovations may offer lower cost, faster construction, higher performance or improved safety, but they do not require contractors to make significant capital or personal
investments. Even in the case of the Trio Structural System, although the dampers are new to construction, they are installed using traditional pinned connections that any steel subcontractor can perform. In the development of the Ductile Precast Concrete Frame, one of the team’s goals was to develop a system that would not require precast concrete manufacturers to make significant investments in formwork (Englekirk 1996).

6.2. **Theory Area #2: Mechanisms of Inter-firm Collaboration**

Several researchers have tried to identify mechanisms of inter-firm collaboration for teams of disparate agents in situations that would otherwise be non-cooperative. Some of the mechanisms cited by researchers are bond, team protocol, and superordinate goals.

6.2.1. **Variable #1: Value chain**

The value chain describes how information and value-added activities contribute to projects. To measure this variable, changes in the value chain during each project and in reuse were studied along with the timeline of events in the developed and use of the innovations.

6.2.1.1. **Measure #1: Value chain over time**

A project’s value chain shows which firms exchanged information, resources or services. How the value chain changes over the course of a project shows the dynamic nature of construction projects. For example, for a project with a design-bid-build delivery system, the value chain would start out with only the owner and its architect. The architect would then hire design consultants, such as mechanical and structural engineers. These firms would work together to produce the plans and specifications that detail the design of the project. These plans and specifications are then passed along from the architect to the owner. The owner then solicits bids for the project from several general contractors. The value chain then undergoes a major change after a general contractor is selected. The GC and its subcontractors are added to the value chain. The role of the architect and the other designers diminishes during this phase; they may only visit the site periodically to monitor the progress of the work.

The evolution of a project’s value chain depends on the delivery system used. In the case of the construction management delivery system, the design and construction functions are not separated. The construction manager is part of the project from the start, along with the designers. Thus, they are able to provide the designers with construction-related input. Their advice can lead to reduced cost, schedule savings or improved quality.
Structural engineers or architects introduced five of the innovations, while the remaining five innovations were introduced by contractors (Table 6.4). Of the latter five innovations, four came from subcontractors and one from a general contractor. One might predict that most structural engineering innovations would come from structural designers, but only four out of the ten innovations were developed by structural designers. It is very surprising that so many innovations came from subcontractors because those firms are not typically involved during the design process. There is an important question of credibility here as well. Most subcontractors are not perceived as having much structural engineering expertise. Thus, those subcontractors that wish to introduce structural system innovations must get their ideas validated by a structural designer. Regulations require that a project's structural design be approved by a licensed structural engineer.

<table>
<thead>
<tr>
<th>Source</th>
<th># of Innovations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architect or Engineer</td>
<td>5</td>
</tr>
<tr>
<td>General Contractor</td>
<td>1</td>
</tr>
<tr>
<td>Subcontractor</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 6.4 – Sources of innovations

Of the ten innovations studied, four innovations have not been reused at this point (Table 6.5). These were the Trio Structural System, the Tension Braced Dome, the Moveable Arched Scaffold and the Ductile Precast Concrete Frame. It appears that the Trio Structural System has not been reused because it is best-suited for very tall buildings in high-seismic areas and there are few projects available with those characteristics. Another Tension Braced Dome is currently in the early design stages and will be implemented. Again, there are less opportunities for reuse of this innovation since it is only applicable for large arenas. Also, the Moveable Arched Scaffold is only necessary for very special projects involving the renovation of the interior of a barrel vault roof.

Of those that were reused, in three cases the same firms were involved in all reuses. These innovations were the STMF, the Precast/Prestressed Structural Diaphragm Wall and the Hybrid Moment-resisting Precast Concrete Frame.

In the case of the STMF, the maintenance of the partnership of JD2, Earl Construction and Cole/Yee Schubert is important because each firm contributes important expertise and resources. JD2 and Cole are especially important to the partnership because they provide important technical expertise. In the three projects studied, the owner was the same. They were so pleased with the results of the first
project that they retained Earl Construction for the next two as well, with the understanding that Earl
would use JD2 and Cole for the structural system. However, JD2 does not feel that Earl Construction is
essential to the partnership; they feel that virtually any competent general contractor can be involved.
This is because JD2 and Cole handle the bulk of the coordination involved in the design and construction
of the STMF. In addition, JD2 understands that other steel subcontractors could attempt to implement the
STMF. By marketing it under a brand name and publicizing their involvement in its first
implementations, JD2 hopes to retain its market share in STMF construction (Mayo 1998).

In the case of the Precast/Prestressed Concrete Structural Diaphragm Wall, the same foundations
subcontractor (Trevi Icos), precast concrete manufacturer (Northeast Concrete Products) and structural
designer (Weidlinger Associates) have been involved in each implementation. Icos was the one who first
developed and introduced the system and they have chosen Weidlinger in each case because of their
reputation in design. Icos has used Northeast for each project because of their expertise in precast
concrete fabrication. Another reason why Icos has used both firms repeatedly is that they have
progressed along the learning curve for this innovation, which saves time and money in the
implementation process (Wieners 1998). This innovation has been implemented before in similar forms
in Europe and some firms elsewhere in the US have unsuccessfully attempted to develop a similar system.
However, Icos is known in the New England construction industry for their successful implementations of
their system. This is why they have been the only ones to implement it in this area.

In the two implementations of the Hybrid Moment-resisting Precast Concrete Frame, Charles
Pankow Builders has chosen to use Robert Englekirk Consultants for the structural design. They did this
because Suzanne Nakaki, an engineer affiliated with Englekirk, was a part of the committee that oversaw
the development of the system. In addition, Charles Pankow Builders led the development effort. Thus,
the two firms have expertise specific to the system, which gives them an advantage over other firms that
have no experience with it.

<table>
<thead>
<tr>
<th>Reuse</th>
<th># of Innovations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same firms</td>
<td>3</td>
</tr>
<tr>
<td>Different firms</td>
<td>3</td>
</tr>
<tr>
<td>No reuse</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 6.5 -- Reuse of innovations
6.2.1.2. Measure #2: Timeline of development and use

The chart below summarizes for each project the stage at which the commitment was made to use the innovation (Table 6.6). In 12 of the 17 projects, commitment was made during the early part of the design phase. In two cases, the Pilot House and the Marine Midland Arena, commitment was made late in the design process. Finally, in the remaining three cases, the innovation was committed to during the bid phase. Those projects were Grand Central Station, the Old Colony Line and the Seaport Hotel. In all three cases, however, the innovation had been developed in preparation for a competitive bid. Of the five projects committed to after early design, four involved a redesign stage to incorporate the innovation. Using the moveable arched scaffold on the Grand Central Station project did not require redesign simply because the system was being developed to allow the construction processes to proceed in parallel.

<table>
<thead>
<tr>
<th>Stage</th>
<th># of Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Design</td>
<td>12</td>
</tr>
<tr>
<td>Late Design</td>
<td>2</td>
</tr>
<tr>
<td>Bid</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 6.6 – Stage of project for commitment to innovation

In terms of development, three of the ten innovations were developed in response to project specific requirements. These innovations are the Trio Structural System, the Fabric Roof and the Moveable Arched Scaffold. These innovations relied on existing expertise. For example, the Trio Structural System was developed based on decades of research, development and experience on the part of Taylor Devices and the structural designer. In addition, the fabric roof was a modification and application of existing techniques by Rubb. Likewise, the moveable arched scaffold could not have been developed without UBS’s years of experience in complex scaffold design and construction.

6.2.2. Variable #2: Bond

The measures of this variable are trust, reputation and length of relationship. The first refers to the amount of trust that exists between two firms, a quality that is typically built up through a long-standing working relationship. For example, two firms that have worked together for years have a chance to get a feeling for the credibility and integrity of the other party. Reputation refers to the standing of a
firm in its industry. For example, a firm may develop a reputation of quality and skill that is accepted by many firms, even those that have not worked with the firm before.

