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ADVANCED TECHNOLOGY FOR
LARGE
STRUCTURAL SYSTEMS

Lehigh University

REVIEW AND ANALYSIS OF MODULAR CONSTRUCTION PRACTICES

by

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Abstract

This study is part of a research project entitled "Modular Design and Construction of Low and Mid-Rise Buildings" funded by the Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University. The project has two broad objectives: (1) to identify opportunities to use modular construction methods for building frame systems, and (2) to develop new modular construction technology and methodology that can be used for building frame systems. This report achieves the first objective of the research project.

The report has two objectives: (1) to study current modular construction practices to identify broad advantages and disadvantages, and key differences from conventional construction practices, and (2) to identify opportunities to advance the technology and methodology of modular construction. A study of the literature and a survey of 31 companies was conducted to achieve these objectives. The results of these interviews are included in this report, and findings are summarized below.

Broad advantages and disadvantages of current modular construction practices are identified. The following advantages are identified: (1) reduced cost, (2) increased quality, (3) improved safety, (4) reduced schedule, (5) reduced social and environmental impacts, and (6) increased possibility of construction. Broad disadvantages that are identified include: (1) the need for additional material, (2) the need for additional construction effort, and (3) the need for addition coordination of activities. Another finding of this research is that modular construction activities are more involved and complex than conventional construction activities because of the interdependency among the activities, and because many of the activities are performed earlier in the project.

Certain essential characteristics of successful modular projects are also identified in the report. The characteristics are categorized within three areas: (1) project management, (2) design and engineering, and (3) fabrication. An example of a project management characteristic is having a module task team; an example of a design and engineering characteristic is designing the modules early; and an example of a fabrication characteristic is using standardization in shop fabrication and assembly.

Opportunities to advance modular construction technology and methodology for building frame systems are identified. Areas requiring future development are identified.

Executive Summary

OBJECTIVES AND APPROACH

This study is part of a research project entitled "Modular Design and Construction of Low and Mid-Rise Buildings" funded by the Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University. The goal of this study is to complete the first phase of this research project, with two specific objectives:

(1) To study current modular construction practices to identify advantages, disadvantages, and key differences from conventional construction practices.

(2) To identify opportunities to advance the technology and methodology of modular construction.

Modular construction includes methods in which materials and/or prefabricated components are assembled together offsite or onsite before being installed to their final position. Modular construction methods were investigated for a wide variety of construction types, including: bridge, industrial, light industrial/commercial, prison, residential, and ship construction; and from a variety of perspectives, including: fabricator, project manager, architect, structural engineer, engineer, erector, and manufacturer.

The research was separated into two tasks, as follows:

(1) Task 1: Investigate current modular construction practices.
- *Task 1.1:* Investigate current modular construction methods through a study of literature and a survey of industry.
- *Task 1.2:* Compare modular and conventional construction methods to identify the key differences.
- *Task 1.3:* Identify the broad advantages, driving forces, and broad disadvantages of modular construction methods.
- *Task 1.4:* Identify the key characteristics of successful modular construction projects.

(2) Task 2: Identify opportunities to advance modular construction technology and methodology, with emphasis on building frame construction.

Task 1.1 was accomplished from a study of literature and a survey of industry. The literature study included the review of technical magazines, journals, reports, and books. The survey of industry included interviews with 31 companies within the six different types of construction. Examples of modular construction projects and general modular construction practices were identified from the interviews.

Task 1.2 was accomplished by developing descriptions of modular construction activities from the literature and comparing them with conventional construction activities to identify important differences. Task 1.3, which identified the broad advantages, driving forces, and broad disadvantages of modular construction, was based on information gathered from the study of literature and the survey of industry. Task 1.4 was accomplished by analyzing the results of Tasks 1.1 through 1.3.

Task 2 identified opportunities to advance modular construction technology and methodology for building frame systems based on analysis of the findings from Task 1.

CONCLUSIONS

Conclusions in four areas are presented: (1) advantages and disadvantages of modular construction, (2) review of modular construction activities, (3) driving forces of modular construction, and (4) characteristics of successful modular projects.

Advantages and Disadvantages of Modular Construction

Several advantages and disadvantages of modular construction are identified in Chapters 2 and 4, which are summarized in Chapter 6. Six broad advantages are identified: (1) reduced cost, (2) increased quality, (3) improved safety, (4) reduced schedule, (5) reduced social and environmental impact, and (6) increased possibility of construction. Both the literature and the industry survey identified the first four broad advantages. The literature identified the last two advantages; however, these advantages were not specifically identified by the individuals interviewed in the industry survey.

Six broad disadvantages are identified: (1) the need for additional material, (2) the need for additional effort, (3) the need for additional coordination of activities, (4) increased cost, (5) increased risk, and (6) reduced adaptability to design changes. Both the literature and the industry survey identified the first three disadvantages. The literature also identified the last three disadvantages. Although the individuals interviewed in the survey may have encountered these last three drawbacks, they did not emphasize them as broad disadvantages of modular construction.

Review of Modular Construction Activities

Modular construction activities differ from those in conventional construction, as discussed in detail in Chapter 3. The differences identified in Chapter 3 are supported by the findings from the industry survey presented in Chapter 4. The construction activities in modular construction differ from those in conventional construction by: (1) an increase in effort, (2) an increase in portions of work performed earlier in the project, and (3) an increase in the interdependency among construction activities.

Planning and procurement are more involved and complex in modular construction than conventional construction because of the increased interdependency among construction activities. Design and engineering, and fabrication are more complex in modular construction because of additional design effort needed to provide the modules with structural integrity for transportation, handling and erection and because the majority of onsite construction work is transferred to the fabrication shops. The planning of transportation, handling, and erection in modular construction is more involved and complex than in conventional construction because transportation can involve large-scale 3-dimensional modules that may require special transportation methods and equipment.

Driving Forces of Modular Construction

Driving forces of modular construction were identified by the survey of industry. Six driving forces were identified: (1) site resource constraints, (2) reduced cost, (3) reduced schedule, and (4) improved safety; as well as combinations of: (5) reduced cost and schedule, and (6) site resource constraints and reduced schedule. Of the six, three were most common among the individuals interviewed: (1) site resource constraints, (2) reduced cost, and (3) reduced cost and schedule.

Characteristics of Successful Modular Construction Projects

In order to be successful, modular projects should have several essential characteristics, as discussed in Chapter 5. These characteristics include: (1) having a module task team, (2) expecting cultural resistance, (3) having an active project management team, (4) knowing how to divide the facility into appropriate modules, (5) making an early evaluation and commitment to a module concept, (6) selecting the fabricator early, (7) developing and maintaining an appropriate procurement schedule, (8) expecting savings in the construction activities, (9) designing the modules early, (10) using standardization, (11) expecting additional design and engineering effort, (12) minimizing the handling of the modules, (13) maintaining good relationships with construction officials, and (14) locating the fabrication shops near water.

RECOMMENDATIONS

Chapter 7 identifies further development needed to advance modular construction technology and methodology for building frame systems. The recommendations are divided into two groups - technology and methodology. "Modular construction technology" refers to new systems and components for building frames, and new construction equipment to produce these systems. "Modular construction methodology" refers to the procedures used in: (1) planning and evaluating the feasibility of modular construction (e.g., business decision-making procedures), (2) design and engineering procedures, (3) fabrication, and (4) transportation, handling, and erection.

Technology

Advances in modular construction technology require the development of new modules and components for constructed facilities. The recommendations for advancing modular construction technology for building frame systems follow.

(1) Develop new building frame systems specifically to exploit onsite preassembly methods.

(2) Increase the use of onsite self-aligning and/or self-locking connections such as the patented safety pinhole connection and the ATLSS connection [Perreira, 1993; Fleischman et al, 1993].

(3) Create innovative modular building frame designs within the limitations of available transportation methods (e.g., transporting building modules in folded form).

(4) Prefabricate more complex 2- or 3-dimensional modules for building frame systems rather than 1-dimensional components (e.g., fabricated beams and columns) or simple 2-dimensional components, such as those used in pre-fabricated metal buildings or precast floor systems.

(5) Reduce the number of onsite connections to decrease erection time.

(6) Integrate the service (i.e., electrical, mechanical, plumbing, insulation, etc.) systems and building frame systems in the fabrication shop.

Methodology

Advances in modular construction methodology can be made through development in several areas, including: (1) the planning, and design and engineering (i.e., the decision-making) process, and (2) the fabrication, transportation, handling, and erection process.

• Planning, and Design and Engineering:

(1) Develop procedures to determine an optimal conceptual design that takes advantage of modular construction by identifying the extent of modularization that will make the project successful from the owner's business and/or financial perspective. The methods for optimization should include the selection of the size, weight, and dimensions of modules considering fabrication, transportation, handling, and erection.

(2) Develop procedures to evaluate the use of modular construction methods in the construction of building frame systems.

(3) Develop procedures for the selection of the best transportation method for modules that consider the module dimensions and weight, and transportation economics.

(4) Develop procedures for detailed economic analyses of modular and conventional construction approaches for a project.

(5) Create new concepts for innovative and productive management teams responsible for the planning and management of modular projects.

• Fabrication, Transportation, Handling, and Erection:

(1) Create more convenient methods to disassemble and relocate facilities without demolishing them.

(2) Develop construction methods that assemble the modules as close as possible to, but not necessarily at, the construction site to reduce transportation effort.

(3) Develop construction methods to increase the use of onsite preassembly of components prior to erection.

Chapter 1

Introduction

1.1 INTRODUCTION

This study is part of a research project entitled "Modular Design and Construction of Low and Mid-Rise Buildings" funded by the Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University.

This project has two broad objectives: (1) identify opportunities to use using modular construction methods for building frame systems, and (2) develop technologies and methodologies to advance the use of modular construction methods for building frame systems. The research approach consists of five tasks: (1) investigate current modular construction practices, (2) identify opportunities to advance modular construction technology and methodology with emphasis on building frame systems, (3) analyze the opportunities in current design-fabrication-erection practice for building frame systems, and identify those for which modular construction offers the greatest potential benefits, (4) develop new modular construction technology, and (5) develop methods for selecting appropriate levels of prefabrication and preassembly and for designing prefabricated and preassembled components. This study addresses Tasks 1 and 2 of the research project.

1.2 RESEARCH OBJECTIVE

The objective of this report is to complete the first two tasks of the research project discussed above. There are two specific objectives:

(1) To study current modular construction practices to identify advantages, disadvantages, and key differences from conventional construction practices.

(2) To identify opportunities to advance the technology and methodology of modular construction.

1.3 SCOPE OF RESEARCH

Modular construction includes methods in which materials and/or prefabricated components are assembled together offsite or onsite before being installed to their final position. Tatum et al [1987] have defined three levels of "special construction methods," which include:

(1) *Prefabrication:* a manufacturing process, generally taking place at a specialized facility, in which various materials are joined to form a component part of the final installation.

(2) *Preassembly:* a process by which various materials, prefabricated components, and/or equipment are joined together at a location away from the final point of assembly for subsequent installation.

(3) *Module:* a product resulting from a series of offsite assembly operations; it is usually the largest transportable unit or component of a facility.

This research investigates the three modular construction methods identified by Tatum et al [1987], but focuses more specifically on: (1) offsite prefabrication, (2) onsite preassembly, which involves assembling components onsite at ground level and then erecting them into their final position, and (3) modularization, which involves the construction of complete 3-dimensional large-scale modules that are fabricated and assembled offsite, transported to the construction site, and erected into their final position with minimal fabrication and assembly work onsite.

Modular construction methods are investigated for a wide variety of construction types, including: bridge, industrial, light industrial/commercial, prison, residential, and ship construction; and from a variety of perspectives, including: fabricator, project manager, architect, structural engineer, engineer, erector, and manufacturer. The purpose of the investigation is to report on the state of modular construction practice and to identify opportunities to advance modular construction technology and methodology with emphasis on the area of building frame systems.

1.4 RESEARCH APPROACH

The research has been separated into two tasks, as follows:

(1) Task 1:Investigate current modular construction practices.

- *Task 1.1* Investigate current modular construction methods through a study of literature and a survey of industry.

- *Task 1.2* Compare modular and conventional construction methods to identify the key differences.

- *Task 1.3* Identify the broad advantages, driving forces, and broad disadvantages of modular construction methods.

- *Task 1.4* Identify the key characteristics of successful modular construction projects.

(2) Task 2: Identify opportunities to advance modular construction technology and methodology with emphasis on building frame construction.

Task 1.1 is based on a study of literature and a survey of industry. The literature study includes the review of technical magazines, journals, and reports, and books. The survey of industry includes interviews with approximately 31 companies within the six types of construction. Examples of modular construction projects and general modular construction practices are identified from the interviews. The companies that are interviewed range from local erectors of pre-engineered metal buildings to large international companies that typically act as project managers.

Task 1.2 is accomplished by developing descriptions of modular construction activities from the literature and comparing them with conventional construction activities to identify important differences in the planning, engineering, and construction activities. Task 1.3, which identifies the broad advantages, driving forces, and broad disadvantages of modular construction, is based on information gathered from the study of literature and a survey of industry. Task 1.4 is accomplished by analyzing the results of Tasks 1.1 through 1.3.

Task 2 identifies opportunities to advance modular construction technology and methodology based on analysis of the findings from Task 1.

1.5 OUTLINE OF REPORT

This report consists of an executive summary, seven chapters, and two appendices. The executive summary presents a summary of this report, its conclusions, and provides a discussion of future research work. The present chapter has outlined: (1) the related research project, (2) the research objectives, (3) the scope of research, and (4) the research approach. Chapter 2 presents an overview of the advantages and disadvantages of modular construction that have been identified through a study of literature. Chapter 3 describes construction activities based on the study of literature and compares them with conventional construction activities. Chapter 4 describes recent modular construction projects and practices, based on a survey of individuals associated with 31 selected companies. This chapter describes the driving forces, specific benefits, broad advantages, and broad disadvantages of modular construction that were identified by the individuals interviewed. Chapter 5 describes essential characteristics of successful modular construction projects. These essential characteristics were identified through the study of literature and the survey of industry.

Chapter 6 presents a summary of current modular construction practices. This chapter reviews, analyzes, and discusses the results obtained from the previous four chapters. Chapter 7 presents opportunities to advance modular construction technology and methodology for building frame systems; it discusses technology and methodology that should be developed in order to exploit some existing opportunities in modular construction for building frame systems.

Appendix A lists the companies that participated in the survey of industry. The list is arranged in chronological order and includes: the company names, descriptions, and addresses; and the telephone numbers, and the names of the individuals interviewed. Appendix B presents a survey and comparison of three computer programs that are used to determine the feasibility of using modular construction methods for industrial projects.

Chapter 2

Review of Advantages & Disadvantages of Modular Construction

2.1 INTRODUCTION

From the literature, it appears that modular construction is used if certain advantages can be obtained or if a project appears impossible to construct with conventional construction methods. For example, modular construction is often used when onsite construction is limited by constraints such as a lack of skilled labor, a lack of work space, or difficult weather conditions; and it may provide an opportunity to pursue a difficult project without significant economic penalties. Glaser et al [1979] state "the modular approach can offer significant savings compared with conventional project execution . . . There is a greater likelihood of completion on schedule and the resulting quicker return on investment." Hyland et al [1977] state that "modular construction of Liquified Natural Gas (LNG) facilities on barges . . . can result in considerable savings in both foreign and domestic projects."

Modular construction methods have potential advantages and disadvantages when compared with conventional construction methods. This chapter reviews the broad, advantages and disadvantages of modular construction that have been identified from a study of the literature. Table 2.1 summarizes the broad advantages and disadvantages of modular construction.

The literature that was used for this study includes technical magazines, technical reports and journals, and text books. Some of the technical magazines and journals include issues of: (1) Engineering News Record, (2) Civil Engineering, (3) Chemical Engineering, (4) Hydrocarbon Processing, (5) Oil and Gas Journal, (6) Chemical Engineering Process, (7) Modern Steel Construction, and (8) Journal of Construction. Reports and textbooks that were used are in the list of references.

2.2 ADVANTAGES

Modular construction methods can provide a project with many advantages. Hesler [1990] identifies the following advantages: (1) constructability, (2) improved schedule, (3) savings in field labor and in field management, (4) quality and productivity, and (5) testing. Wells [1979] identifies advantages that include: (1) acquiring a single responsible source, (2) testing, (3) training operators, (4) controlling the schedule, and (5) reducing cost. Taylor [1991] states that advantages of the use of prefabricated precast concrete members in the construction of parking garages include: (1) speed of construction, (2) accuracy, (3) built-in fire resistance, (4) design flexibility, (5) single responsibility, (6) onsite simplicity, and (7) economy.

Table 2.1
Potential Broad Advantages and Disadvantages of Modular Construction

ADVANTAGES	DISADVANTAGES
Increased Quality	Additional Material
Improved Safety	Additional Effort
Reduced Schedule	Additional Coordination
Reduced Cost	Increased Cost
Reduced Social & Environmental Impact	Increased Risk
Increased Possibility of Construction	Reduced Adaptability to Design Changes

In general, by carefully implementing modular construction methods, advantages in several broad areas can be obtained, including: (1) reduced cost, (2) increased quality, (3) improved safety, (4) reduced schedule, (5) reduced social and environmental impact, and (6) increased possibility of construction [Tan et al, 1984]. These advantages are discussed below.