6.2.2.1. Measure: Trust, reputation and length of relationship

The importance of this variable is difficult to measure. On several of the projects studied, the firms involved responded that they did have a working relationship with another member of the project team. However, only a couple of those people interviewed said that this was a major factor in the implementation of the innovation.

On the Chapultepec Tower project, the structural designer, CSG, had worked with the owner, Reichmann, on a previous commercial development project. This relationship led the owner to select them for Chapultepec. In addition, Dr. Rahimian of CSG said that Reichmann’s trust in their competence made it easier for CSG to convince them to commit to the novel structural system incorporating the dampers.

On the Marine Midland Arena project, trust played an important role in the cooperation between Birdair (roof design/build subcontractor), Ellerbe Becket (project architect/engineer), and Huber Hunt and Nichols (construction manager). Bill Mullin, of Huber Hunt and Nichols, the construction manager on the project, said, “All three firms trusted each other. Had three strangers shown up at the table, it would have been a lot tougher because they would not have felt as comfortable” (Mullin 1998).

On other projects, firms chose partners with whom they had worked before (Table 6.7). This was true in the following cases:

- **Dow Jones Garage**: Interstate chose Zaldastani because they had worked together on a previous application of the system.

- **Tufts Health Plan Garage**: Kennedy and Rossi chose Zaldastani because they had worked together for more than six years on other types of projects.

- **Seaport Hotel and Pilot House**: Trevi Icos chose Northeast Concrete and Weidlinger Associates because they worked together on the Old Colony Line project. However, before the Old Colony Line project, they had not developed a relationship.

- **JFK Airport**: VRH and TAMS had worked together in design-bid-build situations before choosing to joint venture on this project.

- **Special Truss Moment-Resisting Frame**: On the first application, Earl Construction contacted JD2 because they had worked together several times before. JD2 then chose
Cole/Yee/Schubert as the structural designer because they had worked together before and JD2 knew that Cole was experienced in earthquake engineering. On the two subsequent applications, these three firms worked together again based on their experience together on the first project.

<table>
<thead>
<tr>
<th>Previous Experience</th>
<th># of Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>4</td>
</tr>
<tr>
<td>Some</td>
<td>5</td>
</tr>
<tr>
<td>Multiple</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 6.7 – Amount of previous experience between project team members

Reputation was found to be an important element in just a few cases. For example, for the implementation of the STMF, JD2 chose Cole/Yee/Schubert as the structural designer because they knew of their expertise in earthquake engineering and plastic analysis of structures (Mayo 1998). In addition, part of the reason why Icos chose Weidlinger as their structural designer of the Precast Diaphragm Wall system was that Weidlinger has an excellent reputation in the Boston area for quality design as well as for helping subcontractors with engineering issues (Kirmani 1998). Also, Spancrete (precast concrete manufacturer/erector) was brought into the Wiltern Center Garage project because of their reputation for quality and service in California (Englekirk 1996).

6.2.3. **Variable #3: Team protocol**

In order to measure this variable, several issues were considered, including the role of the lead firm and organization and team rules. In construction, the lead firm with respect to the structural system is the structural designer. As mentioned previously, regulations state that this firm must be licensed and must approve all aspects of the structural design. In terms of organization and team rules, in construction, firms are typically organized around their set of projects. For example, a design firm may have support staff in accounting, human resources and drafting, but their engineering staff is typically organized by projects. The firm therefore resembles more of an amalgam of disparate project teams supported by peripheral staff.

6.2.3.1. **Measure: Role of lead firm and organization versus team rules**

In the discussion above regarding the sources of these innovations, it was shown that subcontractors introduced four of the innovations. This seemed surprising, considering that they are
structural engineering innovations. However, it is important to point out that structural designers played a major role in each of these cases. For the moveable arched scaffold, MTA engineers reviewed the subcontractor’s design. Weidlinger Associates, a structural design firm, designed the precast concrete slurry walls for each project studied. For the special truss moment-resisting frame, although it was introduced by a steel subcontractor, a structural designer was required to perform the design. The designers in these two cases were also the engineers of record for those projects. The structural engineer in each case served as a validation mechanism for the subcontractor’s innovation.

In terms of organization and project team rules, the latter are most common in construction projects. They are negotiated among a specific set of firms with respect to the particular project. In all cases, the structural engineer is the arbiter of the technical feasibility of structural system innovations. Another issue related to team rules is that engineering and construction firms typically allow their employees some amount of freedom to organize their team as they see fit for the project. For example, in the case of Chapultepec Tower, the structural design firm allowed its project executive a great deal of leeway in staffing the project and conducting the work. This executive still had responsibilities to protect its firm from liability, but the firm did not dictate or closely monitor the executive’s design decisions.

6.2.4. Variable #4: Objectives

6.2.4.1. Measure: Superordinate goals

These goals are set by owners to guide the project team members in their work. The chart below summarizes the data on the owners’ objectives behind the application of each innovation (Table 6.8). On nine of the projects studied, the owners were mainly concerned with developing a facility with improved long-term performance. Owners wanted low cost in nine cases. This result is interesting because it is a widely held belief that construction innovations typically are implemented to lower project costs (Quigley 1982). These results do not support that view.

<table>
<thead>
<tr>
<th>Objective</th>
<th># of Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term performance</td>
<td>9</td>
</tr>
<tr>
<td>Construction speed</td>
<td>1</td>
</tr>
<tr>
<td>Low cost</td>
<td>9</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>4</td>
</tr>
<tr>
<td>Total *</td>
<td>17</td>
</tr>
</tbody>
</table>

* Note: Projects can have multiple objectives, so the total number of objectives is greater than total number of projects.

Table 6.8 – Owner’s objectives for projects
The chart below summarizes the data for the expected benefits of the innovations (Table 6.9). This analysis is similar to that of the owner’s objectives, but it also adds the secondary benefits of the innovations. For example, seven projects benefited from improved construction speed, although this was the owner’s objective in only two of the cases. In addition, this analysis shows that the innovations studied were more likely to improve the quality of the completed facility rather than to lower its cost.

<table>
<thead>
<tr>
<th>Expected Benefit</th>
<th># of Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low cost</td>
<td>9</td>
</tr>
<tr>
<td>Construction speed</td>
<td>7</td>
</tr>
<tr>
<td>Quality</td>
<td>14</td>
</tr>
<tr>
<td>Total *</td>
<td>30</td>
</tr>
</tbody>
</table>

* Note: Innovations can have multiple benefits, so the total number of benefits is greater than total number of projects.

Table 6.9 – Expected benefits of innovations

6.3. Theory Area #3: Inter-firm Collaboration for Innovation

As discussed in Chapter 2, firms in many industries have chosen to develop innovations through partnerships with other firms. In this way, firms are able to leverage their own capabilities by sharing the capabilities of other firms without having to develop them in-house. In addition, this strategy allows firms to share risk. This is especially important in the development of innovative products, which may involve a great deal of risk. The term ‘virtual corporation’ is often used to describe firms that develop products using inputs from the market, as opposed to vertically integrated firms that have the full range of required resources in-house.

6.3.1. Variable #1: Nature of innovation

The nature of an innovation refers to the ways in which it differs from standard practice. This is measured in two ways. The first is whether the innovation embodies different core concepts or reinforces those of the dominant design. The second measure is whether the innovation contains differences in the linkages between the core concepts and components of the dominant design (Henderson & Clark 1990). Thus, depending on its nature, an innovation can have significant implications for inter-firm cooperation. The greater the degree of changes in the linkages between the core concepts and components, the greater the required level of coordination across disciplines.
The nature of the innovation also determines the amount of inter-firm cooperation required during the development phase. For example, innovations that change core concepts of standard practice may require specialized knowledge. In addition, if the innovation has architectural implications, it may require inputs from other disciplines. In the highly fragmented and specialized construction industry, innovative product development typically requires inputs from several firms. Each firm involved contributes their specialized expertise or core competencies.