2.2.1 Reduced Cost

Tatum et al [1987] state that lower project costs can result from using modular construction. In some cases, a reduction of capital costs by up to 20% is possible [Shelley, 1990]. Hesler [1990] states that "in-depth studies have shown that modular power plants show capital cost savings of 20% or more and schedule savings approaching 40%." Shelley [1990] states that most modular construction experts would agree that modular construction can save between 5% and 10% of the total cost for most projects."

Examples of reduced costs through modular construction include the following: John Brown of John Brown Engineers & Constructors, Inc. stated that savings of at least 7% of the total contract amount was obtained by using modular construction methods rather than conventional methods for over 40% of the process facilities for the Sullom Voe Oil Terminal in the Shetland Islands [Parkinson et al, 1982]; Tatum et al [1987] state that it has been estimated that "the modular engineering concept can save up to 10% of the total cost of a facility, cut onsite labor 25%, and reduce the plot [working] area 10% to 50%;" Hesler [1990] states that "despite its relatively high cost for the initial design, savings in other areas can make the technique a cost effective design strategy."

Tatum et al [1987] state that cost savings can emerge from two areas: (1) from work performed indoors in a more controlled environment, rather than outdoors onsite in a possibly hostile environment, and (2) from shop labor rates, which are usually lower than those onsite. Reduced cost is an advantage that generally develops from specific cost-efficient items such as: (1) fewer onsite construction manhours, (2) less onsite management [Hesler, 1990], (3) lower financing costs from decreased construction time, (4) reduced site mobilization effort [Shelley, 1990], (5) completing the project early, and (6) increased domestic/international competition for fabrication and assembly contracts [Shelley, 1990].

Labor rates in fabrication shops are normally lower than onsite construction because of the uncertainties involved in onsite work. Leonard Wikman, project engineering manager for Bechtel Corporation, stated that transferring the labor force from the field into an indoor facility can reduce labor costs by 50% [Shelley, 1990]. Onsite construction manhours and skilled labor costs decrease due to the transfer of onsite work into fabrication shops. This reduction of onsite manhours decreases the need for onsite management as well as the overall construction time.

The site mobilization costs are reduced by fabricating the modules in a shop environment, which reduces the amount of equipment and labor located in remote construction sites, and reduces the need for housing and other living facilities onsite. Serge Randhava, chairman of a Houston-based constructor of small industrial facilities, stated that by maintaining a fabrication shop specifically for the fabrication of modules, the need to mobilize (e.g., provide housing for workers) is non-existent [Shelley, 1990]. Hyland et al [1977] state that "savings can also result because there is no need to build infrastructure and support facilities for extensive labor forces in remote locations." This quote refers to potential savings due to the fact that support facilities for the labor force (such as housing and other living accommodations) are not needed; although site work (such as building roads for transporting the modules) is necessary.

An increase in domestic/international competition can reduce costs by increasing the quantity and diversity of potential fabricators for a project. Contractors unable to compete for a project using conventional construction because of geographical location can use modular construction methods, regardless of the location [Tatum, 1987].

The advantages of reduced cost are not always obvious. Whittaker [1984] states that both cost savings and cost increases occur in modular construction projects; cost savings emerge from working in a more controlled environment, and cost increases emerge from the extra design and engineering, and transportation and handling effort, as discussed later in Chapter 3. Whittaker [1984] also stated "the net effect of all these considerations can only be judged for each project. Detailed and accurate quantifications of the effects on cost and timing of the different possibilities is unlikely to be available. Even in retrospect, there is a good deal of judgement, not to say speculation, involved in an economic assessment." Bolt et al [1982] state that "in spite of additional cost items such as extra structural steel, more expensive form of transportation, the 1,000-ton crane, and extra engineering and management effort," the Sullom Voe modular construction project "showed a saving in installed cost over conventional construction of about 7%."

2.2.2 Increased Quality

Increased quality is an advantage that develops from specific quality-effective items such as: (1) a better work environment [Shelley, 1990], (2) increased availability of a skilled labor force, (3) increased quality control, and (4) increased module testing [Tan et al, 1984]. The potential to produce a high quality facility is increased because work is performed in a controlled indoor environment. Huebel [1979] states that "better quality, due to fabrication in a controlled environment by skilled craftsmen, can be expected." Robert Clement, vice-president of the process systems sector for Applied Engineering Company (AEC), stated that one advantage is that the required equipment, tools, computer systems, and routines remain in the fabrication shop for the activities that occur there [Shelley, 1990]. Quality can increase because the skilled labor working in the fabrication shop is more permanent than the temporary skilled labor onsite [Kim, 1993]. In a particular residential project, Paul Ruiz, structural engineer with Ryan-Biggs Associates, stated "shop fabrication of the large modules resulted in an extremely high quality level and enabled the near zero tolerances to be met" [Modern Steel Construction, 1993].

Quality is also increased since a module can be easily inspected as it is assembled in the fabrication shop. In addition, the modules can be tested in the fabrication shop prior to the module leaving the shop. Frank Vigani, senior research engineer, stated that the start up of modules built at Aristech Chemical Corporation's pilot plant at Monroeville, PA was efficient because the modules' instrumentation and electrical systems were pre-tested at the fabrication shop [Shelley, 1990].

2.2.3 Improved Safety

Improved safety is an advantage that develops from specific safety-effective items such as: (1) working in a controlled environment, and (2) working at ground level. Improved safety can be obtained through modular construction because the majority of the assembly work is performed in fabrication shops, where the controlled environment is conducive to safer practices because the required equipment and materials are readily available. Improved safety is easier in fabrication shops than onsite where bad weather, a lack of space and/or skilled labor, and uncertainties may exist. The transfer of onsite work into fabrication shops also reduces the number of onsite personnel. Robert Sinuc, general manager of investment engineering for General Electric, stated that assembling a plant in a fabrication shop eliminates "acute safety hazards associated with bringing a construction crew into the middle of an operating process plant." Working at ground level is one specific activity that reduces the potential danger of height-related accidents. By assembling the modules at ground level, the work can be performed with the aid of ladders rather than equipment such as cherry-pickers or cranes, and thus, height-related accidents can be significantly reduced.

2.2.4 Reduced Schedule

Reduced schedule is an advantage that develops from several specific schedule-effective items such as: (1) working in a more controlled environment, (2) performing activities in parallel, (3) increasing the control of schedule [Wells, 1979], (4) higher productivity from the permanent work force in fabrication shops, and (5) the opportunity to train operators at fabrication shops rather than on-site [Wells, 1979]. In modular construction, work can be expedited by the availability of more controlled (indoor) environments. Controlled environments reduce the impact of poor weather and other site conditions.

The design and procurement activities usually overlap in modular projects because general contractors are involved at an early point in the project, during the design and engineering phase, rather than later in the procurement (bid) phase. For example, Mullet [1989d] indicates that design and engineering must be in progress when qualifying, selecting, and procuring the fabrication and handling services and equipment, because of the interdependency of modular construction activities (Chapter 3). Working several tasks simultaneously can be a significant advantage of modular construction because, for example, the site work can be performed in parallel with the module assembly. Robert Bobst, associate director of engineering for the Polyolefins Division of Union Carbide, stated "during a modular project, a lot of things go on in parallel that would ordinarily be carried out in series for a stickbuilt project" [Shelley, 1990]. Bobst stated that one 20-module project took 12 months to fabricate and deliver compared with 18-20 months using conventional construction; he credited shop efficiency and working in parallel for this schedule savings [Shelley, 1990]. Shelley [1990] indicates that modular construction can shorten construction time by 50%, and early completion of a project can reduce the financing expenses and associated costs.

Increased control of the construction schedule is an advantage that can be obtained by carrying out the construction activities independently. For example, the schedule can be accelerated by starting the assembly work prior to the site work. Gene Cribb, corporate director of project management of Rhone-Poulenc, Inc., stated "using modular construction, we were able to begin the engineering and construction on schedule offsite, while the permitting was being carried out at the site" [Shelley, 1990].

The productivity of a more permanent work force and the training of operators in fabrication shops can also reduce the schedule. Serge Randhava stated that "the marked improvement we see in the productivity of a permanent staff of skilled craftsmen translates into a shorter project duration" [Shelley, 1990]. Being able to train operators on completed modules at fabrication shops rather than onsite is also an advantage [Wells, 1979].

2.2.5 Reduced Social and Environmental Impact

The ability to reduce the social and environmental impact of construction projects is a major advantage of modular construction. Many countries are concerned with the potential impact of a project on their local environment and infrastructure. Nahas [1978] states that in the Middle East, skilled labor is often imported from other countries. However, when the imported labor disrupts the local economy, a limit of acceptable imported labor may be reached and the project may be cancelled [Nahas, 1978]. For example, in a particular project, the Saudi Petrochemical Project cited by Tatum et al [1987], one of the driving forces for using modular construction was the socio-political implications of importing foreign workers. The project was possible using modular construction to reduce the social and environmental impact [Tatum et al, 1987]. Huebel [1979] states that "reducing the field construction effort minimizes the effect of the project on the surrounding environment." Hyland et al [1977] state that "if these projects were not built on barges, the massive work force brought into a country could cause rapid inflation, political unrest, and perhaps an unwanted change in a country's social structure."

2.2.6 Increased Possibility of Construction

The ability to construct at remote locations is a major advantage of modular construction. Without modular construction as an alternative to conventional construction, construction in many geographical locations, such as the North Slope in Alaska, would not be feasible because of the hostile environment. Projects in remote locations that are not feasible using conventional construction are often feasible using modular construction.

Modular construction can be used to overcome site resource constraints in remote, hostile locations. The phrase "site resource constraints" is used to indicate the lack of onsite resources such as space, labor, and an appropriate construction environment. Tatum et al [1987] identify several typical constraints: (1) site constraints, (2) labor constraints, (3) environmental constraints, and (4) project constraints. Project constraints include items such as demanding schedules and tight budgets. The first three constraints are site resource constraint, and are discussed below.

Site constraints and site characteristics play an integral part in determining whether the project can be constructed by modular or conventional methods. If adverse topography exists onsite, the site is in a remote area, or access is constricted by existing structures, modular construction may be a feasible approach since it can reduce the required movement of labor and material onto the site (although, it can increase the size of the components moved onto the site.) Labor constraints exist when there is a deficiency in the quality, quantity, or skill types of the labor available at the site. Environmental constraints include the lack of significant infrastructure at or adjacent to the site, adverse social and political conditions of the site, and poor onsite weather conditions. Adverse social and political conditions may develop from importing skilled labor to the site, as discussed earlier. Poor weather conditions can be a significant site constraint. Modular construction is often used for sites in remote areas where the weather is not conducive to construction for major portions of the year.

2.3 DISADVANTAGES

Modular construction can have disadvantages as well as advantages. This section discusses the main disadvantages that were identified from the literature. These disadvantages include a need for: (1) additional material, (2) additional construction effort, (3) additional coordination, (4) increased cost, (5) increased risk, and (6) reduced adaptability to design changes. These disadvantages are discussed below.

2.3.1 Need for Additional Material

The need for additional material is a disadvantage of modular construction that develops from the structural requirements of the modules. The additional material can include more or larger structural members, more bracing for transportation loads, and redesigned (or increased capacity) structural connections. Shelley [1990] indicates that about 30% more structural steel, which is usually used for rigging and transporting the module, is required. The additional material can increase costs by about 0.5% of the total project cost [Kliewer, 1983]. Additional bracing is often placed on the modules. The bracing, which provides the modules with strength, stiffness, and stability during transport and erection also provides support for equipment and can become a permanent part of the structural frame [Nahas, 1978]. Since each module is assembled individually, additional onsite connections may be needed to join the modules. Additional work and construction cost are often associated with the additional material.

2.3.2 Need for Additional Effort

The need for additional effort is a disadvantage of modular construction. This disadvantage includes increased effort in the following areas: (1) planning and scheduling, (2) design and engineering, (3) procurement, (4) fabrication, (5) inspection, and (6) transportation, handling, and erection [Tatum et al, 1987].

More planning and scheduling is required for a modular project than a conventional project because of the greater interdependence of planning, design, fabrication, and transportation, handling, and erection. Detailed planning as well as detailed cost estimates are required early in the project. Early detailed schedules are required, for example, for the design, fabrication, and transportation activities. In fact, the actual planning phase of a modular construction project is often lengthened compared to a conventional construction project [Mullet, 1984a].

The additional design and engineering activity is needed: (1) to avoid later design changes, (2) to provide the module with sufficient strength, stiffness, and stability to withstand the transportation, handling, and erection loads, and (3) to design the connections between modules. In addition to the increase in design and engineering activity, the required effort is performed earlier in the project. The procurement activity also increases in scope because it involves more vendors and fabrication shops, and there is a need for rigorous fabricator and fabrication shop evaluation [Tatum et al, 1987].

In modular construction, the effort involved in the fabrication activity increases compared with that of conventional construction due to the transfer of onsite work into fabrication shops. The need for inspection and supervision in fabrication shops can increase because a larger number of workers are involved assembling the modules in parallel in various fabrication shops [Whittaker, 1984]. Transportation, handling, and erection, which are more complex in modular construction, set limitations on the module dimensions and weight and must be addressed early in the planning of the project. Transportation studies are required to thoroughly analyze the possible transportation methods.

2.3.3 Need for Additional Coordination

As the interdependence of construction activities increases, the need for communication and control mechanisms between activities increases. The need for additional coordination is a disadvantage of modular construction that relates to the interdependence of activities. Because many activities are performed in parallel rather than in series as in conventional construction, there is an increase in activity coordination [Tatum et al, 1987]. Figure 2.1 shows the required coordination among the modular activities.

The coordination of module design and engineering with module fabrication is essential. In fact, it is favorable to include the fabrication and construction personnel in the design activity [Armstrong, 1972]. Coordination of design with transportation, handling, and erection is essential since transportation, handling, and erection set limitations on the module dimensions and weight. Bruce Smith, project advisor with Davy McKee (London) stated "you can make it [the module] as big as you want, provided you can move it out of the shop" [Parkinson et al, 1982]. Proper coordination of these two activities is needed to avoid expensive rework to reduce the size of a module to meet transportation, handling, and erection requirements.

Additional coordination between design and procurement is required since the handling equipment must be available, when needed. The contract for handling the module should be finalized prior to the conclusion of the module design [Stubbs et al, 1990]. The coordination between design and permitting increases because of the movement of the module through public/private land and/or waters to its final location onsite. This coordination may involved state, local and/or foreign regulatory agencies depending on the project [Wells, 1979]. The coordination between fabrication and procurement increases because there may be more fabrication shops involved in modular construction projects than in conventional construction projects [Tatum et al, 1987].

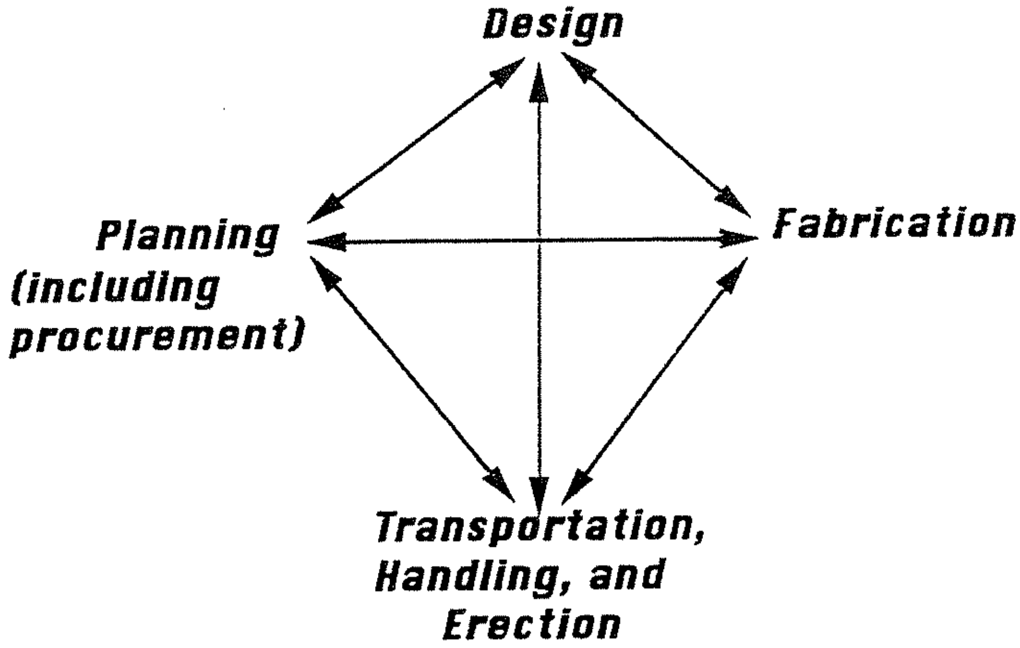


Figure 2.1 Coordination among Modular Construction Activities

The coordination of module fabrication with transportation, handling, and erection is also important. The means of transportation, for example, must be available upon completion of module fabrication, and the handling equipment should have a larger lifting capacity, since most modules are quite heavy. When handling and/or lifting the modules, adequate equipment must be available to avoid equipment breakdowns and the corresponding loss of time and money [Armstrong, 1972].

Another area of coordination in modular construction involves quality control and inspection. In conventional construction, the work performed on the facility at the construction site can be inspected in place by representatives of the owner and the responsible engineer. However, in a modular construction project, modules are often fabricated and assembled at various locations (perhaps in different countries) and the ease of physically inspecting the facility and communicating among the individuals involved in inspection is not a simple process. When a module is fabricated in the United States, for example, and then delivered to a construction site in another country, proper coordination of quality control and inspection between the countries is essential to maintain the construction schedule and to avoid delays due to rework to comply to the country's codes and regulations. If the fabrication shops are in more than one country, the required coordination increases [Tatum et al, 1987].

2.3.4 Increased Cost

Increased cost is a disadvantage in modular construction associated with the disadvantages listed above. Glaser et al [1979] state that the additional manhours required for design and engineering of a modular construction project increase the design and engineering cost by approximately 10%; Kliewer [1983] cited an engineering cost increase of 15%. For example, because there was a need to comply to Canadian standards as well as U.S. standards in a particular project, Thomas C. Esper, general manager of the Rack Structures Group, stated "we roughly doubled the engineering cost, but we made sure the building would work" [Modern Steel Construction, 1991]. The additional design and engineering cost can reduce the savings achieved in the erection activity [Armstrong, 1972].

Glaser et al [1979] state that because of the effort needed to evaluate and select vendors, fabricators, and fabrication shops, and to administer contracts, the cost associated with procurement increases by 20% in modular construction projects. The costs of the fabrication and transportation activities increase by approximately 17% and 13%, respectively [Glaser et al, 1979]. Shelley [1990] states that the transportation cost is about 1-2% of the value of the module. Glaser et al [1979] state that the increase in transportation cost is mainly due to the specialized transportation methods used and the module insurance. Cost increases also arise from the need for additional material [Glaser et al, 1979].

Despite the increased cost listed above, most modular construction projects show a savings in installed costs over conventional construction. However, Hesler [1990] states that the costs involved in the first modular construction project are usually greater because of inexperience.

2.3.5 Increased Risk

Increased risk is another disadvantage of modular construction. Because modular construction introduces changes to the standard project organization, new risks develop such as those identified by Hesler [1990], which include the risks of: (1) utilizing non-qualified engineering and construction firms, (2) encountering module loss and/or module transport damage, (3) having improper project management, (4) encountering problems with the fabrication shops (in terms of capabilities and location), (5) encountering engineering and procurement problems (in terms of timely performance and interdependency of activities), and (6) using an "all eggs in one basket" approach.

2.3.6 Reduced Adaptability to Design Changes

Reduced adaptability to design changes is another disadvantage of modular construction. Modular construction increases the interdependency of construction activities, thus, changes in a design can disrupt a wide variety of inter-related activities. Once the design has been approved and the other interdependent activities are undertaken, the design should not change; modular construction is not adaptable to design changes.

2.4 SUMMARY

This chapter presents a review of the advantages and disadvantages of modular construction generated from a study of the literature. Both the advantages and disadvantages can be classified into two categories: (1) the advantages and disadvantages common to most modular projects, and (2) the advantages and disadvantages unique to specific modular projects.

The advantages common to most modular projects include: (1) improved safety, and (2) reduced social and environmental impact. The disadvantages common to most modular projects include: (1) the need for additional material, (2) the need for additional effort, (3) the need for additional coordination of activities, and (4) the increased risk of modular construction. The advantages unique to specific modular projects include: (1) reduced cost, (2) reduced schedule, (3) increased quality, and (4) increased possibility of construction; and a disadvantage unique to specific modular projects includes increased cost.

This chapter has presented the broad advantages and disadvantages of modular construction. By analyzing these advantages and disadvantages, one can conclude that modular construction is worth considering if: (1) the potential advantages can be achieved using modular construction rather than conventional construction, (2) the potential disadvantages can be overcome, and (3) the appropriate conditions, that drive the use of modular construction, exist. However, it should be realized that modular construction is not for every project; it is an alternative to conventional construction [Clement et al, 1989]. For example, modular construction is often used because certain advantages can be obtained or because the project appears impossible to construct with conventional construction methods. If this is the case, detailed investigation of modular construction technology and methods must be made to ensure that the project will be successful.

Chapter 3

Review of Modular Construction Activities

3.1 INTRODUCTION

This chapter discusses five activities of a modular construction project: (1) planning, (2) design and engineering, (3) procurement, (4) fabrication, and (5) transportation, handling, and erection, as shown on Table 3.1. Of the five, planning is the most significant activity in a modular construction project; its complexity is well beyond that of conventional construction. Tatum et al [1987] state that modular construction projects are sometimes planned in reverse; "the eventual method of transportation sets upper limitations on the size and shape of the modules. Loadout dates to support special transport and handling equipment often drive the fabrication schedule. The fabrication yards cannot be laid out until the sequence of module loadout is set."

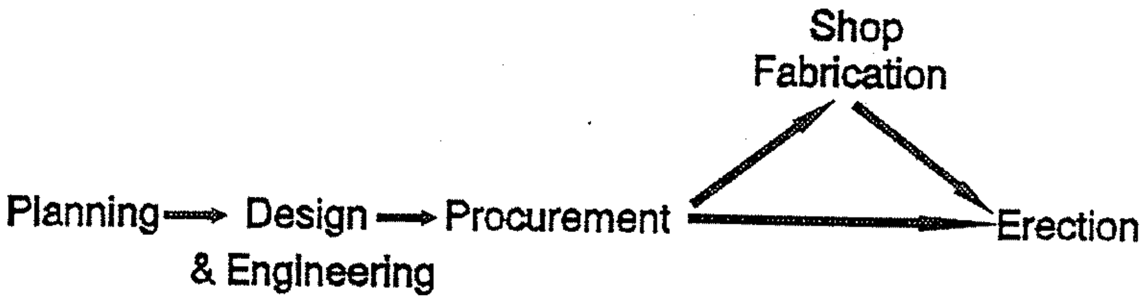
Table 3.1
Activities in Modular Construction

MODULAR CONSTRUCTION				
Planning	**Design & Engineering**	**Procurement**	**Fabrication**	**Transportation Handling, & Erection**

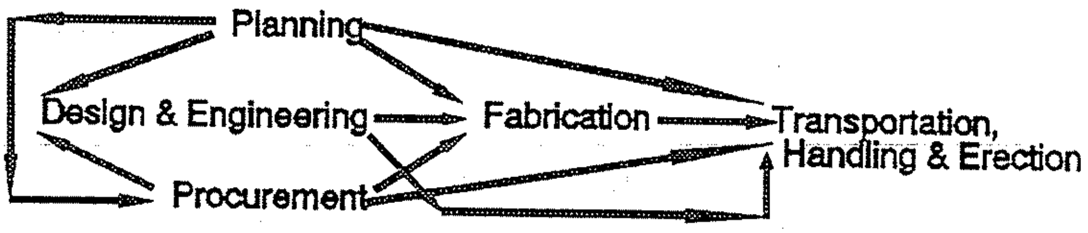
Compared to conventional construction, modular construction requires greater interaction among the construction activities. Modular construction redefines the relationships among activities that are usually independent in conventional construction. Unlike standard construction, where many of the major design and engineering, and construction activities are performed in sequential order, the activities are often performed in parallel in various engineering offices, fabrication shops, and at the construction site. The planning of many construction activities often needs to occur early in the project. For example, the permit acquisitions and transportation, handling, and erection activities are addressed early in the project since special permits may be required to transport the modules, depending on their dimensions and transportation methods.

Figure 3.1 shows both the conventional and modular flow of construction activities. Note the interdependence of activities in the modular flow.

Each activity of modular construction is discussed in this chapter. The section describing planning ranges from project control to site planning. Procurement of modular construction activities is discussed within the planning section due to its significant interdependence with other activities and the need for early procurement. The remaining sections describe: (1) design and engineering, (2) fabrication, and (3) transportation, handling, and erection. These sections include discussions of these activities and their differences when compared to the same activities in conventional construction.



Conventional Flow



Modular Flow

Figure 3.1 Interdependency of Modular Construction Activities

3.2 PLANNING

Planning in modular construction is critical because it must anticipate, predict, and control other construction activities. Planning activities occur throughout the project; they range from the initial conceptual planning to the planning of the final construction activities. Planning deals with the initial organization, planning, and procurement of the other construction activities (design and engineering, fabrication, and transportation, handling, and erection). Planning is also critical because modular construction methods do not adapt well to changes. Once the module design has been approved, it is essential to avoid changes that will produce additional expenses and delays in schedule. There is little flexibility in the fabrication and assembly of the modules; they must be constructed within the specifications and completed on schedule to avoid costly delays. Discussion of the planning activities in this section shows that planning in modular construction is more critical, complex, and interdependent than planning in conventional construction. The following planning activities are discussed: (1) project control, (2) module planning, (3) procurement, (4) transportation studies, and (5) site planning.

3.2.1 Project Control

Project control continues throughout the life of the project. It encompasses everything from setting the initial budget to paying the final bill. For modular construction, inadequate control can allow a project to lose all potential advantages. The initial expenses are often greater in a modular project compared with a conventional project, and thus, there is more risk for the owner and contractors. Two of the most important objectives of project control: (1) cost control, and (2) schedule control, are discussed below.

- **Cost Control:**

Armstrong [1972] states "project management is the name of the game -the proper control of all aspects of costs that go into a construction project." Tracking cost is a means of controlling the project. Certain modular construction costs are sometimes greater than those of conventional construction, however, the total modular project cost may be reduced considerably. Clement et al [1989] identify project cost elements for the construction of modules for industrial and chemical/process plants. Table 3.2 shows a summary of these elements; note the typical changes in costs involved in modular projects.

In addition to the elements shown in Table 3.2 that decrease project cost, other factors such as: (1) early completion of the project, (2) lower financing charges due to a shorter project schedule, (3) reduced onsite labor force, and (4) reduced rework and replacement, can reduce the overall project cost.

While costs can increase in specific project activities and decrease in others, the overall project cost provides a clearer indication of the cost effectiveness of modular construction methods. Robert Clement, Vice-President of the process systems sector for

Applied Engineering Company (AEC) states "the objective isn't to make every element [of modular construction] less costly. It's the bottom line that counts" [Shelley, 1990].

Table 3.2
Elements that Change the Cost of Modular Projects
(after Clement et al, 1989)

Costs	Modular vs. Conventional
Management	
Project Management, Control, & Administration	+
Quality Assurance	-
Project Procurement	=
Design and Engineering	
Project	+
Process	=
Piping & Layout	+
Equipment, Electrical, & Instrument	=
Civil	--
Structural, Modeling	+
Indirect Costs (expenses, insurance & taxes)	=
Earthwork and Site Specialties	=
Concrete	
Site & Substructure Concrete	=
Superstructure Concrete	-
Equipment Foundations	---
Buildings, Structural, and Architectural	
Structural Steel	+
Miscellaneous Steel Specialties	---
Transportation, Handling, and Erection	
Studies, Planning	+
Equipment and Methods	+

Legend

+	cost increases with modular construction
=	similar cost for both modular and conventional construction
-	minor cost decreases with modular construction
--	moderate cost decreases with modular construction
---	significant cost decreases with modular construction

- **Schedule Control:**

Maintaining control of the project schedule is a key function of project control activities. If the schedule is reduced, many potential or existing costs can be reduced or eliminated. The schedule of a modular project differs from that of a conventional project in many ways. Philip G. Young, Vice-President with Ralph M. Parsons Company in Pasadena, California, states "on a stick-built job, you can go into construction with 40% of the engineering done, but on a modular one, you had better have about 90% of your engineering done" [Parkinson et al, 1982]. Having 90% of the engineering done prior to commencing construction requires a tight schedule with very little float time since changes in completion dates can be significantly detrimental to a modular project. Parkinson et al [1982] state "you have to build and ship the modules in sequence, so you have much less flexibility."

3.2.2 Module Planning/Conceptual Design

The conceptual design activity selects feasible module designs including the proposed size, material, and weight. Bolt et al [1982] state "the first design parameter established for a modularized plant is the maximum size and weight of a module that is practical and economical to transport from its construction yard to the plant site."

The conceptual design activity depends upon attributes related to the other construction activities. For example, the conceptual design and the transportation methods are interdependent. Stubbs [1990] states that although the module dimensions and transportation methods vary between projects, the selection of a cost effective combination of the two is the key to achieving the benefits of modular construction. The weight of the modules and the handling equipment are also interdependent; the design of large modules must consider the handling equipment's lifting capacity.

Table 3.3 lists other factors that are usually addressed in the conceptual design [Mullet, 1984c].

Table 3.3
Factors in Module Planning
[after Mullet, 1984c]

Transportation Factors
- Transporting, rigging & shipping concepts
- Dimensional control
- Module size & weight
- Shipping protection
- Module center of gravity

Other Miscellaneous Factors
- In situ corrosion protection
- Base frame concept
- Structural design criteria (e.g., seismic, shipping)
- Module layout
- System tie-ins & interfaces
- Module frame foundation
- Fabrication requirements

3.2.3 Procurement

This section discusses planning activities involved in procuring modular construction materials and services for the following activities: (1) design and engineering, (2) fabrication, and (3) transportation, handling, and erection.

- **Procurement of Design and Engineering:**

The procurement of design and engineering services includes: (1) identifying the required services, and (2) identifying and selecting qualified engineering firms. These activities occur early in the project. The owner usually procures the design and engineering services. Identifying and selecting engineering firms early in the project is important; it is more difficult than in conventional construction because the firms that provide design and engineering services for modular projects must have different capabilities than firms involved in only conventional construction [Tatum et al, 1987]. The engineering firms involved in modular construction should have a much wider range of capabilities; they should not only have extensive experience in the design and engineering of modular projects, but should also have extensive knowledge of the other modular construction activities and how these activities are interrelated.

- **Procurement of Fabrication:**

The procurement of fabrication services should occur early in the project. This activity includes: (1) pre-qualifying contractors and equipment vendors, (2) establishing the number of fabricators and fabrication shops to use, and (3) selecting the fabricators and fabrication shops.

Pre-qualifying Contractors and Vendors: The pre-qualification of contractors and vendors is an important and complex task in the procurement of fabrication services. Tatum et al [1987] state that in procuring fabrication services, "procurement contracts must incorporate many of the requirements previously limited to the construction phase ... The expertise needed for many of the methods makes pre-qualifications of bidders even more important to assure adequate capabilities." The procuring of the contractors must occur early in the project. However, the early selection of qualified contractors is complicated by uncertainties in the module characteristics and the transportation methods. Thus, a contractor may be selected without knowing whether or not he has adequate equipment to safely fabricate and assemble, and handle the modules. Despite this uncertainty, selecting contractors early in the project is necessary due to the interdependency of activities, and the need to have the contractors participate in the design process. This participation is favorable since the contractors can identify potential problems and/or concerns from a contractor's point of view [Glaser et al, 1979]. Specific factors are considered in pre-qualifying contractors and vendors. For example, to select qualified fabricators, consideration of both the fabricators' capabilities and shop characteristics are essential. The capabilities of fabricators' should include the ability to provide effective material control systems, and the ability and experience to fabricate and assemble the modules. A significant fabrication shop characteristic is the shop location. The locations of the fabrication shops impact both the transportation method and the module dimensions and weight. The locations of the fabrication shops, the transportation method, and the module dimensions and weight, must be planned interdependently to ensure the best module design, with the least expensive transportation method, and the best fabrication shop location [Carreiro, 1968]. Important shop characteristics other than location include proper working conditions, appropriate shop equipment, and an adequate labor force. In addition, large assembly and handling areas should be available for temporary module connections and module accessibility. If the modules are completed before the construction site is prepared for their final placement, storage space may be required to avoid onsite congestion.

Establishing the number of fabricators and fabrication shops: Contracting an adequate number of fabricators and fabrication shops is critical. Since many fabricators can be selected for one project, the required number of fabricators should be determined upfront. For one particular project [Modern Steel Construction, 1991], Thomas C. Esper, general manager of Rack Structures Group, indicated that nine major material suppliers and five fabricators were used. The number of fabrication shops that must be contracted should be determined early in the project. The use of a large number of fabrication shops allows more work to be performed in parallel, but requires a greater effort to manage.

Selecting fabricators and fabrication shops: Tatum et al [1987] state that the selection of fabricators is more difficult than in conventional construction because the fabricators should be experienced in all tasks associated with fabricating and assembling modules. They should also be knowledgeable about other modular construction activities since they can affect the module fabrication and assembly. However, Tatum et al [1987] also state that there can be tradeoffs in the selection of fabricators because of: (1) the need to have one contractor act as a single responsible source for the project, and (2) the need for both experience and knowledge of modular construction technology and methods.

- **Procurement of Transportation, Handling, and Erection:**

The procurement of transportation, handling, and erection services should occur early in the project since it must be performed interdependently with decisions about the dimensions and weight of the modules. Glaser et al [1979] indicate that procurement of the transportation, handling, and erection services is usually performed by either the general contractor or the fabricator. Regardless, the person responsible for procuring these services should be established early in the project. Procuring the transportation, handling (i.e., loading/unloading), and erection equipment requires significant investigation because it must be capable of transporting, handling, and erecting the modules, which may extremely large and difficult to handle. In addition to concerns about equipment capabilities, the availability of this often specialized equipment is also a concern. For example, Mullet [1984a] indicates that certain barges can require at least 24 months of advanced reservation. Thus, it is critical to determined and procure the required transportation equipment early. A thorough study of the equipment is required to ensure that all the equipment and labor necessary for transporting, handling, and erecting the modules is procured [Glaser et al, 1979].