To measure this variable, the innovations were categorized from the perspective of each project team member. As another measure, the core competencies and strategies of the firms involved were also studied.

6.3.1.1. *Measure #1: Categorization of innovation from different perspectives*

Each innovation case study was categorized from the perspective of each firm involved in its implementation. The goal was to better understand the impact of the innovations on each project team member. This data is contained in Appendix C and is summarized below in Table 6.10. The results show that, although none of the innovations investigated are radical, several are system innovations. As a whole, the innovations have the greatest impact on structural designers; five of the ten innovations are system innovations from the designer’s perspective. Two innovations, the Fabric Roof and the Precast Concrete Slurry Wall, are system innovations from the perspectives of the roof subcontractor and the foundation subcontractor, respectively. None of the other innovations had as much of an effect at the subcontractor level. In summary, the innovations have the greatest effect on structural designers, constructors and subcontractors.

<table>
<thead>
<tr>
<th>Firm Type</th>
<th>No effect</th>
<th>Incremental</th>
<th>Modular</th>
<th>Architectural</th>
<th>System</th>
<th>Radical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Subcontractor</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Constructor</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Structural Engineer</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Architect</td>
<td>2</td>
<td>6</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Owner</td>
<td>0</td>
<td>7</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.10 – Number of innovations of each type with respect to position in the value chain
6.3.1.2. Measure #2: Core competencies and strategies

This data provides an understanding of the motives of the project team members in organizing to implement the innovations. For example, some firms partnered with others in order to share expertise to implement an innovation. On the other hand, some firms were found to be vertically integrated so that they could perform both the design and construction necessary to implement an innovation.

In analyzing the role of business strategy, it is important to point out that, in two cases, a manufacturing company played a key role. These companies were Taylor Devices and Rubb Systems. Taylor supplied the fluid viscous dampers for Chapultepec Tower, and Rubb designed and fabricated the roof system for the building at JFK Airport. The strategies of these firms contrasted sharply with those of the other finns in the case studies, who were all construction industry firms. Taylor has not made attempt to modify their product for use in buildings; they simply provide output data to structural engineers for their product line. They have decided not to add in-house structural engineering capabilities. They have assumed a rather inflexible strategy for the implementation of their product in construction projects. Their product line is unchanged from what it was when they only sold dampers for military and aerospace applications.

Although they specialize in developing systems for the construction industry, Rubb's business strategy is similarly inflexible. They have a line of building systems that buyers can select from a catalog. The systems are standardized in terms of materials and configuration; buyers can only customize them according to size. However, the building system that they used on the UCLA and JFK Airport projects was not part of their established product line. It was an adaptation of their existing systems, but was unique. They developed it for the UCLA project and then adapted it to fit the geometry requirements of the JFK building. Although it has been well-received by users and the architectural press, Rubb has chosen not to market the system further to the occupied buildings segment. They would rather continue marketing their standardized building systems for the warehouse and hangar markets.

These business strategies appear to be typical of manufacturers; they are involved in mass-producing standardized products and are not receptive to developing products for just one or a small number of applications (Slaughter 1993). This contrasts with the strategies of all of the construction firms involved in the projects discussed in this paper. For example, Vulcraft, the steel supplier for the STMF projects, may seem to be a manufacturer. However, although they do mass-produce standardized steel shapes, they are willing to fabricate custom-designed trusses. Northeast Concrete Products is another good example. Like Vulcraft, they offer standardized products, but they also are receptive to fabricating custom-designed members, such as the precast concrete panels used on the projects studied. This strategy
fics the nature of the construction industry; each project is unique and therefore companies must develop flexible systems that can be adapted to the particular conditions of each project.

6.3.2. Variable #2: Appropriation of innovation benefits

To measure this variable, the internal and external appropriations of the benefits of the innovations were studied. This is related to the core competencies and strategies discussed above. Firms who come up with an idea for an innovation must make an important strategic decision with regards to how they will distribute the benefits of the innovation. This decision can impact the company’s success in marketing the innovation. If the innovation benefits the owner, then they may be more likely to assume the risk of using the innovation on one of their projects. Likewise, if the source of the innovation shares the benefits with other project team members, then those firms may be more likely to cooperate with the source of the innovation.

6.3.2.1. Measure: Internal versus external appropriations

This problem is very complex in construction because few firms are integrated. Thus, firms must share the benefits of innovation. Of the ten innovations studied, in none of the cases did a single firm capture all of the benefits of an innovation. In the case of the Fabric Roof, Rubb captured most of the benefits because it developed, designed and fabricated the roof system. However, another firm performed the actual erection of the roof. For the rest of the cases, the sources of the innovations shared the benefits of their innovations with other project team members.

6.3.3. Variable #3: Sharing of competencies

To measure this variable, sharing was analyzed at two levels, among peers and among firms at different positions in the value chain. The goal was to better understand what types of firms were contributing knowledge to the development and implementation of the innovations studied.

6.3.3.1. Measure: Among peers and among project value chain

An interesting result of this analysis is that universities were found to contribute to the development of four of the innovations. In the case of the Trio Structural System, the State University of New York at Buffalo performed much of the research and testing of the fluid viscous dampers that showed that they could be used in buildings to dissipate seismic energy. For the Special Truss Moment-Resisting Frame, a professor at the University of Michigan developed the design guidelines for the system. Professors at the University of California at San Diego carried out full-scale tests of the Ductile
Precast Concrete Frame to prove that it could perform well. In addition, the University of Washington performed tests of the Hybrid Moment-Resisting Precast Concrete Frame. In all four cases, the universities contributed their competencies and resources in structural testing.

Only one case was found in which a firm shared competencies with a peer to develop an innovation. In the case of the Trio Structural System, the main structural design firm developed it with the aid of another design firm that had experience with similar systems. Every other instance of competency sharing took place between firms at different levels of the value chain. For example, a foundation subcontractor came up with the idea for the Precast Concrete Slurry Wall, but they worked with a structural design firm to fully develop the system. Likewise, in all three implementations of the Special Truss Moment-Resisting Frame, a structural designer worked closely with a steel subcontractor. An interesting result of this analysis is that none of these firms decided to bring additional competencies in-house so that they would not have to share. For example, the foundation subcontractor mentioned above could hire an engineering staff to perform the design of the Precast Concrete Slurry Wall in-house. However, they have not, due to the pitfalls of vertical integration, which include added risk and problems of asset utilization.

6.4. Cross-Tabulation of Measures

Several of the measures are interrelated. To better understand these relationships, the data was cross-tabulated. The results of this phase of the analysis are contained in the following sections.

6.4.1. Project Delivery System and Innovation Source

The table below shows the relationship between the overall project delivery system and the source of the innovation (Table 6.11). The results indicate that, for delivery systems that integrate the design and construction phases of a project, contractor innovations are more likely to occur. Seven of the ten contractor-led innovations came about when the delivery system was CM at risk or design/build. This result is predictable because decisions regarding the structural system are typically made during the design phase. Thus, one would expect that, for a contractor to introduce an innovation, it would have to be involved during that stage of the project.

The results are inconclusive regarding the relationship between delivery system and designer-led innovation. However, these results make sense, because the designer’s role in a project is less affected by different delivery systems that the contractor’s role is.
### Project Delivery System

<table>
<thead>
<tr>
<th>Source</th>
<th>DBB (# of projects)</th>
<th>CM (# of projects)</th>
<th>DB (# of projects)</th>
<th>Total (# of projects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designer</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Contractor</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 6.11 – Project delivery system versus innovation source

### 6.4.2. Innovation Source and Expected Benefits from the Innovation

One might expect that contractor-led innovations would mostly be geared towards lowering the cost or reducing the duration of a project (Table 6.12). This theory is based on the fact that contractors often compete with one another for projects based on cost. In addition, for lump sum and GMP contracts with a savings-sharing clause, contractors reap the benefits of any cost reduction that they introduce. On the other hand, one would expect that designers would be primarily concerned with innovations that improve the quality of the facility. After all, this is the main part of their job as designers.