3.2.4 Transportation Studies

Transporting modules can be a difficult task, requiring special methods and equipment. During the planning phase, transportation studies usually include investigations of: (1) transportation routes, (2) transportation methods, and (3) transportation, handling, and erection equipment and methods.

- **Transportation Routes:**

A transportation route investigation usually determines the most effective route to transport the modules from potential fabrication shops to the construction site [Mullet, 1984d]. Thus, a transportation route study should be performed interdependent with the task of pre-qualifying fabrication contractors, since the locations of the fabrication shops are reviewed at that point. The route investigations should identify potential obstacles, such as overhead utilities, trees, and bridges, which may require extra preparation. For example, Hesler [1990] indicates that in one particular project "each (module) was transported from Idaho to rural Wyoming over an interstate highway that had been modified (a multi-million-dollar expenditure) to avoid cloverleaf intersections and relocation of utility lines." He also states that none of the modules suffered major damage because of the "extremely precise" planning and the accurate transportation schedule. Once all the possible routes have been established and studied, the feasible options are reviewed to determine which can provide the most economical transportation.

- **Transportation Methods:**

Possible transportation methods should be investigated early in the project to ensure compatibility with the module design. Three typical methods of transportation include: (1) land, (2) water, and (3) air. Combinations of these methods are also used.

Land: There are several possible methods of land transportation: (1) conventional trucks and tractor-trailer units, (2) air cushions, (3) rail systems, and (4) heavy haul transporters [Mullet, 1984d]. Truck transportation is common and is often economical, but it can impose physical limitations on module dimensions and weight to meet public highway regulations. Air cushions are used to suspend and transport the module loads; they tend to reduce the stress on the road by spreading the load over a wider area. Air cushions are common in England where they have been used repeatedly with success [Armstrong, 1972]. Rail systems are also used, particularly if existing rail access can be used to reduce costs. However, as the size of the module increases, rail transportation can become ineffective due to the loading/unloading expenses associated with it [Reidelbach, 1971]. Heavy haul transporters include two categories of transports: crawler and rubber-tired transporters [Mullet, 1984d]; both can be combined with water transport. Crawler transporters are economical when the site is near to water. However, Bass [1982] states that "as the distance of the site from the navigable waterway increases, crawler transportation of large modules becomes less practical." Although they perform well on unimproved roads, these transporters require a large inventory of spare parts to avoid potential delays [Bass, 1982]. Rubber-tired transporters are capable of leveling their loads, and work well for long hauls on public roads. Both crawler and rubber-tired transporters can move up to 4,000 tons [Shelley, 1990]. Highway regulations often affect the transport of modules by land. Each state in the United States has its own regulations. Height restrictions reflect the potential conflicts with overhead utilities, bridges, and other vertical barriers. These height restrictions affect the modular housing industry by limiting the height of modular homes. As a result, many modular homes have flat roofs; however, these limitations have generated innovation, and industry is currently providing "pop-out" (i.e., hinged) roof systems that allow the delivery of a modular home with a sloped roof by transporting it with a flat roof, and then, upon delivery, unfolding the roof [Reidelbach, 1971; Nanticoke, 1993]. The state of Pennsylvania's limitations on the maximum truck load size are 14.0 feet in width (except as authorized), 80.0 feet in length, and 14.5 feet in height. However, with special permits, larger modules can be transported, but additional constraints, such as the use of public and private escorts, are imposed. In addition to the size restrictions, limitations are placed on the axle weight, the available roads, and the time of day that these roads can be used. Federal safety standards also limit module dimensions, weight, time of transport, and usable routes [Sullivan et al, 1980].

Water: Water transportation can be effective if the location of the construction site and the fabrication shops are adjacent to water, and if the modules cannot be transported by truck or rail because of their size and weight [Mullet, 1984d; Bass, 1982; Prosser, 1993]. There are several methods of water transportation, including barges and special purpose ships and vessels. Barge transportation includes the use of Roll-On/Roll-Off (RO/RO) barges, which have large clear decks areas that can carry large modules. These non-powered barges are towed from one place to another [Mullet, 1984d]. Ships, such as the Roll-On/Roll-Off ships, can travel at a rate of approximately 12 knots/hour compared to RO/RO barges, which travel at approximately 6 knots/hour [Bolt, 1982]. Other vessels, such as Roll-on/Roll-Off vessels, heavy lift vessels, and break bulk cargo vessels, are also options for water transportation. Self-propelled RO/RO vessels, which have flat decks, are capable of transporting heavy components [Mullet, 1984d]. Self-propelled heavy lift vessels are ideal for moving large modules. Break bulk cargo vessels, which do not allow modules to be rolled onto their decks, require additional handling equipment to lift the module on and off the decks [Mullet, 1984d].

Air: Air transportation methods are not as common as land and water transportation because land and water transportation is more economical. However, helicopter air transportation can be used in modular construction. Helicopters are capable of lifting approximately 9 tons with minimal size limitations [Armstrong, 1972]. They can eliminate the concern for highway regulations and other module size limitations. Unfortunately, helicopters tend to be an expensive mode of transportation [Sullivan, 1973]. A comparison of helicopter transportation with other methods should consider all the functions that a helicopter can perform. For example, a helicopter not only delivers the module to the site, but also place it in its final position, which eliminates the need for handling equipment (i.e., cranes) [Carreiro, 1968]. Hence, even though helicopters appear to be more expensive, they may be feasible based on an analysis of the total cost of transportation, handling, and erection. In addition, helicopters can be used in combination with land and water transport.

Summary: The selected transportation method affects all other activities in a modular project. Thus, detailed analyses of potential transportation methods need to be performed to determine the most effective alternative. Many factors influence which alternative will function best for a given project. For example, transportation by water can eliminate or significantly reduce the potential traffic control expenses required for land transportation. The cost of traffic control can be significant for transporting through a congested city such as New York City. In addition, transportation by water can eliminate or reduce significantly the potential socio-economic impacts of closing major highways, intersections, and so on. If the fabrication shops are near water, transportation by water is more economical [Falcon Steel, 1993]. Of the three transportation methods discussed, land transportation is predominantly used by the modular housing industry [Sullivan, 1980; Nanticoke, 1993]; water transportation is predominantly used by the petro-chemical industry [Air Products, 1993; Prosser, 1993]. Combinations of land, water, and air transportation methods are also possible. In fact, there were several example cited in the literature that involved fabrication shops that were at close proximity to water, and a construction site that was inland. Thus, both water and land methods were used.

- **Transportation, Handling and Erection Equipment and Methods:**

This section discusses transportation, handling, and erection equipment, and handling and erection methods. In addition to transportation routes and methods, the transportation, handling, and erection equipment should be identified early in the project, as discussed in Section 2.2.3. An investigation of the handling and erection methods is also necessary. The investigation of the handling methods should address how the modules are to be moved from the fabrication shops to the selected transportation methods, and from the transportation methods onto the construction site. The investigation of erection methods should address how the modules are to be erected into their final positions, including the required onsite equipment, labor, working space, and other resources. Erection methods are often less involved than in conventional construction because many activities that are conducted onsite in conventional construction are performed in fabrication shops.

3.2.5 Site Planning

The site planning activities are concerned with onsite work such as the construction of permanent and/or temporary foundations, access roads, and utilities. The construction of foundations and access roads should be planned early to avoid construction delays. If access roads cross over existing bridges, and other infrastructure, planning is required to ensure that the module loads will not damage the existing infrastructure; shoring or bracing may be required. Onsite utility planning is important since heavy equipment and modules may cross over underground utilities, in which case, safety precautions such as temporarily utility shut down should be implemented. Additional site factors, such as those listed in Table 3.4, should also be addressed in site planning [Mullet, 1984c].

Table 3.4
Onsite Planning Factors
[after Mullet, 1984c]

- Excavation
- Pile cap construction
- Underground piping connections
- Site appearance & accessibility
- Piling requirements
- Construction drainage
- Electrical connections
- Fire protection

3.2.6 Summary

The planning of modular construction projects is of significant importance because the planning activities anticipate, predict, and control the construction methods and activities. Planning a modular project is more complex than a conventional project because it addresses the significant interactions among modular construction activities. This section has discussed the following planning activities: (1) project control, (2) module planning/conceptual design, (3) procurement, (4) transportation studies, and (5) site planning.

Project control enables modular projects to obtain the potential advantages of module construction. Module planning/conceptual design sets the primary design parameters of the modules which impact all the other construction activities. Procurement of the design and engineering involves the identification of the required services as well as the identification and selection of the engineering firms. The procurement of fabrication increases in complexity because of the various fabrication shops involved. Planning of the fabrication activity is considerably different and more complex than for a conventional project. The procurement and planning of transportation, handling, and erection must occur early in the project because of the impact of these activities on the module dimensions and weight and to ensure that adequate equipment is available to transport, handle, and erect the modules. Site planning determines the site work needed to handle and erect the modules in their final positions onsite.

Planning is critical because modular construction methods do not adapt well to changes. Modular construction requires early decisions about the design and construction of the modules, using minimal or potentially inaccurate information. Changes may require modifications to the transportation methods, the fabrication and assembly process, the procurement of materials and services, and the project control. Mullet [1984] indicates that design changes are not only difficult and disruptive, but also costly.

3.3 DESIGN AND ENGINEERING

The design and engineering activities are essential to the success of a project since they must determine characteristics of the module that will both use modular construction methods to best advantage, and enable the modules to perform effectively in service. Clifford A. Hoag, project manager of C.F. Braun & Co. states "a modular project is made or broken in the engineering phase. You have to engineer the job to transfer the largest amount of labor out of the field and into the module fabrication shop" [Parkinson et al 1982]. The design and engineering activities must be focused on the modules. Stubbs et al [1990] state "because each module will be designed, procured, fabricated, shipped, and erected independently, all drawings and documentation must be produced on a module-by-module basis." Mullet [1984c] states that "modularization requires a different approach in engineering; not only in terms of layout and design [production], but also with respect to organization, methods, and control [management]." This section discusses the management and production aspects of the design and engineering activities.

3.3.1 Management

The management aspects of design and engineering activities in a modular construction project is affected by: (1) design sequence, and (2) design process complexity.

- **Design Sequence:**

The design sequence of a modular project differs from that of a conventional construction project because much of the design and engineering effort is performed early in the project, along with the planning of: (1) procurement, (2) fabrication, and (3) transportation, handling, and erection activities. Stubbs et al [1990] state that "while the objectives of modularized and conventional projects are the same, there are major differences in timing, location, and method of completion." For example, in industrial construction, the detailed design work performed by electrical, plumbing, and other trades usually occurs during the construction phase in conventional construction. However, in modular construction, it is performed earlier in the project.

- **Design Process Complexity:**

Tatum et al [1987] state that the complexity of design and engineering activities increases in modular construction due to requirements such as: (1) working in parallel, with less design time, (2) communicating with other participants at various fabrication sites, (3) changing drawing formats to include module breakdown details, and so on.

3.3.2 Production

The production aspects of design and engineering activities are more involved than for a conventional project because of the need for modules to maintain structural integrity during transportation, handling, and erection, and because of the connections needed between modules. The design and engineering production includes additional design effort in: (1) tolerances and connections, (2) stability, (3) structural integrity, and (4) code compliance.

- **Tolerances and Connections:**

Because modules must fit into their final locations within the main structure and between adjacent modules, special attention is placed on tolerances and connections. Inadequate fit is unacceptable and costly to adjust onsite. Connections between modules are different than connections between components in conventional construction. They often carry greater loads and are subject to tighter tolerances.

- **Stability:**

Design and engineering must address the need for module stability in transport and in-situ. Both Bolt et al [1982] and Tatum [1989] state that the center of gravity and height/weight ratio must be properly addressed for modules transported by water.

- **Structural Integrity:**

Design and engineering effort related to structural integrity is increased since the modules are exposed to additional forces during transportation, handling, and erection [Mullet, 1984d; Glaser et al, 1979]. If not designed properly, the modules can suffer minor or even severe structural damage [Carreiro, 1979]. Concern for structural integrity increases the engineering of: (1) lifting points, (2) acceleration forces, and (3) weight and stiffness. The lifting points require additional design attention to ensure that they are strategically located to avoid damage to the module while lifting. The need to tolerate large acceleration forces during transportation, handling, and erection requires additional design and engineering effort. The module's weight and stiffness increases because modules are designed to be stiff and strong to avoid damage in transport, especially if the transport method cannot control the module's horizontal movement [Tatum, 1987].

- **Code Compliance:**

Addressing added code requirements is an issue if the project is constructed in or transported to another jurisdiction (i.e., local, state, nation). For example, Modern Steel Construction [1991] discusses the design of an automated storage warehouse that had to comply with both U.S. and Canadian building codes. To simplify the differences in codes, this project was designed to U.S. standards and then checked against Canadian standards and modifications were made, where needed. In addition, the project used a Canadian engineer to certify the design.

3.4 FABRICATION

Fabrication activities for modular construction are more complex than the shop fabrication activities of conventional construction because the majority of onsite work is transferred into fabrication shops. Stubbs et al [1990] and Tatum et al [1987] state that fabrication encompasses a large degree of both the shop fabrication and field assembly/erection activities of conventional construction. Mullet [1984d] states "the operation required to produce process plant modules is a hybrid of the two operations normally encountered as distinct phases in the EPC (engineering, procurement, and construction) cycle of conventional projects: (1) shop fabrication, and (2) field erection." Two aspects of fabrication are discussed below: (1) fabrication and assembly, and (2) quality control and testing.

3.4.1 Fabrication and Assembly

Fabrication and assembly can be categorized into management and production. The management of the fabrication and assembly differs from that in conventional construction because modular projects perform typical onsite work offsite in fabrication shops. Management of fabrication and assembly includes arrangement of: (1) the fabrication and assembly sequence, (2) the material and equipment, and (3) the labor force.

- **Fabrication and Assembly Sequence:**

The sequence of activities in module fabrication is significantly different than conventional fabrication and erection. Because two conventional construction activities (fabrication and onsite assembly) are combined into one (module fabrication in the shop), many activities that normally occur in series are now performed in parallel. With such changes in the activity sequences, it is critical to manage the fabrication of modules so that the activities can occur in parallel.

- **Material and Equipment:**

The management of material and equipment in module fabrication is different than in conventional fabrication. The material used for components in the module assembly must be tracked throughout the fabrication and assembly process. Once assembled, modules should go through an identification or marking process to ensure efficient onsite module-to-module connections. Successful module fabrication relies heavily on proper material management and scheduling [Bass, 1982].

- **Labor Force:**

The management of labor in module fabrication is different than in conventional construction because most of the work is conducted in fabrication shops. The labor force in a fabrication shop can be trained and controlled more efficiently and effectively than in the field. The labor force in a shop environment tends to be permanent, and can be more skillful and stable than the labor force hired onsite [Halla Engineering, 1993].

The fabrication and assembly production activities range from fabricating and assembling structural components to testing and commissioning the installed equipment in a completed module. Bass [1982] identifies several specific steps in fabricating an industrial module (i.e., modules for a chemical/process plant) offsite: (1) installing major equipment on the base of the module, (2) fabricating the module superstructure, (3) installing remaining equipment, (4) installing the module enclosure, (5) installing the module instrumentation, and (6) testing and commissioning the module. Important aspects of fabrication and assembly production activities that have not yet been covered are discussed below.

- **Maintaining Accessibility:**

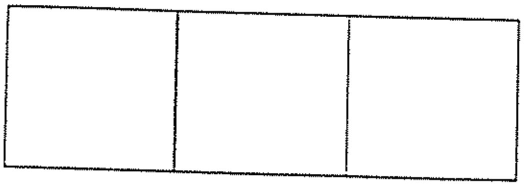
Maintaining accessibility is a concern in both the module and the fabrication shop. A lack of accessibility within the module can cause inefficient module production, which may prevent efficient use of labor. Thus, the modules should be large enough to provide adequate working space, but small enough to avoid high costs in transportation, handling, and erection. Fabrication shop accessibility is necessary to provide a safe construction environment; there should be an adequate number of assembly areas in a fabrication shop to avoid congestion during production.

- **Working at Ground Level:**

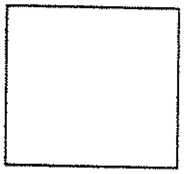
Fabrication and assembly can benefit from performing the work at ground level. For example, assembling a vertical module on its side in a horizontal position can reduce the required work above ground and the need for scaffolding and other height-related equipment [Shelley, 1990]. Figure 3.2 shows this reduction in work above ground. In addition to increasing the work at ground level, vertical modules that are fabricated and assembled on their sides at ground level can increase the possible working space if they are broken down to specific independent modules as shown in Figure 3.3. In this figure, it is shown that the possible working area can increase to 150% of the original area. In a particular automated storage warehouse project, sections of a rack building were assembled in large 28-ton modules at ground level, then erected into position [Modern Steel Construction, 1991]; Thomas C. Esper, P.E., general manager of the Rack Structures Group, stated "the construction process used by Broad, Vogt, & Connant is unique in that we assembled the rack building in large modules on the ground. We tried to reduce the number of man-hours of people working high in the air."

- **Working in Parallel:**

Fabrication and assembly can benefit from performing work in parallel rather than in series as in conventional construction. Working in parallel provides the opportunity for fabrication and assembly to occur at various fabrication shops for the same project. In addition, various modules within one shop can be worked on simultaneously.

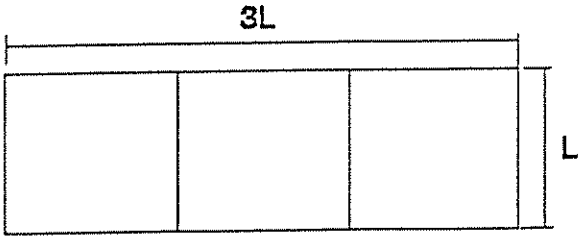


PLAN VIEW
(module on its side)
* All work is performed at ground level

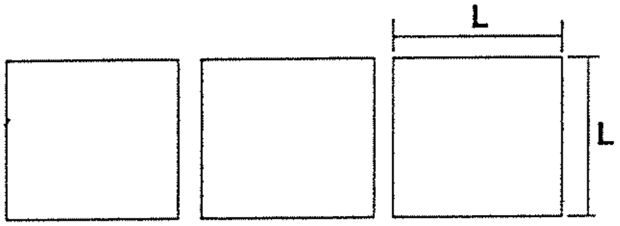


PLAN VIEW
(module in an upright position)
* 1/3 of the work is performed at ground level

Figure 3.2 Reduced Work above Ground (after Tatum et al, 1987)



PLAN VIEW
(a three level structure on its side)
* Working space perimeter = 8L



PLAN VIEW
(a three level structure broken into 3 modules)
* Working space perimeter = 12L

Figure 3.3 Increased Working Space by Working at Ground Level (after Tatum et al, 1987)

3.4.2 Quality Control and Module Testing

Quality control and module testing is discussed in this section. When module assembly occurs in a fabrication shop, quality control can be provided as the modules advance through the assembly phases. Shop fabrication and assembly can enhance the quality of a project by: (1) using module inspectors continuously in the fabrication shops, (2) taking advantage of the more controlled environment in fabrication shops, (3) using more efficient and precise shop equipment, (4) providing adequate training for a more permanent work force, and (5) using standardization and repetition. Fabrication and assembly activities can provide modules that meet high quality standards because of the controlled environment available in a fabrication shop.

The fabrication and assembly activity also includes module testing. Shop testing is advantageous because fabrication and assembly errors can be identified, and adjusted before the modules leave the fabrication shop. If a faulty module leaves the shop, correcting it onsite can severely impact the schedule and cost of the project, especially if the construction site is in a remote location [Stubbs et al, 1990]. The connections of multi-module structures as well as the connections for piping, equipment, and structural members are also tested in the fabrication shop to ensure proper alignment onsite.

3.5 TRANSPORTATION, HANDLING, AND ERECTION

This section discusses transportation, handling, and erection of the modules from the fabrication shops to the construction site. Transportation, handling, and erection activities play a significant role in a modular project, however, most of the transportation, handling, and erection work is performed in the planning stage of the project, as discussed in section 3.2.4.

If the module concept takes the selected transportation methods and routes into account, the activities of transportation, handling, and erection can be performed successfully. The site should be ready to accept the module upon delivery; and the handling equipment should be prepared to unload the modules and place them into their final positions. Hoag [1983] states that "the vendor preassemblies arrive at the jobsite ready for installation, final testing, and operation." Other onsite erection activities are typically minimal, compared to conventional construction.

In addition to the actual movement of modules, the activities in transportation, handling, and erection usually include: (1) onsite module testing, if necessary, (2) module connections, and (3) equipment connections (i.e., for industrial facilities). Additional testing is required if the modules experience large accelerations during transportation; large accelerations can result from: (1) wave loading of barges, ships, or vessels, if transporting by water; (2) rough terrain, if transporting by land; and (3) the use of improper transportation and handling equipment. Once erected to their final position, the modules are permanently connected. Connection of the modules and equipment is typically an efficient process, because the modules and equipment are usually test-connected offsite in the fabrication shops to ensure proper connection onsite.

3.6 SUMMARY

In summary, this chapter has covered the following modular construction activities: (1) planning, (2) design and engineering, (3) procurement, (4) fabrication, and (5) transportation, handling, and erection. The discussion has indicated that modular construction activities are more complex than those of conventional construction because modular construction requires many activities: (1) to be conducted earlier in the project,

(2) to be more interdependent in nature, (3) to be increased in scope, and (4) to be in need of extensive coordination with other activities.

This chapter includes specific discussions of activities of modular construction. Planning is critical because modular construction methods do not adapt well to changes, and changes in design and execution can create major disruptions to the project. Interdependence among construction activities plays an important role in the planning of modular projects.

The design and engineering is more involved than in conventional construction because of the need to avoid later design changes, the need to provide the modules with sufficient structural integrity during transportation, handling, and erection, and the need to design the connections between modules. Fabrication is an activity that includes fabricating and assembling modules offsite in fabrication shops. This activity increases in scope because it combines two conventional construction phases (i.e., shop fabrication and assembly/erection) into one.

Transportation, handling, and erection is, of course, an important aspect of modular construction. Most of the logistics of transportation, handling, and erection are covered upfront in the project planning due to the dependence of the module conceptual design on transportation, handling, and erection methods. The actual transportation, handling, and erection of the completed modules is more complex than in conventional construction because of the size of the modules and the specialized transportation, handling, and erection equipment and methods needed.

Chapter 4

Industry Survey of Modular Construction Projects & Practices

4.1 INTRODUCTION

Individuals from 31 companies were interviewed to identify examples of current modular construction methods. Two types of information were gathered from the interviews: (1) examples of specific projects that took advantage of modular construction methods, and (2) information on general modular construction practices. This chapter discusses both types of information as well as the findings that have been derived from this information.

Of the 31 companies that participated in the interviews, thirteen companies provided information on specific modular construction projects and eighteen companies provided information on general modular construction practices. Information on only nine specific projects was gathered from the thirteen companies because, in some cases, more than one company was involved in the same project. The projects include four types of construction: (1) bridge, (2) industrial, (3) light industrial/commercial, and (4) prison. Table 4.1 lists the names of the companies that provided information on these projects, the names of the projects they discussed, and the roles of the company in the project. Table 4.2 shows the type of construction involved in the projects, the number of projects, and the company names. De La Torre and Sause [1994a] provide a detailed presentation of the information gathered from these thirteen companies.

Information on general modular construction practices was obtained from interviews with eighteen companies. These companies use various levels of modular construction methods, from prefabricated 2-dimensional components, such as those used for pre-engineered metal buildings, to complete 3-dimensional modules, such as those used for industrial and chemical process plants. Table 4.3 lists the companies that provided the information on general modular construction practices, and the role of the company in typical projects. Table 4.4 shows the type of construction each company is involved in. The five general types of construction include: (1) industrial, (2) light industrial/commercial, (3) prison, (4) residential, and (5) ship. De La Torre and Sause [1994b] provide a detailed presentation of the information gathered from these eighteen companies.

Table 4.1
Companies that Provided Information on Specific Projects

COMPANY (PROJECT NAME)	ROLE
(1) Falcon Steel Company, Inc. ("Tribeca" Bridge)	Fabricators
(2) Allied Steel Products Corporation (Steam Stripper)	
(3) Eastern Exterior Wall Systems, Inc. (Comfort Suite Hotel)	
(4) Quickway Metal Fabricators, Inc. (IBM Building)	
(5) Gate Concrete Products (Pre-Trial Detention Facility)	
(6) Tindall Concrete Virginia, Inc. (Greensville Correctional Facility)	
(1) Air Products and Chemicals, Inc. (Helium Purification/Liquefaction Production Facility	Project Managers
(2a) Foster Wheeler Constructors, Inc. * (Maraven Refinery Expansion Project)	
(2b) Foster Wheeler Energy, Ltd.* (Light Diesel Hydrotreater)	
(3) Texaco, Ltd. (Light Diesel Hydrotreater Project)	
(4) Environmental Resources Management, Inc. (Steam Stripper)	
(1) Pierce-Goodwin-Alexander-Linville, Architects (Pre-Trial Detention Facility)	Architects
(1) Sverdrup Civil, Inc. (Pre-Trial Detention Facility)	Structural Engineers
(1) The Consulting Engineers Group, Inc. (Pre-Trial Detention Facility)	Engineers

* In counting the total number of participating companies, Foster Wheeler Constructors, Inc. and Foster Wheeler Energy, Ltd. are treated as one company since both are part of Foster Wheeler, USA.

The chapter is organized as follows. First, the methodology for selecting the interviews is discussed. Then findings derived from the interviews are discussed in the following specific areas: (1) the driving forces of modular construction, (2) specific benefits and broad advantages of modular construction, (3) the relationships between the driving forces and the broad advantages, (4) disadvantages of modular construction, and (5) the relationships between module characteristics and transportation methods.

Table 4.2
Companies that Provided Information on Specific Projects and the Type of Construction Involved

TYPE OF CONSTRUCTION	NO. OF PROJECTS	COMPANY
Bridge	1	Falcon Steel Company, Inc.
Industrial	1	Air Products and Chemicals, Inc.
	1	Foster Wheeler Constructors, Inc.
	1	Foster Wheeler Energy, Ltd.
		Texaco, Ltd.
Light Industrial/ Commercial	1	Allied Steel Products Corp.
		Environmental Resources Management, Inc.
	1	Eastern Exterior Wall Systems, Inc.
	1	Quickway Metal Fabricators, Inc.
Prison	1	Gate Concrete Products
		Pierce-Goodwin-Alexander-Linville
		Sverdrup Civil, Inc.
		The Consulting Engineers Group, Inc.
	1	Tindall Concrete Virginia, Inc.
TOTAL	9	

Table 4.3
Companies that Provided General Information on Modular Construction

COMPANY (SPECIFIC TYPE OF CONSTRUCTION)	ROLE
(1) Halla Engineering & Heavy Industries, Ltd. (Large Storage Tank Construction)	Fabricators
(2) IHI, Inc. (Heavy Vessel Construction)	
(3) The Prosser Company, Inc. (MCPC)	
(4) Keystone Structures, Inc. (PEMB)	
(5) Lehigh Valley Building Systems, Inc. (PEMB)	
(6) Porta-King Building Systems (PEMB)	
(7) Quickway Metal Fabricators, Inc. (Detention Facility)	
(8) Love Homes (Modular Housing)	
(9) Nanticoke Homes, Inc. (Modular Housing)	
(10) Bath Iron Works Corporation (Shipbuilding)	
(11) Ingalls Shipbuilding (Shipbuilding)	
(1) Jacobs Applied Technology, Inc. (MCPC)	Project Managers
(2) R.M. Parsons Company (MCPC)	
(1) Berkus Group, Architects (Modular Housing)	Architects
(1) BE & K-Delaware (Industrial Construction)	Structural Engineers
(1) Allentown Applicators & Erectors (PEMB)	Erectors
(1) Butler Manufacturing Company, Inc. (PEMB)	Manufacturers
(2) Rotondo/Penn-Cast (Pre-Cast Concrete Modular Prison Cell Construction)	

<u>LEGEND</u>

MCPC	Modular Chemical Plant Construction
PEMB	Pre-Engineered Metal Building

Table 4.4
Companies that Provided General Information on Modular Construction and the Type of Construction Involved

TYPE OF CONSTRUCTION	COMPANY
Industrial	BE & K-Delaware
	Halla Engineering & Heavy Industries, Ltd.
	IHI, Inc.
	Jacobs Applied Technology, Inc.
	R.M. Parsons Company
	The Prosser Company, Inc.
Light Industrial/ Commercial	Allentown Applicators & Erectors
	Butler Manufacturing Company, Inc.
	Keystone Structures, Inc.
	Lehigh Valley Building Systems, Inc.
	Porta-King Building Systems
Prison	Quickway Metal Fabricators, Inc.
	Rotondo/Penn-Cast
Residential	Berkus Group, Architects
	Love Homes
	Nanticoke Homes, Inc.
Ship	Bath Iron Works Corporation
	Ingalls Shipbuilding

4.2 METHODOLOGY

The 31 companies that were interviewed were selected based on three considerations. The first consideration was their availability and willingness to participate. The companies that were located within adequate driving distance were asked for a site interview. The companies that were not located within driving distance were interviewed by telephone.

The second consideration was to select companies that use various levels of modular construction within various types of construction. The intent was to obtain information on various types of modular construction so that broad knowledge of modular construction technology and methodology could be developed for potential application to building frame systems. The survey covered six different types of construction: (1) bridge, (2) industrial, (3) light industrial/commercial, (4) prison, (5) residential, and (6) ship. Table 4.5 shows the total number of companies involved in each type of construction.

The third consideration for selecting companies was to interview individuals with different roles within the construction process. The interviews of the individuals with different roles provided information from different points of view. The roles of the individuals that were interviewed include: (1) fabricator, (2) project manager, (3) architect, (4) structural engineer, (5) engineer, (6) erector, and (7) manufacturer. Table 4.6 shows the roles of the individuals that were interviewed. The individuals who provided information on specific projects are distinguished from those that provided general information on modular construction practices.

Table 4.5
Types of Construction of the Companies Interviewed

TYPE OF CONSTRUCTION	PROJECT SPECIFIC	GENERAL	TOTAL
Bridge	1	0	1
Industrial	3	6	9
Light Industrial/ Commercial	4	5	9
Prison	5	2	7
Residential	0	3	3
Shipbuilding	0	2	2
TOTAL	13	18	31

Table 4.6
Roles of the Companies/Individuals Interviewed

ROLE	PROJECT SPECIFIC	GENERAL	TOTAL
Fabricator	6	11	17
Project Manager	4	2	6
Architect	1	1	2
Structural Engineer	1	1	2
Engineer	1	0	1
Erector	0	1	1
Manufacturer	0	2	2
TOTAL	13	18	31

4.3 DRIVING FORCES OF MODULAR CONSTRUCTION

A driving force is a primary factor influencing the use of modular construction methods. Thus, a driving force is a critical factor that forces a project to use modular construction; the use of conventional construction methods may not necessarily produce a successful project. The driving forces of modular construction were identified by analyzing the information obtained from the companies listed in Tables 4.1 and 4.3. The driving forces that led the companies to use modular construction (as indicated by the individuals that were interviewed) include: (1) site resource constraints, (2) reduced cost, (3) reduced schedule, and (4) improved safety; as well as combinations of: (5) reduced cost and schedule, and (6) site resource constraints and reduced schedule. These are discussed in Section 4.3.1. The relationships between the driving forces and the types of construction are discussed in Section 4.3.2.

4.3.1 Driving Forces

4.3.1.1 Site Resource Constraints

Site resource constraints are driving forces identified by some of the individuals interviewed. "Site resource constraints" is the term used to indicate the lack of site resources such as space, labor, and an appropriate construction environment. When an individual indicated that site resource constraints were driving forces, the implication was that the company was forced to use modular construction methods if they wanted to proceed with the project.

Of the thirteen individuals that discussed nine specific projects during the interviews, two stated that their projects were driven to use modular construction methods because of site resource constraints (Figure 4.1).

For example, the Maraven Refinery Expansion project in Venezuela used modular construction methods because of the site's remoteness, its access by water, and its lack of skilled labor. The Light Diesel Hydrotreater project in Wales, UK was also driven by site resource constraints because the site conditions made construction difficult because of rough terrain and severe weather, and there was a lack of skilled labor.