However, the results show that this is not always true. In this study, contractors introduced more innovations that improved quality than they did innovations that lowered cost or improved construction speed. In addition, they introduced more innovations that improved quality than designers did.

### Innovation Source

<table>
<thead>
<tr>
<th>Expected Benefit</th>
<th>Designer (# of innovations)</th>
<th>Contractor (# of innovations)</th>
<th>Total * (# of innovations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low cost</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Construction speed</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Quality</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Total *</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

*Note: Innovations can have multiple benefits, so the total number of benefits is greater than total number of innovations.

Table 6.12 – Innovation source versus expected benefit of innovation

### 6.4.3. Investment in Co-Specialized Assets and Innovation Contract

Connections can also be drawn between the innovation contract and the presence of investment in co-specialized assets. One would expect that such investment would be most likely in cost plus contracting situations and to a lesser degree under GMP contracts. This is because cost plus contracts reimburse the contractor for all project expenses. GMP contracts would be conducive to this type of investment because the cost ‘cushion’ leaves room for the contractor to spend more than they typically would under a lump sum contract. One would not expect to find this kind of investment in lump sum
contracting situations; the contractor is too focused on cost minimization and does not have much leeway in such cases.

Although nine instances of no investment under a lump sum contract were found, the results show that this hypothesis is not always true (Table 6.13). Where one would predict few, if any, cases, this research found eight instances of some investment in co-specialized assets under a lump sum contract. However, it should be noted that in five of those cases, the contract sum was negotiated, not competitively bid. Thus, one would expect that the contractor included some of the investment cost in its price.

<table>
<thead>
<tr>
<th>Innovation Contract</th>
<th>No Investment (# of projects)</th>
<th>Some Investment (# of projects)</th>
<th>Total (# of projects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lump sum</td>
<td>9</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>GMP</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cost Plus</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>8</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 6.13 – Investment in co-specialized assets versus innovation contract

6.4.4. Value Chain Change and Investment in Co-Specialized Assets

In this case, the presence of an investment in co-specialized assets was cross-tabulated with the changes in the project team in reuse (Table 6.14). One would predict that there would not be any investment when different firms were involved in the reuse of an innovation, because firms would be less likely to make investments that are linked to an innovation if they were not sure that they would be involved in the reuse. However, the results do not support this theory. Two cases were found in which firms did invest in co-specialized assets even when they were not involved in reuse. These innovations were the Double Helical Ramp and the Fabric Roof. In the first case, a different subcontractor developed specialized formwork to construct the system for each implementation of the innovation. For the Fabric Roof, the general contractor and designer were different for the two implementations, but the roof subcontractor was the same. This subcontractor invested in developing a special connection mechanism for the system.

<table>
<thead>
<tr>
<th>Investment in co-specialized assets</th>
<th>Project Team Changes in Reuse</th>
<th>Total (# of re-used innovations)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Different firms (# of re-used innovations)</td>
<td>Same firms (# of re-used innovations)</td>
</tr>
<tr>
<td>None</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Some</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 6.14 – Project team changes in reuse versus investment in co-specialized assets
6.4.5. Project Delivery System and Timing of Commitment to the Innovation

This cross-tabulation shows the relationship between overall project delivery system and the stage of the project during which commitment was made to implement the innovation (Table 6.15). The data shows that sometimes innovations are introduced during the bid stage of DBB projects. Such situations, however, are often difficult because they require some redesign, which adds cost and time to the project. The data also shows that, for CM and DB, innovations were introduced at the earliest stages of the projects. This results makes sense, because these delivery systems integrate the design and construction functions of projects. The earlier in a project that an innovation is introduced, the less likely it is that redesign will be required. In addition, 12 innovations were introduced under these integrated delivery systems, while only five were introduced under DBB. This indicates that adding construction input during the design phase may increase the relative occurrence of innovation.

<table>
<thead>
<tr>
<th>Project stage</th>
<th>DBB (# of projects)</th>
<th>CM (# of projects)</th>
<th>DB (# of projects)</th>
<th>Total (# of projects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early design</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Late design</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Bid</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 6.15 – Project delivery system versus project stage for commitment to innovation

6.4.6. Expected Benefits from the Innovation and Innovation Contract

This cross-tabulation shows the relationship between the project contract and the expected benefits of the innovation (Table 6.16). This analysis was done at the level of the project contract level so that it would be meaningful for owners who are interested in how the type of contract that they use influences how they can achieve their goals for a project.

One would expect that cost reducing innovations would occur in lump sum contracting situations due to competitive bidding and budgetary pressures on the contractor. As a result of these pressures, one would expect that innovations that improve quality would not occur in lump sum situations. However, this study includes seven instances in which quality-improving innovations were introduced even with a lump sum contract.
<table>
<thead>
<tr>
<th>Expected Benefit</th>
<th>Lump sum (# of projects)</th>
<th>GMP (# of projects)</th>
<th>Cost plus (# of projects)</th>
<th>Total * (# of projects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low cost</td>
<td>3</td>
<td>6</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Construction speed</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Quality</td>
<td>7</td>
<td>7</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>Total *</td>
<td>8</td>
<td>9</td>
<td>0</td>
<td>17</td>
</tr>
</tbody>
</table>

* Note: Innovations can have multiple benefits, so the total number of benefits is greater than total number of projects.

Table 6.16 – Project contract versus expected benefit of innovation

6.5. Summary

The measures of the variables related to principal-agent and team theory show that, in contrast with the theories, innovation occurs in construction despite the widespread use of outcome-based contracts. For Theory Area #2, Mechanisms of Inter-firm Collaboration, the analysis trust was found to play an important role in the formation of successful partnerships. In addition, owners’ superordinate goals were found to be effective in driving project teams to deliver innovative projects. Finally, the analysis of the measures of Theory Area #3, Inter-firm Collaboration for Innovation, showed that most of the innovations studied affected structural designers and contractors the most. In addition, a key difference in strategy was found between construction industry firms and manufacturing firms. The latter were found to be less inclined to develop products that are adaptable to a variety of implementation conditions. Another result was that none of the firms were found to have brought competencies in-house to appropriate more of the benefits of an innovation. The firms seemed to be comfortable with their position in the value chain and with sharing competencies with other firms.

The data for the larger sample of 30 innovations support the analysis of the ten case studies. This data is summarized in Appendix C and the table below compares the large sample data to the case study data (Table 6.17).
<table>
<thead>
<tr>
<th>Measure</th>
<th>Result</th>
<th>Case Study Data</th>
<th>Large Sample Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovation Benefit *</td>
<td>Construction speed</td>
<td>41%</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>Quality</td>
<td>82%</td>
<td>43%</td>
</tr>
<tr>
<td></td>
<td>Low cost</td>
<td>53%</td>
<td>27%</td>
</tr>
<tr>
<td>Innovation Source</td>
<td>Designer</td>
<td>50%</td>
<td>57%</td>
</tr>
<tr>
<td></td>
<td>Contractor</td>
<td>50%</td>
<td>37%</td>
</tr>
<tr>
<td></td>
<td>Research Lab</td>
<td>0%</td>
<td>7%</td>
</tr>
</tbody>
</table>

* Note: Innovations can have multiple benefits, so the total number of benefits is greater than total number of projects.