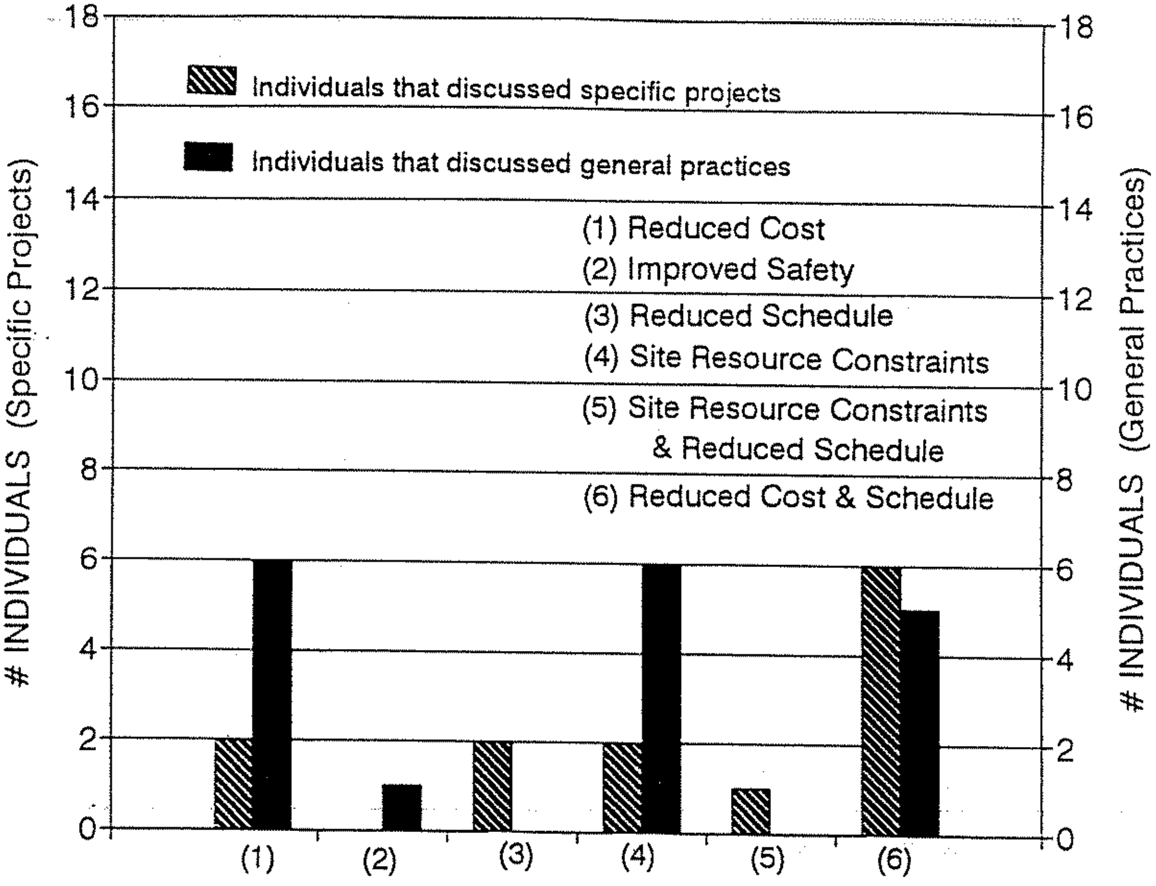


Figure 4.1 Individuals that Identified Driving Forces

Six of the individuals that provided information on general modular construction practices mentioned site resource constraints as driving forces of modular construction (Figure 4.1). One individual involved in residential construction indicated that driving forces are often a lack of material (i.e., wood) and labor unavailability. The remaining five individuals concerned with site resource constraints are involved with industrial construction. One individual indicated that site resource constraints such as severe weather and a lack of labor at the construction site are the driving forces of modular construction for their projects.

4.3.1.2 Reduced Cost

Reduced cost was also identified as a driving force. "Reduced cost" is the term used to indicate that reducing total project costs was the concern that motivated the use of modular construction methods. Two individuals that discussed specific projects indicated that reduced cost was a driving force because modular construction was perceived to be cost effective. These two individuals discussed projects in the bridge and light industrial/commercial categories.

For the "Tribeca" bridge project, the fabrication shop was near water, thus, a barge was the selected transportation method. Although transportation by barge is usually more costly than transportation by truck, transportation by barge proved cost effective in this project because of the fabrication shop's proximity to water, and the traffic control expenses that would have been required to truck the module through downtown New York. For the light industrial/commercial project, four large pipe trusses were welded off-site and shipped to the site. Fabricating the trusses in a fabrication shop was more cost effective than welding the individual truss components onsite because the welding was performed in a more controlled (indoor) environment.

Six individuals that provided information on general modular construction practices also identified reduced cost as a driving force. Three individuals involved in light industrial/commercial construction (pre-engineered metal buildings) indicated that considerable cost savings are possible because most of the material preparation is transferred to a fabrication shop, which is a more controlled environment than the construction site.

4.3.1.3 Reduced Schedule

Reduced schedule is a driving force identified by two individuals that discussed specific projects. "Reduced schedule" is the term used to indicate that a demanding schedule (i.e., the project must be completed within a specified, limited period of time) was the concern that motivated the use of modular construction methods.

For the Greensville County Correctional Facility project, meeting the designated schedule was essential [PCI Journal, 1991]. By reducing the overall project schedule, the project was able to acquire associated cost savings such as reduced financing costs, reduced labor expenses, and reduced equipment expenses. The fabricator of the prefabricated exterior wall system of the Comfort Suites Hotel project indicated that prefabrication of sections of buildings is an alternative construction method for projects that have fast-track schedules. None of the individuals discussing general modular construction practices mentioned schedule alone as a driving force.

4.3.1.4 Improved Safety

"Improved safety" is a term used to indicate the need to improve safety onsite. None of the individuals discussing specific modular construction projects mentioned improved safety. However, improved safety is a driving force identified by one individual discussing modular construction practices for industrial plants. The modular construction practice identified by the individual considerably reduces the amount of work that is performed at a significant height above the ground. Pre-assembled units, which consist of a complete story of beams, columns, bracing, equipment, platforms, stairs, handrails, and so on are assembled at ground level. Upon completion, each story is erected onto the lower one and placed into its final position with the use of a patented safety pinhole connection.

4.3.1.5 Reduced Cost and Schedule

The combination of both reduced cost and schedule was identified to be a driving force by six individuals discussing specific projects. In the construction of the Steam Stripper in West Chester, Pennsylvania, the module was one hundred percent complete when it was delivered to the site. The module was fabricated in a shop environment to expedite the schedule and reduce the cost. Other concerns in this project included the limited space available onsite and the handling of the module onsite, which was a challenge, because the module had to be lifted over several existing structures (approximately 90 feet into the air) in order to place it on its foundation. Another project driven by both reduced cost and schedule was the construction of the Pre-Trial Detention Facility at Jacksonville, Florida. This fifteen story pre-cast concrete facility was constructed under a very tight schedule and budget. In order to expedite the schedule, three types of modules were incorporated into the facility. The modules included: (1) rooms for cells, (2) mechanical chase units, and (3) showers, quiet rooms, and library rooms. The facility was required to be in operation on a specific date; thus, construction was required to stay on a tight schedule.

Five individuals that provided information on general modular construction practices mentioned the combination of reduced cost and schedule as a driving force of modular construction. One individual is involved in residential construction; two are involved in light industrial and commercial construction (pre-engineered metal buildings) and another two of these individuals are involved in prison construction. They stated that costs are reduced and that working in a fabrication shop environment allows them to complete the modules early and reduce the overall schedule.

4.3.1.6 Site Resource Constraints and Reduced Schedule

The combination of site resource constraints and reduced schedule was identified as a driving force for modular construction projects by one individual interviewed. The driving forces of modular construction in the Helium Purification and Liquefaction Production Facility project in Algeria were a substantial lack of space, labor force, an appropriate construction environment onsite, and a demanding schedule. None of the individuals that discussed general modular construction practices mentioned the combination of site resource constraints and reduced schedule as a driving force for modular construction.

4.3.2 Relationship Between Driving Forces and Types of Construction

Specific patterns between the driving forces and the types of construction surfaced from the information obtained from the interviews. There were six construction types: (1) bridge, (2) industrial, (3) light industrial/commercial, (4) prison, (5) residential and (6) ship. There were six driving forces: (1) site resource constraints, (2) reduced cost, (3) reduced schedule, (4) reduced cost and reduced schedule, (5) site resource constraints and reduced schedule, and (6) improved safety. Table 4.7 shows the relationships that were observed from comparing driving forces with the type of construction.

One of the relationships that was seen consistently is between site resource constraints and industrial construction. The individuals that discussed the industrial projects all mentioned that site resource constraints were driving forces of modular construction for their projects, with the exception of one individual who identified improved safety as the driving force. Site resource constraints were also identified as driving forces for modular residential construction. Another pattern that surfaced is that reduced cost is the driving force for modular bridge and ship construction. All of the individuals that were involved in prison construction, with the exception of one, identified reduced cost and schedule as the driving forces for the modular construction of prisons. The one exception identified reduced cost as the only driving force. Other patterns were observed, but they were not as consistent as the ones mentioned above.

Table 4.7
Relationships Between Driving Forces and Construction Types

	DRIVING FORCES					
Type of Construction	**Rdd Cost**	**Rdd Sch**	**Imp Sfty**	**SRC**	**SRC & Rdd Sch**	**Rdd Cost & Sch**
Bridge	1S					
Industrial			1G	2S 5G	1S	
Light Industrial/ Commercial	1S 3G	1S				2S 2G
Prison		1S				4S 2G
Residential	1G			1G		1G
Ship	2G					
Sub-total	8	2	1	8	1	11
TOTAL	31					

LEGEND

Rdd Reduced Sfty Safety Imp Improved
SRC Site Resource Constraints Sch Schedule
S Individuals that provided information on specific projects
G Individuals that provided information on general practices

4.4 SPECIFIC BENEFITS & BROAD ADVANTAGES OF MODULAR CONSTRUCTION

A "broad advantage" is the term used to indicate one of the general benefits derived from the use of modular construction. Broad advantages are derived from taking advantage of specific benefits of modular construction. The individuals interviewed mentioned specific benefits that they achieved using modular construction. To effectively discuss the broad advantages, it is first necessary to outline the specific benefits that are possible using modular construction. De La Torre and Sause [1994a, 1994b] include a more detailed discussion of these specific benefits.

Several specific benefits that are possible through the use of modular construction were identified by the individuals that were interviewed. These benefits include: (1) working in a more controlled environment, (2) reducing the fabrication and assembly schedule, (3) providing for increased quality, (4) reducing the cost of fabrication and assembly, (5) using "single source responsibility" in contracting, (6) reducing the required traffic control, and (7) early project completion.

Some of these benefits are self-explanatory, but others require further explanation, as follows:

"Working in a more controlled environment": working in a fabrication shop environment rather than onsite, which provides benefits by: (1) working with certainty (e.g., knowing the weather conditions), (2) working indoors, (3) working at ground level, and (4) working with available shop equipment.

"Reducing the fabrication and assembly schedule": a reduction in the project schedule that can be achieved by increasing the amount of assembly work in fabrication shops and decreasing the amount of assembly work onsite. This provides benefits by: (1) performing assembly work in parallel in one or more fabrication shops rather than in sequence onsite, (2) performing repetitive work, (3) completing the module almost 100% in the fabrication shop, (4) starting and completing the fabrication and assembly work early and in parallel with other activities, such as permit acquisition and site construction work, and (5) reducing delays due to language barriers (for projects located overseas).

"Providing for increased quality": an increase in quality that can be achieved in a fabrication shop by: (1) providing for inspection in the fabrication shop, (2) providing for module testing in the fabrication shop, and (3) providing a permanent labor force and permanent equipment in the fabrication shop rather than a temporary labor force and temporary equipment onsite.

"Reducing the cost of fabrication and assembly": a reduction in cost that can be achieved in the fabrication shop by: (1) paying lower labor rates in a fabrication shop compared with field labor rates, (2) not involving unions in the fabrication shop, and (3) fabricating and assembling large components or modules in the fabrication shop to avoid the handling of many small components onsite.

"Reducing the required traffic control": a reduction in the cost and effort involved in traffic control that can be achieved by using a barge (or other water transportation) to transport the modules rather than using a truck. In conventional construction methods, the cost for transportation, which is typically performed by truck, can be high because of difficult traffic control requirements in busy cities and tight clearances near existing structures. In modular construction, the required traffic control can be decreased by using a barge, when appropriate. But otherwise, transportation and handling costs can be substantially higher than for conventional construction. Since transport by barge is

usually more expensive than by truck, transport by barge is justified by fabricating and assembling larger components to exploit its capacity for transporting large modules.

There are many potential broad advantages that can be achieved using modular construction methods. The four broad advantages that were identified from the interviews are: (1) reduced cost, (2) increased quality, (3) improved safety, and (4) reduced schedule.

4.4.1 Reduced Cost

Reduced cost was considered a broad advantage by 25 of the 31 individuals interviewed. Reduced cost was considered a broad advantage by ten of the thirteen individuals that discussed specific modular construction projects (Figure 4.2), and by fifteen of the eighteen individuals that discussed general modular construction practices (Figure 4.2). One individual mentioned reduced cost as an advantage of constructing building additions using modular construction methods. All individuals that did not categorize reduced cost as a "broad advantage" said that, in their experience, cost varied from project to project. That is, the cost of modular construction may not always be an advantage, because cost was usually increased by the additional transportation, engineering, and material requirements of modular construction, and cost was usually decreased by lower labor rates, early completion of the project, the benefits associated with early completion, and so on. In order to estimate the cost impact of modular construction methods, these individuals felt it was necessary to compare the costs of both the modular and conventional methods for a specific project.

Several specific benefits that are possible using modular construction may be categorized as cost-effective advantages. These specific benefits include: (1) working in a more controlled environment, (2) reducing the fabrication and assembly scheduling, (3) reducing the cost of fabrication and assembly, and (4) reducing the required traffic control.

4.4.2 Increased Quality

Increased quality was considered a broad advantage by 28 of the 31 individuals interviewed. Increased quality was considered a broad advantage by eleven of the thirteen individuals that discussed specific modular construction projects, and by seventeen of the eighteen individuals that discussed general modular construction practices. Several individuals mentioned that modular construction practices enable better quality construction because most of the material preparation is performed in a fabrication shop. Another individual mentioned that the quality of their project was improved by working with non-traditional construction materials (e.g., titanium, teflon-lined steel, etc.) in a fabrication shop as opposed to onsite, which was not conducive to working with these materials.

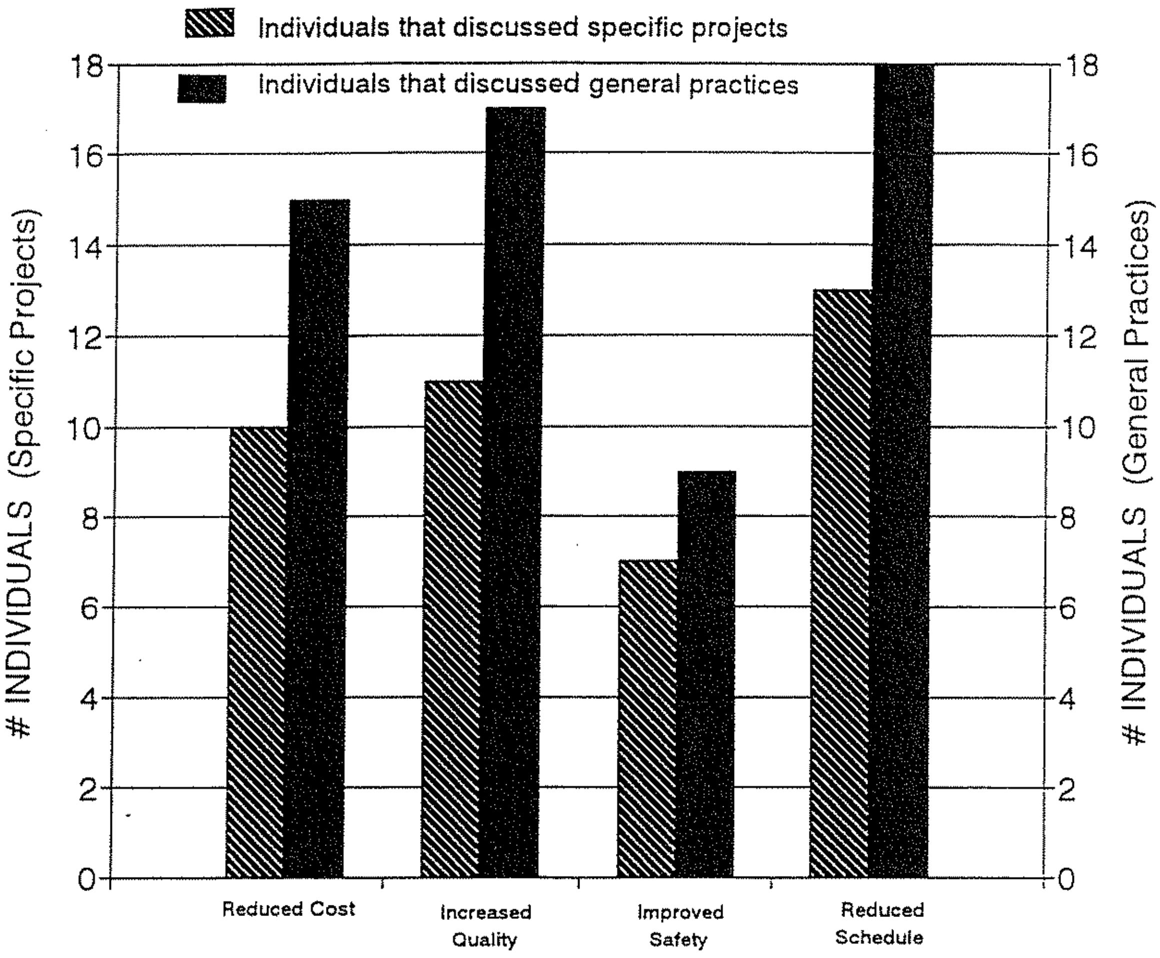


Figure 4.2 Individuals that Identified Broad Advantages

Several specific benefits that are possible using modular construction may be categorized as quality-effective advantages. These specific benefits include: (1) providing for increased quality, and (2) working in a more controlled environment.

4.4.3 Reduced Schedule

Reduced schedule was identified as a broad advantage by all of the 31 individuals interviewed. One individual stated that, through the use of modular construction methods, his project team managed to reduced the overall schedule of the project by approximately three months. Another individual mentioned that the construction of modular homes is fast; a modular home can be built and occupied within two months after the beginning of construction. Several individuals mentioned that having a single source responsible for the entire module fabrication and assembly process is a time-saving advantage because the individuals do not have to deal with several different subcontractors.

Several specific benefits that are possible in using modular construction may be categorized as schedule-effective advantages. These specific benefits may include: (1) reducing the fabrication and assembly schedule, (2) working in a more controlled environment, and (3) using "single source responsibility" in contracting.