Table 6.17 – Comparison of case study and large sample data

Although the results do not correlate exactly, both sets of data follow the same general trends. In both sets of data, quality was the most common innovation benefit. In addition, for both sets of data, there was a large percentage of contractor-led innovation. Thus, the large sample of 30 innovations in general validates the results of the analysis of the ten in-depth case studies, but also indicates differences that may offer promise in future research.
7. SUMMARY AND CONCLUSIONS

7.1. Summary

The purpose of this research was to examine the cooperation and coordination among firms in the development and use of innovations for large complex projects. In order to understand this issue, the first step was to conduct a review of the existent relevant literature.

Three areas of theory were studied. The first area included the theories regarding the principal-agent relationship and teams of agents. These theories provided an understanding of contract types, risk allocation, opportunism and the problem of verifying an agent’s behavior. The second theory area included studies on mechanisms of cross-disciplinary cooperation. Most of these studies involved the use of surveys and interviews with firms to understand the factors that lead to success in product development by multi-disciplinary teams. The third area included studies on inter-firm collaboration and cooperation in innovative product development. This area is the least developed of the three, having arisen within the last decade or so. These studies came about largely in response to recent trends in manufacturing toward the use of external sources of technical knowledge and information for innovative product development. The literature in this area provided an understanding of the concepts of competency and asset sharing as well as business strategy as it relates to innovative product development.

In order to study this issue, a set of structural system innovations for building construction were examined. The data from the innovation studies were then analyzed with respect to the theories found during the literature review phase. A set of 30 innovations was assembled and case studies were developed for ten innovations implemented on 18 projects. Information regarding the development and use of the ten innovations was collected, as well as, for each implementation, data regarding contracts, delivery systems, transaction costs, value chain relationships, bond between project team members, project objectives, project rules and sharing among team members.

7.2. Conclusions

An analysis of the ten in-depth innovation case studies and the set of 30 innovations showed some interesting results. One result was that all of the innovations were implemented under outcome-based contracts. This result is surprising because the common perception in the literature is that the widespread use of outcome-based contracting hinders innovation. Also surprising was that, of the innovations introduced by contractors under outcome-based contracts, many were quality enhancing. One would expect that, due to the cost pressures of their contract, a contractor would be more likely to implement cost-saving innovations.
Another result of this study was that, in more than 75% of the projects, the innovation was designed and implemented through an integrated delivery system. This strong correlation between innovative activity and the integration of the design and construction functions supports the belief that the traditional delivery system used in construction, which separates design from construction, is a barrier to innovation. In addition, it was found that contractors were more likely to introduce innovations on projects that used integrated delivery systems. This result shows a strong relationship between early construction input on projects and contractor-led innovation. This result also adds support to the belief that the traditional delivery systems hinder innovative activity. The data regarding project delivery systems and project stage at which commitment was made to the innovation was also cross-tabulated. This analysis showed a strong relationship between integrated delivery systems and early commitment to innovations. Committing to an innovation early in a project is beneficial because it reduces the need for rework and allows more time during the design phase for coordination of the innovation with the other components.

In terms of investment in co-specialized assets related to the innovation, the results were also surprising. In more than 75% of the projects studied, some investment in co-specialized assets was made. Furthermore, such investment was found to have been made by firms working under outcome-based contracts. This finding contradicts the expected result, which is that such investment should occur most frequently in behavior-based contracting situations. Another interesting result regarding transaction costs was that most of the innovations were developed such that they could be implemented using commonly available equipment and materials. Thus, the developers sought to reduce the need for investment in physical assets specific to the innovations. This strategy makes sense in the context of the construction industry because it makes the innovation easier to implement in many projects that may differ significantly in their specific design, location, and resources. Construction firms are typically selected for projects under market conditions, which means that they cannot predict whether they will be involved in successive implementations of an innovation. Thus, they would have little incentive to make an investment in a co-specialized asset, but this research demonstrates that construction firms will invest in co-specialized assets if those assets can be easily adjusted to be used on future projects.

An important result concerning transaction costs should also be mentioned. For the implementation of one innovation, the involved firms took steps to implement information systems that allowed them to exchange project information over the Internet to speed up the innovation implementation process and to reduce their transaction costs. This case showed the potential benefits of such an investment. It was, however, the only case that demonstrated significant investment to avoid future transaction costs.
The goal of this study was to contribute to the development of the theory of inter-firm cooperation for innovative product development, particularly as it relates to the construction industry. The results are surprising in some cases because they do not follow the predictions of relevant areas of management theory. Thus, one could question whether the results are widely applicable to innovative product development in any field or even to just the construction industry. The results may be simply specific to the particular set of innovations that were selected for this study.

Future research can explore the generalizability of the findings. Research in other specific building systems, building innovation in general, and comparative studies to other industries can explore the extent to which these findings are applicable to other specific fields. In addition, research on construction contracts and delivery systems could pursue in more depth the role of these formal organizational factors in the implementation of innovations. In addition, it would be interesting to study situations in which a real estate developer or other project owner uses the same general contractor exclusively on all of its projects. In such instances, the results for variables such as transaction costs, contracts, and bond may be significantly different.

This research also has strategic value for project owners, designers, and construction companies. Owners that want to include innovations in their projects can use the findings of this research to understand what steps they can take to do so. For instance, they may be able to use different project delivery systems or contract types to create a climate for innovation. In addition, they may try to set superordinate goals in terms of performance or quality to excite the project team to innovate. Owners that want innovative projects may also want to consider the role of trust and long-term relationships among project team members.

Designers and contractors that have developed innovations and are trying to find projects to use them on can also benefit from this research. From their perspective, transaction costs, reputation, trust, project team rules, the nature of the innovation, and the sharing of competencies and benefits are important issues that they can control. For example, a subcontractor with an innovative concept can learn a lot from the findings regarding reputation, transaction costs, and the sharing of competencies and benefits.
APPENDIX A: CONSTRUCTION CONTRACTS

• **Lump Sum**

  The owner pays the contractor a fixed sum of money to complete the work. The price typically includes all labor, materials, project overhead, company overhead, and profit (Gordon 1994).

• **Unit Price**

  The contractor is paid a pre-set cost per unit of each item of work completed. For example, it may receive $100 per cubic yard of concrete poured. In this system, the amount of work completed must be measured accurately. The unit costs include labor, materials, project overhead, company overhead, and profit (Gordon 1994).

• **Cost Plus Fee**

  The contractor is reimbursed for the cost of the work as it is completed. The amount paid includes labor, materials, and project overhead. In addition, the contractor receives a fee, which covers company overhead and profit. This fee may be a fixed amount or it may be based on a percentage of the construction cost (Gordon 1994).

• **Guaranteed Maximum Price (GMP)**

  This is a form of a cost-plus contract in which the contractor is reimbursed for its costs up to a predefined limit called the guaranteed maximum price. If the GMP is exceeded, the contractor must cover the costs itself. On the other hand, if the contractor completes the project at a cost less than the GMP, there may be some sharing of the savings between the owner and contractor, if agreed to in the contract. Such an agreement gives the contractor an incentive to keep project costs down (Gordon 1994).

• **Fee for services**

  Project owners typically use this type of contract with architects and other designers or consultants. The fee may be a fixed amount or a percentage of the construction cost.

• **Annual subsidy**

  This type of contract is typically used for maintenance contracts that extend over a number of years. In addition, they may be used in Build-Operate-Transfer situations, in which the BOT team operates the built facility for a number of years. In both cases, the project owner pays a fixed amount annually.
APPENDIX B: CONSTRUCTION PROJECT DELIVERY SYSTEMS

- **Design-Bid-Build (DBB)**

  In this delivery system, the owner contracts first with an architect for design services. The architect is responsible for all design work, including engineering. Once the design is completed, the project is put out to bid and a general contractor (GC) is selected, typically based on lowest cost. The owner holds a separate contract with the GC. The GC then hires specialty subcontractors to complete individual portions of the work. For example, there are subcontractors that specialize in structural steel erection, foundation construction, and plumbing installation, among others. In this delivery system, the design and construction phases are distinctly separated; there is no interaction between the designers and the contractor during the design phase.

- **Multiple Primes (MP)**

  The organization of this delivery system is similar to that of DBB, except that the owner does not use a GC, instead it contracts directly with multiple contractors (general and specialty). Thus, the owner assumes the project management and coordination duties that the GC would have in the DBB system.

- **Construction Management (CM)**

  There are two forms of this delivery system, agency CM and CM at risk. In both cases, the owner hires a construction manager during the pre-construction phase of the project to supplement its in-house construction capabilities. The CM is the owner’s consultant on construction-related issues and helps with issues such as value engineering and cost estimating during the design phase. An agency CM performs these duties and monitors progress during the construction phase, acting as the owner’s representative. In the agency CM case, the owner typically contracts directly with subcontractors. However, some owners use an agency CM in conjunction with a general contractor. In the case of CM at risk, the CM holds the contracts with the subcontractors and sometimes with designers. Thus, this delivery system is similar to DBB, except that there is construction input during the design phase.

- **Design/Build (DB)**

  In this delivery system, the owner typically hires an architect simply to develop a conceptual design of the project. Based on this, the owner solicits proposals from design/build teams, which usually consist of a joint venture of a general contractor and an architect or engineer. The joint venture is responsible for both the detailed design and construction of the project. Thus, the owner has just one contract that covers design and construction. The DB entity may hold contracts with design consultants.
and subcontractors. This delivery system provides the greatest degree of integration of the design and construction functions.

- **Turnkey**

  This delivery system is similar to DB except that the contracting entity is responsible for the short-term financing of the project, as well as design and construction. Thus, the owner does not pay for the project until it is completed.

- **Design/Build/Operate/Transfer (DBOT)**

  This delivery system is like turnkey, except that the DB team is also required to finance and operate the facility for some fixed amount of time. Over the operation period, the team receives revenue to cover the cost of the design and construction of the facility and profit. The owner takes over the operation of the facility after this time expires. Alternatively, the owner may contract with another party for design services, creating a BOT situation. In another form of this delivery system, a team assumes ownership of the facility as well. This is commonly referred to as privatization.
APPENDIX C: INNOVATION DATA