4.4.4 Improved Safety

Improved safety was considered a broad advantage by 16 of the 31 individuals interviewed. Improved safety was considered a broad advantage by seven of the thirteen individuals that discussed specific modular construction projects, and by nine of the eighteen individuals that discussed general modular construction practices. One individual mentioned that their modular construction practices improve safety by reducing the amount of work that is performed at a significant height above the ground in the field, and allowing the majority of the work to be performed at ground level. Another individual mentioned that improved safety is an advantage that is obtained by building some modules upside-down, which also improves accessibility. The upside-down modules allow workers to take advantage of gravity and reduce the required welding and placement of large components in an inverted position. Another individual mentioned that improved safety is a broad advantage because it increases productivity in the shop environment. This individual's company uses a loose material (i.e., dirt and sawdust) on the floor to act as a padding and to prevent glue remnants from sticking to the floor and creating a situation prone to accidental falls. One specific benefit that is possible using modular construction may be categorized as a safety-effective advantage: working in a more controlled environment.

4.5 RELATIONSHIPS BETWEEN DRIVING FORCES & BROAD ADVANTAGES

Some of the driving forces identified from the interviews coincide with the broad advantages they mentioned. Three driving forces (reduced cost, reduced schedule, and improved safety) were identified as broad advantages. When an individual indicated that these were driving forces, the implication was that there was a need to obtain them as broad advantages. That is, these advantages were perceived as essential to the project. Thus, reduced cost, reduced schedule, and improved safety play dual roles; they are driving forces that influence the use of modular construction as well as advantages that are derived from modular construction.

Site resource constraints were identified as driving forces but not as broad advantages. When an individual indicated that site resource constraints were driving forces, the implication was that the company was forced to use modular construction methods if they wanted to proceed with the project. Thus, modular construction methods allowed the companies to use fabrication and assembly in a fabrication shop to overcome the site, labor, and environmental constraints imposed by the location of the construction site. Increased quality was identified as a broad advantage, but not as a driving force because, even though it is an advantage that could be exploited, it is not driving the use of modular construction.

4.6 BROAD DISADVANTAGES OF MODULAR CONSTRUCTION

In addition to the potential advantages of modular construction, several disadvantages of modular construction were identified. A "broad disadvantage" is the term used to indicate one of the unfavorable conditions that develops from the use of modular construction. This section discusses three broad disadvantages that were identified from the interviews: (1) the need for additional material, (2) the need for additional effort, and (3) the need for additional coordination of construction activities. These broad disadvantages are discussed below.

4.6.1 Need for Additional Material

Modular construction methods generally require additional material because of the need to maintain the structural integrity of the modules during transportation, handling, and erection. The need for additional material when using modular construction methods (as compared to conventional construction methods) was considered a broad disadvantage by fourteen of the thirty-one individuals interviewed, including four of the thirteen individuals that discussed specific modular construction projects (Figure 4.3), and ten of the eighteen individuals that discussed general modular construction practices (Figure 4.3).

One individual provided an example of problems in the structural design of modules. The module design was originally based on dynamic loads acting on the structure during transport by ship. Ultimately, the modules were transported by barge. However, the dynamic loads for transport by barge were higher than those for transport by ship. Hence, extra steel members, larger steel members, and additional bracing were required to compensate for the higher loads.

4.6.2 Need for Additional Effort

The need for additional effort was considered to be a broad disadvantage of modular construction methods by all of the 31 individuals interviewed. The specific activities that require increased effort include: (1) planning, (2) material management, (3) transportation studies, (4) design and engineering, (5) fabrication, (6) procurement, and (7) site work. Many individuals stated that the amount of planning effort increased in several areas: (1) transportation planning, (2) scheduling and permitting, (3) identifying the handling equipment, and (4) dealing with existing structures. Other individuals mentioned that increased material management was needed.

Most of the individuals mentioned that transportation studies increase in scope, and that it is important to perform these studies along with the module conceptual design. Individuals also stated that more design effort is involved in modular construction because the modules require additional connections for onsite placement and permanent attachments, and the modules are also quite complex (especially the 3-dimensional modules). Conceptual design of the modules and studies of transportation methods are interdependent (refer to Section 4.7).

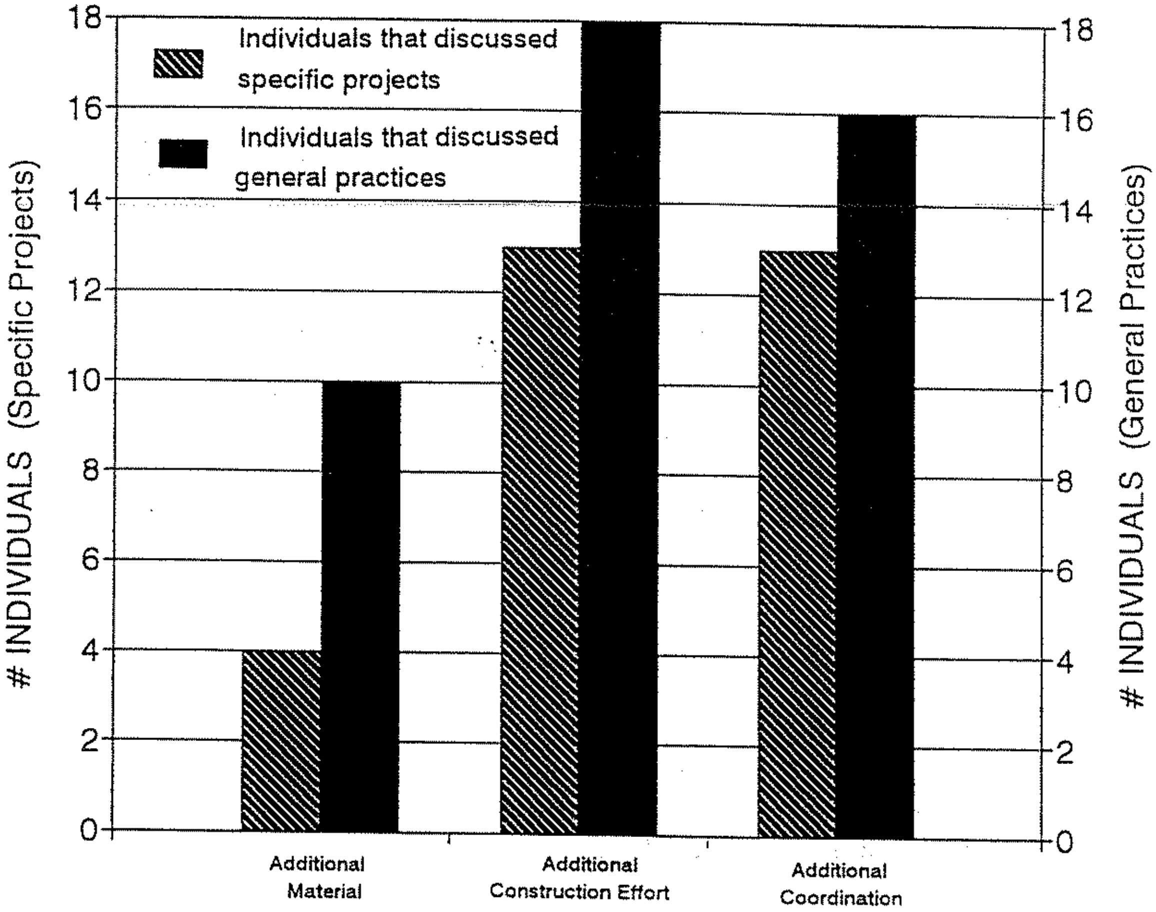


Figure 4.3 Individuals that Identified Broad Disadvantages

One individual mentioned that an increase in the procurement activity was needed due to the additional fabrication and assembly activities and contractors involved. He stated that it is essential to know each contractor's capabilities and limitations. Increased site work was also identified as one of the requirements of a modular construction project.

4.6.3 Need for Additional Coordination

The need for additional coordination of design and construction activities was considered a broad disadvantage by 29 of the 31 individual interviewed. The need for more coordination was considered a broad disadvantage by all of the thirteen individuals that discussed specific modular construction projects, and by sixteen of the eighteen individuals that discussed modular construction practices.

The coordination that increases in scope in modular construction includes all types. Several specific types of coordination follow:

"Planning coordination": the coordination between planning and other modular construction activities.

"Design coordination": (1) coordination between design of the modules and other modular construction activities, and (2) coordination between the design of the module and the standards and codes at the location of the project.

"Procurement coordination": the coordination between procurement and other modular construction activities.

"Fabrication and assembly coordination": (1) coordination between the fabrication and assembly of the modules, and other modular construction activities, (2) coordination of the trades involved (i.e., structural, electrical, plumbing, insulation, etc.) in fabrication and assembly, and (3) coordination of fabrication and assembly with quality control and inspection.

"Transportation coordination": (1) coordination between transportation and other modular construction activities, (2) coordination between transportation and contractors involved with equipment connections in industrial construction, and (3) coordination between transportation and permit acquisition.

"Offsite/onsite coordination": (1) coordination between fabrication and assembly of modules, and onsite construction activities.

During the interviews, the individuals discussed the need for several of these different types of coordination. One individual mentioned that there was a need for more transportation coordination to ensure that the equipment was available when necessary. Another individual mentioned that more fabrication and assembly coordination was required in their modular projects. The coordination of fabrication and assembly work between trades (i.e., structural, electrical, plumbing, insulation, etc.) was emphasized. Another individual mentioned that offsite/onsite coordination is essential.

4.7 RELATIONSHIPS BETWEEN MODULE CHARACTERISTICS AND TRANSPORTATION METHODS

The 31 individuals that were interviewed shared information on six types of construction: (1) bridge, (2) industrial, (3) light industrial/commercial, (4) prison, (5) residential, and (6) ship. These types of construction involve the transportation of large 2- and 3-dimensional modules. This information was analyzed and the relationships between the number of major dimensions of the modules (2 or 3), and the transportation methods were identified. Table 4.8 shows the relationships between the number of major dimensions, the transportation methods, and the construction types. For example, based on the information provided, all of the industrial projects involved complex large-scale 3-dimensional structural steel modules.

Table 4.8
Relationships Between the Number of Major Dimensions and Transportation

<table>
<tr><th></th><th colspan="4">TRANSPORTATION MODE</th></tr>
<tr><th></th><th colspan="2">PROJECT SPECIFIC</th><th colspan="2">GENERAL</th></tr>
<tr><th>CONSTRUCTION TYPE</th><th>LAND</th><th>WATER</th><th>LAND</th><th>WATER</th></tr>
<tr><td>Bridge</td><td colspan="2">3-D</td><td></td><td></td></tr>
<tr><td>Industrial</td><td colspan="2">3-D</td><td colspan="2">3-D</td></tr>
<tr><td rowspan="2">Light Industrial/Commercial</td><td>3-D
2-D</td><td></td><td rowspan="2">2-D</td><td rowspan="2"></td></tr>
<tr><td colspan="2">3-D</td></tr>
<tr><td>Prison</td><td>3-D</td><td></td><td>3-D</td><td></td></tr>
<tr><td rowspan="2">Residential</td><td rowspan="2"></td><td rowspan="2"></td><td colspan="2">3-D</td></tr>
<tr><td>3-D</td><td></td></tr>
<tr><td>Ship</td><td></td><td></td><td colspan="2">3-D</td></tr>
</table>

The companies that were interviewed within the light industrial/commercial industry typically fabricated and transported 2-dimensional modules. The companies that were interviewed involving the construction of prisons fabricated and assembled large 3-dimensional prison cells offsite. These cells were usually precast concrete cells, complete with the accessories of a prison cell; and they were transported by land.

Table 4.9 shows the relationship between the transportation mode and the type of construction using the number of individuals who discussed specific projects or general construction practices. The major relationship derived from this table is that modules for industrial construction are usually transported by both water and land, because most of the industrial modules are large-scale modules; and some of these modules were involved in international projects. Most of the individuals involved in the light industrial and commercial construction indicated that their modules (or 2-D components) were transported by land transportation.

Table 4.9
Relationships Between the Modules and the Transportation Methods

<table>
<tr><th></th><th colspan="4">TRANSPORTATION MODE</th></tr>
<tr><th></th><th colspan="2">PROJECT SPECIFIC</th><th colspan="2">GENERAL</th></tr>
<tr><th>CONSTRUCTION TYPE</th><th>LAND</th><th>WATER</th><th>LAND</th><th>WATER</th></tr>
<tr><td>Bridge</td><td colspan="2">1S</td><td></td><td></td></tr>
<tr><td rowspan="2">Industrial</td><td colspan="2" rowspan="2">3 S</td><td colspan="2">1G*</td></tr>
<tr><td colspan="2">5G</td></tr>
<tr><td rowspan="2">Light Industrial/Commercial</td><td>2S
1S</td><td></td><td rowspan="2">5G</td><td rowspan="2"></td></tr>
<tr><td colspan="2">1S</td></tr>
<tr><td rowspan="2">Prison</td><td rowspan="2">1S
4S</td><td rowspan="2"></td><td>1G**</td><td rowspan="2"></td></tr>
<tr><td>1G</td></tr>
<tr><td rowspan="2">Residential</td><td rowspan="2"></td><td rowspan="2"></td><td colspan="2">1G</td></tr>
<tr><td>2G</td><td></td></tr>
<tr><td>Ship</td><td></td><td></td><td colspan="2">2G</td></tr>
<tr><td>TOTAL</td><td colspan="2">13</td><td colspan="2">18</td></tr>
</table>

<u>LEGEND</u>

S	Individuals that provided information on specific projects
G	Individuals that provided information on general practices

* Transportation was not a significant issue in this project because the modules were preassembled onsite.

** This company has not yet procured and transported its prison modules. It will most likely transport them by land.

Chapter 5

Essential Characteristics of Successful Modular Construction Projects

5.1 INTRODUCTION

This chapter presents essential characteristics of successful modular projects, that were identified by analyzing the information gathered from the study of literature and the survey of industry. Because of the nature of modular construction and the interdependency of its construction activities, there are many characteristics of modular projects that are essential to their success. In this chapter, several essential characteristics are identified and categorized into three areas: (1) project management, (2) design and engineering, and (3) fabrication.

5.2 PROJECT MANAGEMENT

Eight essential characteristics of the management of modular projects are identified. The first three are associated with the planning and organization of modular projects; the first is identified by Glaser et al [1979] and the other two are identified by Clement et al [1989]. The next two are associated with the management of conceptual design; the first is identified by Glaser et al [1979]; and the other by Clement et al [1989]. The remaining three essential characteristics projects involve management of the procurement activity; the first two are identified by Glaser et al [1979]; and the remaining one by Stubbs [1990].

- **Having a Module Task Team:**

Having a module task team allows managers, designers, fabricators, erectors, and transporters to participate in the development of the modules. Tatum et al [1987] state that teams should include design, fabrication, procurement, and construction personnel to ensure that all participants are involved in a process that allows input and criticism from all viewpoints. Each participant should have an established level of authority in the decision-making process [Stubbs, 1990]. Mullet [1984b] states that "from a project management viewpoint, the significant feature emerging from a decision to modularize is that, in effect, another project will have been created within the main project." Module task teams are responsible for every mini-project (module) that results from modularization.

Information from the interviews supports the idea that modular task teams should be created to achieve successful modular projects. For example, the individual from Air Products & Chemicals, Inc. indicated that the use of a module design task force is necessary and beneficial in the organization and planning of the project. He also suggested that the use of a modular consultant can be helpful for the project and the task team, in terms of acquiring module design and fabrication expertise. The individual from Foster Wheeler Energy, Ltd. indicated that an engineering-procurement-construction (EPC) module task team should be created to ensure the success of modular projects. An individual from Gate Concrete Products indicated that one must consider each module as an individual mini-project and that module teams are necessary to ensure successful mini-projects.

- **Expecting Cultural Resistance:**

Many owners may not necessarily understand the advantages of modular construction. Thus, one should expect resistance to using modular construction methods since individuals tend to recall negative experiences in modular construction projects rather than the positive ones. However, Clement et al [1989] states that "these are NOT problems with the module concept. They are problems of approach, application, and implementation."

- **Having an Active Project Management Team:**

Zambon [1981] states "like many sophisticated innovations being applied today, it [modular construction] places a heavy burden on project management and functional groups." An active and involved project management team is essential to the success of modular projects.

Several individuals that were interviewed agreed that this is an essential characteristic of successful modular projects. For example, the individual from Falcon Steel Company, Inc. indicated that it was essential to have an active project management team to perform the coordination of construction activities, and, especially, to address the transportation, handling, and erection activities. The individual from Air Products & Chemicals, Inc. indicated that it is essential for management to be involved and to make decisions early in the project; he mentioned that it is important to know the capabilities and limitations of the contractors involved in the project, and to manage them accordingly.

The individuals from Allied Steel Products Corp. and Environmental Resources Management, Inc. indicated that it is essential to maintain proper project management. They mentioned that special attention should be given to the transportation methods and the associated concerns, such as the handling and erection equipment and methods.