This section contains tables that summarize the data on the construction innovations discussed in this research. The first table summarizes the data for the ten case study innovations. The second table shows how each case study innovation was classified from the perspective of each project team member. The innovation classification models discussed in Chapter 2 were used to compile this data. Finally, the third table in this section contains the data collected for the large sample of 30 construction innovations, which were used as a checking mechanism for the analysis of some of the data from the in-depth case studies. These 30 innovations were not studied in as much detail as the ten innovations presented in Chapter 5.
<table>
<thead>
<tr>
<th>Innovation</th>
<th>Project</th>
<th>Project contract</th>
<th>Innovation contracts</th>
<th>Project Delivery System</th>
<th>Innovation Delivery System</th>
<th>Co-specialized assets</th>
<th>Value chain changes</th>
<th>Time of Commitment</th>
<th>Owner's Objectives</th>
<th>Expected benefits</th>
<th>Source</th>
<th>Previous Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Specialized Resisting Frame</td>
<td>Gateway Oaks IV</td>
<td>Owner/CM - compet. GMP</td>
<td>1. CM/Steel frame - neg. LS</td>
<td>CM at risk</td>
<td>DB - Partnership of designer and fabricator/contractor</td>
<td>IT for shop drawing review</td>
<td>1st use</td>
<td>Early design</td>
<td>Low cost, long-term performance</td>
<td>Quality (new level of performance), low cost</td>
<td>Steel subcontractor</td>
<td>Steel sub and designer</td>
</tr>
<tr>
<td></td>
<td>Johnson Ranch Center</td>
<td>Owner/CM - neg. GMP</td>
<td>1. CM/Steel frame - neg. LS</td>
<td>CM at risk</td>
<td>DB - Partnership of designer and fabricator/contractor</td>
<td>IT for shop drawing review</td>
<td>Same CM, structural designer, steel sub.</td>
<td>Early design</td>
<td>Low cost, long-term performance</td>
<td>Quality (new level of performance), low cost</td>
<td>Steel subcontractor</td>
<td>CM, designer, and steel sub.</td>
</tr>
<tr>
<td></td>
<td>Roseville Corporate Center</td>
<td>Owner/CM - neg. GMP</td>
<td>1. CM/Steel frame - neg. LS</td>
<td>CM at risk</td>
<td>DB - Partnership of designer and fabricator/contractor</td>
<td>IT for shop drawing review</td>
<td>Same CM, structural designer, steel sub.</td>
<td>Early design</td>
<td>Low cost, long-term performance</td>
<td>Quality (new level of performance), low cost</td>
<td>Steel subcontractor</td>
<td>CM, designer, and steel sub.</td>
</tr>
<tr>
<td>3. Hybrid Resisting Precast Concrete Frame</td>
<td>Roosevelt Field Garage</td>
<td>Owner/DB team - neg. LS</td>
<td>1. Owner/DB team - compet. LS</td>
<td>DB</td>
<td>DB - DB team performed design and construction of frame itself</td>
<td>None</td>
<td>1st use</td>
<td>Early design</td>
<td>Long-term performance</td>
<td>Quality (new level of performance)</td>
<td>Contractor</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Eugene Garage</td>
<td>Owner/DB team - compet. LS</td>
<td>1. Owner/DB team - compet. LS</td>
<td>DB</td>
<td>DB - DB team performed design and construction of frame itself</td>
<td>None</td>
<td>Same contractor, engineer</td>
<td>Early design</td>
<td>Long-term performance</td>
<td>Quality (new level of performance)</td>
<td>Contractor</td>
<td>Contractor and designer</td>
</tr>
<tr>
<td>5. Precast Concrete Slurry Wall</td>
<td>Old Colony Line</td>
<td>Owner/GC - compet. LS</td>
<td>1. Owner/designer - FP 2. GC/foundation sub. - compet. LS</td>
<td>DBB</td>
<td>DB - Foundation sub. Contracted for design and performed construction itself</td>
<td>None</td>
<td>1st use</td>
<td>Bid</td>
<td>Low cost, aesthetics</td>
<td>Construction speed, quality (better performance), low cost</td>
<td>Foundations subcontractor</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Seaport Hotel</td>
<td>Owner/GC - compet. GMP</td>
<td>1. Foundation sub./designer - FP 2. GC/foundation sub. - compet. LS</td>
<td>DBB</td>
<td>DB - Foundation sub. Contracted for design and performed construction itself</td>
<td>None</td>
<td>Same foundations sub., precast, structural designer</td>
<td>Bid</td>
<td>Low cost, aesthetics</td>
<td>Construction speed, quality (better performance), low cost</td>
<td>Foundations subcontractor</td>
<td>Foundations sub., precast and designer</td>
</tr>
<tr>
<td></td>
<td>Pilot House</td>
<td>Owner/CM - neg. GMP</td>
<td>1. Owner/designer - FP 2. CM/foundation sub. - neg. LS</td>
<td>CM at risk</td>
<td>DB - Foundation sub. Contracted for design and performed construction itself</td>
<td>None</td>
<td>Same foundations sub., precast, structural designer</td>
<td>Late design</td>
<td>Aesthetics</td>
<td>Construction speed, quality (better performance)</td>
<td>Foundations subcontractor</td>
<td>Foundations sub., precast and designer</td>
</tr>
<tr>
<td>Innovation</td>
<td>Project</td>
<td>Project contract</td>
<td>Innovation contract</td>
<td>Project Delivery System</td>
<td>Innovation Delivery System</td>
<td>Co-specialized assets</td>
<td>Value chain changes</td>
<td>Time of Commitment</td>
<td>Owner’s Objectives</td>
<td>Expected benefits</td>
<td>Source</td>
<td>Previous Experience</td>
</tr>
<tr>
<td>------------</td>
<td>---------</td>
<td>------------------</td>
<td>--------------------</td>
<td>------------------------</td>
<td>----------------------------</td>
<td>------------------------</td>
<td>---------------------</td>
<td>-------------------</td>
<td>------------------</td>
<td>-----------------</td>
<td>---------</td>
<td>--------------------</td>
</tr>
<tr>
<td>6. Hybrid Parking Structure</td>
<td>Dow Jones Garage</td>
<td>Owner/DB team - compet. LS</td>
<td>1. Owner/DB team - compet. LS</td>
<td>DB</td>
<td>DB - DB team performed design, fabrication and erection of superstructure</td>
<td>None</td>
<td>1st use</td>
<td>Early design</td>
<td>Low cost</td>
<td>Low cost, construction speed</td>
<td>Structural designer</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Tufa Health Plan Garage</td>
<td>Owner/GC - neg. GMP</td>
<td>1. Contractor/designer - FF 2. Contractor/Feas. &amp; Erection sub. - compet. LS</td>
<td>DB</td>
<td>DBB - DB team designed system but subcontracted for fabrication and erection</td>
<td>None</td>
<td>Same structural designer</td>
<td>Early design</td>
<td>Low cost</td>
<td>Low cost, construction speed</td>
<td>Structural designer</td>
<td>Contractor and designer</td>
</tr>
<tr>
<td></td>
<td>Logan Airport West Garage</td>
<td>Owner/GC - compet. LS</td>
<td>1. Owner/designer - FF 2. GC/concrete &amp; formwork sub. - compet. LS</td>
<td>DBB</td>
<td>DBB of superstructure</td>
<td>Formwork</td>
<td>1st use</td>
<td>Early design</td>
<td>Long-term performance</td>
<td>Quality (better flow)</td>
<td>Structural designer</td>
<td>None</td>
</tr>
<tr>
<td>8. Fabric Roof</td>
<td>JFK Airport</td>
<td>Owner/DB team - compet. LS</td>
<td>1. DB team/Roof DB sub. - compet. LS</td>
<td>DB</td>
<td>DB - Subcontractor performed design, fabrication and erection of roof</td>
<td>Fabric tensioner</td>
<td>1st use</td>
<td>Early design</td>
<td>Low cost</td>
<td>Low cost, quality (aesthetics)</td>
<td>Architect</td>
<td>None</td>
</tr>
<tr>
<td>9. Tension Broach Dome</td>
<td>Marine Midland Arena</td>
<td>Owner/CM - neg. GMP</td>
<td>1. CM/Roof DB sub. - neg. LS</td>
<td>CM at risk</td>
<td>DB - Subcontractor performed design and erection of roof itself</td>
<td>None</td>
<td>1st use</td>
<td>Late design</td>
<td>Low cost</td>
<td>Low cost</td>
<td>Roof subcontractor</td>
<td>CM, roof sub., and A/E</td>
</tr>
<tr>
<td>10. Moveable Arched Scaffold</td>
<td>Grand Central Station Rehab.</td>
<td>Owner/GC - compet. LS</td>
<td>1. GC/Scaffold sub. - neg. LS</td>
<td>DB</td>
<td>DB - Subcontractor performed design, fabrication and erection of scaffold</td>
<td>Arch, scaffold, rollers</td>
<td>1st use</td>
<td>Bid</td>
<td>Construction speed</td>
<td>Quality (new level of performance), construction speed</td>
<td>Scaffolding subcontractor</td>
<td>Scaffolding sub. and GC</td>
</tr>
<tr>
<td>INNOVATION</td>
<td>SUPPLIER</td>
<td>SUB.</td>
<td>CONSTRUCTOR</td>
<td>STRUCTURAL DESIGNER</td>
<td>ARCHITECT</td>
<td>OWNER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------------------</td>
<td>----------</td>
<td>-----------------------------------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td>------------------</td>
<td>--------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Trio Structural System</td>
<td>No effect</td>
<td>Fabricator/Erector: Incremental</td>
<td>Incremental</td>
<td>System</td>
<td>Architectural</td>
<td>Modular</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Hybrid Moment-Resisting Precast Concrete Frame</td>
<td>Precast: Incremental</td>
<td>Erector: Architectural</td>
<td>Modular</td>
<td>System</td>
<td>Incremental</td>
<td>Incremental</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Ductile Precast Concrete Frame</td>
<td>Precast: Incremental</td>
<td>Erector: Modular</td>
<td>Modular</td>
<td>System</td>
<td>Incremental</td>
<td>Incremental</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Precast Concrete Slurry Wall</td>
<td>Precast: Incremental</td>
<td>Foundation: System</td>
<td>Architectural</td>
<td>Modular</td>
<td>No effect</td>
<td>Modular</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Hybrid Parking Structure</td>
<td>No effect</td>
<td>Erector: Modular</td>
<td>Architectural</td>
<td>Modular</td>
<td>Incremental</td>
<td>Incremental</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Double Helical Ramp</td>
<td>Formwork: Incremental</td>
<td>Concrete: Architectural</td>
<td>Incremental</td>
<td>Modular</td>
<td>Incremental</td>
<td>Incremental</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Fabric Roof</td>
<td>No effect</td>
<td>Fabricator/Erector: System</td>
<td>Modular</td>
<td>System</td>
<td>Architectural</td>
<td>Modular</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Tension Braced Dome</td>
<td>No effect</td>
<td>Erector: Architectural</td>
<td>Modular</td>
<td>Modular</td>
<td>Incremental</td>
<td>Incremental</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Moveable Arched Scaffold</td>
<td>No effect</td>
<td>Scaffolding sub: Architectural</td>
<td>Architectural</td>
<td>Architectural</td>
<td>No effect</td>
<td>Incremental</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#</td>
<td>Project</td>
<td>Project Location</td>
<td>Innovation</td>
<td>Description of Innovation</td>
<td>Benefits</td>
<td>Source of Innovation</td>
<td>Source Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>-------------------------</td>
<td>------------------</td>
<td>------------</td>
<td>-------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>----------------------------------------</td>
<td>-------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Kyobashi Seiwa Building</td>
<td>Tokyo, Japan</td>
<td>Active Mass Driver</td>
<td>Earthquake sensing devices activate hydraulic pumps to move a suspended mass</td>
<td>Quality (new level of performance)</td>
<td>Kajima International, Inc.</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Several</td>
<td>Seoul, Korea</td>
<td>Bakerbilt Eurosteel Floor System</td>
<td>Blower to add steel fibers and superplasticizer to concrete mix; allows</td>
<td>Quality (new level of performance)</td>
<td>C. Ayers Limited</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Lucky/Goldstar Corp. HQ</td>
<td>San Francisco, CA</td>
<td>Barrettes</td>
<td>Use of individual slurry-wall bearing elements as strip piles founded on</td>
<td>Low cost</td>
<td>Soletanche Enterprises</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>San Francisco St. Univ. Dorm</td>
<td>San Francisco, CA</td>
<td>Baumesh Confinement Reinforcement</td>
<td>Wire system to replace ties in reinforced concrete</td>
<td>Construction speed, low cost</td>
<td>Baumann R&amp;D Corp.</td>
<td>Research lab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Los Angeles Tower</td>
<td>Los Angeles, CA</td>
<td>Chevron bracing</td>
<td>Two-story chevron bracing in core of skyscraper in seismic zone</td>
<td>Construction speed, low cost</td>
<td>Seismic Structural Design Associates, Inc.</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Gateway West</td>
<td>Salt Lake City, UT</td>
<td>Face Floor Profile Numbering System</td>
<td>Ductile moment connection for steel frames</td>
<td>Quality (new level of performance)</td>
<td>Seismic Structural Design Associates, Inc.</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Several</td>
<td>Several</td>
<td>Face Floor Profile Numbering System</td>
<td>For accurately measuring flatness of concrete slabs</td>
<td>Low cost</td>
<td>Allen Face &amp; Associates</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Miller Park</td>
<td>Milwaukee, WI</td>
<td>Fan-like Retractable roof</td>
<td>Fan-like retractable roof for baseball stadium</td>
<td>Quality (new level of performance)</td>
<td>Ove Arup</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Wachovia Bank HQ</td>
<td>Winston-Salem, NC</td>
<td>Floor lifted to a higher elevation by jacks</td>
<td>Jacked up the existing 2nd floor up and build a new 2nd floor.</td>
<td>Low cost</td>
<td>Liftplate International</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Hospital extension</td>
<td>Atlanta, GA</td>
<td>Geopier Intermediate Foundation</td>
<td>Alternative to piles and piers for buildings founded on weak soils</td>
<td>Construction speed, low cost</td>
<td>Geopier Foundation Co.</td>
<td>Research lab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Cairo US Embassy</td>
<td>Cairo, Egypt</td>
<td>Grouted bored piles</td>
<td>Grout around piles to increase their end bearing capacity and the friction between the pile and the sand</td>
<td>Low cost</td>
<td>Bauer Foundations</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Fleet Center</td>
<td>Boston, MA</td>
<td>Jet grouting</td>
<td>Used to improve the load-bearing capacity of caissons to allow for top-down construction method</td>
<td>Quality (better performance)</td>
<td>Hayward-Baker</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>All since 1996</td>
<td>Several</td>
<td>Kit of Parts of the USPS</td>
<td>System for the computer-aided modular design of post office buildings</td>
<td>Construction speed</td>
<td>Jones Mah Gaskill Rhodes, Inc.</td>
<td>Architect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Goodwill Games Natatorium</td>
<td>Long Island, NY</td>
<td>Partial preassembly of roof trusses</td>
<td>Novel construction method and sequence</td>
<td>Construction speed</td>
<td>Severud Associates</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>State Office Building</td>
<td>San Francisco, CA</td>
<td>Passive seismic damper</td>
<td>Expansion project following Loma Prieta quake</td>
<td>Quality (new level of performance)</td>
<td>Forelli/Elesser Engineers, Inc.</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#</td>
<td>Project</td>
<td>Project Location</td>
<td>Innovation</td>
<td>Description of Innovation</td>
<td>Benefits</td>
<td>Source of Innovation</td>
<td>Source Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------</td>
<td>------------------</td>
<td>-----------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>----------------------------------------</td>
<td>--------------------------------------------------</td>
<td>--------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Holy Cross Church</td>
<td>Santa Cruz, CA</td>
<td>Post-tensioned masonry</td>
<td>Provides strength to masonry structures</td>
<td>Quality (better performance)</td>
<td>VSL International, Ltd.</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>New York Hospital</td>
<td>New York, NY</td>
<td>Prefabrication of structural steel system</td>
<td>Contractor preassembled multiple trusses and erected them from bargemounted cranes</td>
<td>Construction speed</td>
<td>Thornton-Tomesiati Engineers</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Franklin Park Zoo Tropical Rain Forest</td>
<td>Dorchester, MA</td>
<td>Pressure-stabilized fabric roof</td>
<td>Cable-supported fabric roof on tripod steel arches</td>
<td>Quality (aesthetic)</td>
<td>Weidlinger Associates, Inc.</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Rockwell International</td>
<td>Seal Beach, CA</td>
<td>Seismic Isolators for Retrofit of Concrete</td>
<td>Contractor installed the isolators w/o disrupting business using a specially</td>
<td>Quality (new level of performance)</td>
<td>DIS, Inc.</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>IBM Tower</td>
<td>Atlanta, GA</td>
<td>Slip-form concrete core construction</td>
<td>Use of a slip-form to construct the concrete core of this 30-story tower</td>
<td>Construction speed</td>
<td>Henry C. Beck Contractors</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Several</td>
<td>Several</td>
<td>Sprung Instant Structures</td>
<td>Quick/cheap temp. structures</td>
<td>Construction speed</td>
<td>Sprung Instant Structures</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Arthur Ashe Stadium</td>
<td>New York, NY</td>
<td>Structural 'tree' to support upper seating levels</td>
<td>Inverted pyramid truss to support precast concrete seating at upper levels</td>
<td>Low cost</td>
<td>Cantor Seinuk Group</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Galleria Mall</td>
<td>Riverside, CA</td>
<td>Suspending Vertical Expansion for Mall</td>
<td>Addition of a 2nd story w/o interrupting business</td>
<td>Construction speed</td>
<td>Charles Pankow Builders</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Denver Airport Jeppesen Terminal</td>
<td>Denver, CO</td>
<td>Teflon-coated fiberglass roof</td>
<td>$30 million, 376,000 SF roof in a series of teepee shapes</td>
<td>Quality (aesthetic)</td>
<td>CW Fentress, JH Bradburn &amp; Associates</td>
<td>Architect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Georgia Dome</td>
<td>Atlanta, GA</td>
<td>Tenagriy Dome</td>
<td>Cable-supported, fabric roof; largest ever; patented as Tenagriy Dome</td>
<td>Quality (aesthetic)</td>
<td>Weidlinger Associates, Inc.</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Speculative Office Building</td>
<td>Weston, FL</td>
<td>Tilt-up concrete construction</td>
<td>One of the tallest tilt-up projects in the US, 44-ft-long panels used to erect entire shell in 10 days</td>
<td>Construction speed</td>
<td>Burton, Braswell, Middlebrooks Associates</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Guggenheim Bilbao</td>
<td>Bilbao, Spain</td>
<td>Titanium cladding</td>
<td>Titanium, glass, and steel façade. Complex surface geometry throughout the building.</td>
<td>Quality (aesthetic)</td>
<td>Frank Gehry</td>
<td>Architect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Parking Garage</td>
<td>Madison, WI</td>
<td>Top/down construction</td>
<td>Used this method to construct a 50' deep parking garage beneath a large development</td>
<td>Construction speed</td>
<td>JH Findorff &amp; Son</td>
<td>Contractor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Rowe's Wharf</td>
<td>Boston, MA</td>
<td>Top/down construction</td>
<td>Used this construction technique to build basement parking under a 15-story building on Boston Harbor</td>
<td>Construction speed</td>
<td>Skidmore, Owings &amp; Merrill</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Salt Palace Convention Center</td>
<td>Salt Lake City, UT</td>
<td>Two-span roof truss &amp; proprietary floor vibration analysis method</td>
<td>Roof truss minimized weight &amp; cost &amp; met stringent deflection criteria. Vibration analysis for long-span suspended slab</td>
<td>Quality (better performance)</td>
<td>Reaveley Engineers &amp; Associates, Inc.</td>
<td>Structural designer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
BIBLIOGRAPHY


JD2, Inc. Product Literature on Tru-Frame. Auburn, CA.


THESIS PROCESSING SLIP

FIXED FIELD: ill. name

index biblio

☑ COPIES: Archives Aero Dewey Eng Hum
  Lindgren Music Rotch Science

TITLE VARIES: ☐

NAME VARIES: ☐

IMPRINT: (COPYRIGHT)

☑ COLLATION: 162 p

☑ ADD: DEGREE: ☐ DEPT:

SUPERVISORS:

NOTES:

cat'r: date:

☑ DEPT: C.E. ☐ F 37

☑ YEAR: 1999 ☐ DEGREE: S.M.

☑ NAME: SEMLIES, Christopher