- **Knowing How to Divide the Facility into Appropriate Modules:**

Deciding how to modularize a project is often a complicated decision. For example, Tatum et al [1987] state that specific considerations in determining the extent of modularization include: (1) the relocation of man hours, (2) transportation and handling costs, (3) limitations on the module dimensions, weight, and its cost, (4) additional material requirements, (5) site work requirements, and (6) the increase in design and engineering (i.e., in terms of cost and effort). The individual from Gate Concrete Products agreed that this is an essential characteristic. He indicated that the design should include an adequate breakdown of the portions of the building that are going to be constructed by modular and/or conventional construction methods.

- **Making an Early Evaluation and Commitment to a Module Concept:**

  Making an early commitment to a module concept is essential because all of the activities of a modular project depend on this decision. The evaluation of a module concept includes a review of potential module arrangements and/or layouts, and the results of studies of the feasibility of each module arrangement from the point of view of design and engineering, fabrication, and transportation, handling, and erection. The potential of each module arrangement to exploit the advantages of modular construction is assessed as part of the evaluation.

- **Selecting the Fabricator Early:**

  Selecting the fabricator early allows the fabricator to provide professional input throughout the design of the module. The individuals from Foster Wheel Energy, Ltd. and Texaco, Ltd. indicated that the selection of the fabricator must be performed early, and that he must have extensive modular construction experience.

- **Developing and Maintaining an Appropriate Procurement Schedule:**

  Procurement of equipment, material, services, and so on must be scheduled in a timely manner. The individuals responsible for procuring these items should be identified early in the project. Individuals that were interviewed agreed that this is an essential characteristic. For example, the individual from Falcon Steel Company, Inc. indicated that the scheduling of the transportation equipment is very critical; delayed equipment availability can be very costly to the project. Another individual indicated that construction schedule extensions are very detrimental to modular projects.

- **Expecting Savings in Construction Activities:**

  Stubbs [1990] indicates that although project costs usually increase because of the need for additional design and engineering, savings in project costs are derived from the construction activities. The individuals that were interviewed from Foster Wheeler Energy, Ltd. and Texaco, Ltd. indicated that modular projects must be construction driven; that is, the project must be driven by construction cost considerations.

5.3 DESIGN AND ENGINEERING

Three essential characteristics relating to the design and engineering of a modular project are identified. The first two are identified by Glaser et al [1979] and the third is identified by Stubbs [1990].

- **Designing the Modules Early:**

The design of the modules must be performed early in the project because the design should be established before other interdependent activities can begin. For example, without a design concept for the module, the transportation method cannot be selected because the transportation, handling, and erection activities are dependent upon the module design.

- **Using Standardization:**

In modular construction, fabrication can be simplified if the modules are standardized. Hesler [1990] states that "the [modular] concept begins with standardization of design, which involves two primary premises: (1) the design is made as general as feasible;" and "(2) standardized specifications and often equipment suppliers allow for design repeatability."

The individual that was interviewed from Quickway Metal Fabricators, Inc. indicated that standard welding methods contributed to the success of their modular project that consisted of fabricating and assembling large welded space frames.

- **Expecting Additional Design and Engineering Effort:**

Stubbs [1990] states that it is necessary to expect the need for additional design and engineering effort in modular projects. However, he states that it should also be expected that the additional design and engineering effort will reduce the effort required to correct design errors and/or omissions onsite.

Individuals that were interviewed agreed that this is an essential characteristic. For example, the individual from Air Products & Chemicals, Inc. indicated that civil and structural design is the key to successful modular projects; and that the design effort is increased to avoid structural damage to the modules during transportation. The individual from Foster Wheeler Constructors, Inc. indicated that additional design must be performed to address the additional transportation loads that the modules will be exposed to. One individual indicated that the added design effort is essential because modular construction cannot tolerate design changes without causing costly delays.

5.4 FABRICATION

Three essential characteristics relating to the fabrication of modular projects were identified by individuals that were interviewed. The first one is also discussed by Bolt et al [1992].

- **Minimizing the Handling of the Modules:**

  Handling of the modules should be avoided since excessive handling can cause module damage. For one particular project, Bolt et al [1982] state that "lifting considerations originally did not enter into the determination of the maximum weight;" and "it was the intention that the modules were always moved while supported from underneath and never lifted." The individuals interviewed from Foster Wheeler Energy, Ltd. and Texaco, Ltd. indicated it is critical to minimize the handling of the modules.

- **Maintaining Good Relationships with Construction Officials:**

  Good professional relationships with construction officials can enable project requirements such as: (1) performing module inspections, (2) complying to the country's building codes and standards, (3) establishing communication, and (4) dealing with the cultural and governmental climate, to be performed in an efficient manner. For example, the individual from Air Products and Chemicals, Inc. indicated that a good professional relationship with Algerian construction authorities enabled the regulatory procedures of the project, such as the module inspections and compliance to Algerian construction codes, to be conducted without major delays in schedule.

- **Locating Fabrication Shops Near Water:**

  The location of fabrication shops near navigable waterways can be essential to successful large-scale modular projects because this makes transportation by water more feasible. Prosser [1993] mentions that being close to water allows them: (1) to use water transportation methods, and (2) to acquire large "jumbo" projects in different countries. Bass [1982] states that a project for the North Slope of Alaska used modular construction because of the "proximity of the Prudhoe Bay field to the coast." It should be noted that this characteristic may not be essential to small-scale modular projects, where land transportation is adequate.

5.5 SUMMARY

This chapter identified essential characteristics of successful modular construction projects. These essential characteristics were identified through the review of literature and the survey of industry. Knowledge of these essential characteristics can help in the planning and control of modular construction activities to ensure successful modular projects.

The essential characteristics were categorized into three areas: (1) project management, (2) design and engineering, and (3) fabrication. The project management area included eight project characteristics that are considered to be essential, including: (1) having a module task team, (2) expecting cultural resistance, (3) having an active project management team, (4) knowing how to divide the facility into appropriate modules, (5) making an early evaluation and commitment to a module concept, (6) selecting the fabricator early, (7) developing and maintaining an appropriate procurement schedule, and (8) expecting savings in construction activities.

The design and engineering area included three essential characteristics: (1) designing the modules early, (2) using standardization, and (3) expecting additional design and engineering effort. The fabrication area included three essential characteristics: (1) minimizing the handling of the modules, (2) maintaining good relationships with construction officials, and (3) locating fabrication shops near water.

Chapter 6

Summary of Current Modular Construction Practices

6.1 INTRODUCTION

This chapter summarizes information about modular construction practices presented in Chapters 2, 3, 4, and 5. The summary is organized into the following discussion areas: (1) advantages and disadvantages of modular construction, (2) review of modular construction activities, (3) driving forces of modular construction, and (4) characteristics of successful modular projects.

6.2 ADVANTAGES AND DISADVANTAGES OF MODULAR CONSTRUCTION

Several advantages and disadvantages were identified from a review of modular construction activities. This section summarizes the advantages and disadvantages of modular construction identified in Chapters 2 and 4.

- **Advantages:**

Six broad advantages of modular construction were identified from the literature and industry survey (interviews): (1) reduced cost, (2) increased quality, (3) improved safety, (4) reduced schedule, (5) reduced social and environmental impact, and (6) increased possibility of construction.

Both the literature and the interviews identified the first four broad advantages. Of the four, reduced cost and schedule appear to be related to most of the specific benefits of modular construction identified in Chapter 4. For example, reduced cost was derived from the ability to work indoors in fabrication shops in a more controlled environment, rather than onsite where unfit construction conditions may be present, and the ability to reduce the cost of fabrication and assembly by paying shop labor rates rather than field labor rates. Reduced schedule was also derived from the ability to work indoors in fabrications shops, as well as from the ability to perform work in parallel, for example, being able to perform the module assembly and the site preparation at the same time.

The literature identified the last two broad advantages. However, these advantages were not specifically identified by the individuals interviewed. Reduced social and environmental impact refers to the social and environmental impact of the project at the construction site. Increased possibility of construction refers to the potential of constructing at locations that might not be feasible with conventional methods. The individuals that were interviewed did not emphasize these ideas as advantages, however they appear to be related to the driving forces of modular construction summarized in section 6.4. Table 6.1 shows the relationship between the broad advantages and the specific benefits that were identified from the industry survey (interviews).

Table 6.1
Broad Advantages and Specific Benefits

SPECIFIC BENEFITS	BROAD ADVANTAGES			
	RC	IQ	IS	RS
Working in a more controlled environment	**X**	**X**	**X**	**X**
Reducing the fabrication and assembly schedule	x			**X**
Providing for increased quality		**X**		x
Reducing the cost of fabrication and assembly	**X**			
Using a single responsible source in contracting				**X**
Reducing the required traffic control	x		x	x

LEGEND

RC	Reduced Cost	IS	Improved Safety
IQ	Increased Quality	RS	Reduced Schedule
x	Specific benefits that contribute to the broad advantages		
X	Specific benefits that are primary contributors to the broad advantages		

- **Disadvantages:**

Six broad disadvantages of modular construction were identified from the literature and industry survey (interviews): (1) the need for additional material, (2) the need for additional effort, (3) the need for additional coordination of activities, (4) increased cost, (5) increased risk, and (6) reduced adaptability for design changes.

Both the literature and the interviews identified the first three broad disadvantages. Of the three, the needs for additional effort and coordination of activities appear to be most prevalent, as approximately 90% of the individuals interviewed identified them as drawbacks of modular construction. The need for additional effort occurs in the planning of: (1) design and engineering, (2) procurement, (3) fabrication, and (4) transportation, handling, and erection; and in the conduct of design and engineering and fabrication. The need for additional coordination is derived from the interdependency of activities. Because many activities in modular construction are performed in parallel rather than in series as in conventional construction, greater coordination of activities is needed.

The literature also identified the last three broad disadvantages. Increased cost refers to additional costs incurred when using modular construction. Increased risk is related to the need for specialized expertise and equipment in modular projects, the interdependency of construction activities, and the fact that modular construction is not adaptable to changes. Although the individuals that were interviewed may have encountered these potential drawbacks, they did not identify them as broad disadvantages of modular construction since, for example, some individuals stated that many modular projects show savings in total project cost compared to conventional construction.

6.3 REVIEW OF MODULAR CONSTRUCTION ACTIVITIES

Modular construction activities differ from those in conventional construction in: (1) planning, (2) design and engineering, (3) procurement, (4) fabrication, and (5) transportation, handling, and erection, as discussed in detail in Chapter 3. The differences identified in Chapter 3 were supported by the findings from the industry survey, presented in Chapter 4. The construction activities in modular construction differ from those in conventional construction by: (1) an increase in effort, (2) an increase in portions of work performed earlier in the project, and (3) an increase in the interdependency with other construction activities.

Planning is more involved and complex in modular construction than conventional construction because of its interdependency with other activities. Planning activities include: (1) project control, (2) module planning, (3) procurement (including procurement for design and engineering, fabrication, and transportation, handling, and erection), (4) transportation studies, and (5) site planning. Design and engineering in modular construction is more complex because of the need to avoid design changes during fabrication and assembly, and because of the additional design effort needed to provide modules with structural integrity for transportation, handling, and erection. Additional design effort is also needed to address the tolerances and connections needed for modular construction, and to satisfy codes and standards. Procurement in modular construction is significantly interdependent with the other activities. In a modular project, procurement of: (1) design and engineering, (2) fabrication, and (3) transportation, handling, and erection is often performed during project planning.

Fabrication in modular construction is significantly different than "shop fabrication" in conventional construction because the majority of onsite construction work is transferred into fabrication shops. Table 6.2 identifies specific differences in fabrication, and shows whether these differences create favorable or unfavorable increases or decreases in the fabrication and assembly process.

Table 6.2
Specific Changes in Fabrication

SPECIFIC CHANGES IN FABRICATION	DEGREE OF CHANGE
Work in a more controlled environment	Favorable Increase
Work in parallel in multiple fabrication shops	"
Repetition and standardization	"
Permanent labor force (offsite)	"
Quality control/inspection	"
Offsite testing	"
Material management	Unfavorable Increase
Risks for client	"
Weather concerns/delays	Favorable Decrease
Work above ground	"
Work in series onsite	"
Temporary labor force (onsite)	"
Onsite fabrication and assembly	"
Little flexibility/tolerances	Unfavorable Decrease

As indicated earlier, the planning of transportation, handling, and erection in modular construction is more involved and complex than in conventional construction. The planning of transportation is more complex in modular projects because it can involve large-scale 3-dimensional modules that may require special transportation methods and equipment. If properly planned, the activities of transportation, handling, and erection should only involve the actual transfer and erection of the modules.

The handling of modules requires more careful investigation in modular construction than in conventional construction. The methods and equipment should allow the modules to be efficiently handled in fabrication shops and at the construction site.

Table 6.3 identifies specific differences between the erection process in modular construction and that in conventional construction. The table shows whether these differences create favorable or unfavorable changes in the erection process. In one sense, erection may be considered less complicated, because the modules are often 100% complete upon delivery and little onsite assembly is required. In another sense, erection may be considered more complicated in that larger, heavier, and more complex components are erected. The transfer of fabrication and assembly work to the fabrication shops creates most of the differences shown in the table.

Table 6.3
Specific Changes in Handling and Erection

SPECIFIC CHANGE IN ERECTION	DEGREE OF CHANGE
Space for handling modules onsite	Unfavorable Increase
Onsite space for module storage	"
Structural/equipment connections	"
Capacity of handling and erection equipment	"
Erection time	Favorable Decrease
Field work	"
Handling	"
Onsite labor force	"

6.4 DRIVING FORCES OF MODULAR CONSTRUCTION

This section summarizes the information on the driving forces of modular construction identified from the industry survey. Six driving forces of modular construction were identified by the individuals interviewed in the industry survey: (1) site resource constraints, (2) reduced cost, (3) reduced schedule, (4) improved safety, and combinations of: (5) reduced cost and schedule, and (6) site resource constraints and reduced schedule.

Of the six driving forces identified, three were most common among the individuals interviewed: (1) site resource constraints, (2) reduced cost, and (3) reduced cost and schedule. Thus, it appears that many construction projects use modular construction methods to reduce the cost, or reduce both the cost and schedule of the project; and many projects use modular construction methods to overcome a deficiency of site resources.

6.5 CHARACTERISTICS OF SUCCESSFUL MODULAR CONSTRUCTION PROJECTS

In order for modular construction to be implemented with success, the project should possess certain essential characteristics. Several essential characteristics, which were identified from the study of the literature and the interviews, are listed below. Chapter 5 discussed them in detail.

The essential characteristics are categorized into three areas: (1) project management, (2) design and engineering, and (3) fabrication. Eight essential characteristics in the area of project management are: (1) having a module task team, (2) expecting cultural resistance, (3) having an active project management team, (4) knowing how to divide the facility into appropriate modules, (5) making an early evaluation and commitment to a module concept, (6) selecting the fabricator early, (7) developing and maintaining an appropriate procurement schedule, and (8) expecting savings in construction activities.

Three essential characteristics in the areas of design and engineering are: (1) designing the modules early, (2) using standardization, and (3) expecting additional design and engineering effort. Three essential characteristics in the area of fabrication are: (1) minimizing the handling of the modules, (2) maintaining good relationships with construction officials, and (3) locating the fabrication shops near water.

Chapter 7

Opportunities to Advance Modular Construction Technology & Methodology for Building Frame Systems

7.1 INTRODUCTION

This chapter identifies opportunities to advance modular construction technology and methodology for building frame systems. Current examples of modular construction technology and methodology are presented in De La Torre and Sause [1994c]. "Modular construction technology" refers to new systems and components for constructed facilities, and new construction equipment for producing these facilities. "Modular construction methodology" refers to the procedures used in: (1) planning and evaluating the feasibility of using modular construction (e.g., business decision-making procedures), (2) design and engineering procedures, (3) fabrication, and (4) transportation, handling, and erection. Opportunities to advance modular construction technology and methodology for building frame systems are discussed below. To fully take advantage of the available opportunities, further research and development in these areas is necessary. The identification of the most promising opportunities to advance modular construction technology and methodology are part of this future work.

7.2 MODULAR CONSTRUCTION TECHNOLOGY

Advances in modular construction technology for building frame systems require the development of new modules and components for constructed facilities, and new construction equipment for producing these facilities. In general, advances can be made by developing concepts for larger modules and components for building frame systems that can be shop-fabricated, transported, handled, and erected; and by developing improved transportation, handling, and erection technology for these large modules and components. Building frame systems, such as those in industrial, light industrial, light commercial, and prison construction, currently take advantage of various levels of modular construction such as prefabrication, onsite preassembly, and modularization (i.e., 3-dimensional fabricated modules). Opportunities to advance modular construction technology for building frame systems include the following.

(1) Develop new building frame systems specifically to exploit onsite preassembly methods.

(2) Increase the use of onsite self-aligning and/or self-locking connections such as the patented safety pinhole connection and the ATLSS connection [Perreira, 1993; Fleischman et al, 1993].

(3) Create innovative modular building frame designs within the limitations of available transportation methods (e.g., transporting building modules in folded form).

(4) Prefabricate more complex 2- or 3-dimensional modules for building frame systems rather than 1-dimensional components (e.g., fabricated beams and columns) or simple 2-dimensional components, such as those used in pre-engineered metal buildings or precast floor systems.

(5) Reduce the number of onsite connections to decrease the erection time.

(6) Integrate the service (i.e., electrical, mechanical, plumbing, insulation, etc.) systems and building frame systems in the fabrication shops.

The following three subsections describe the first three opportunities in more detail.

7.2.1 Onsite Preassembly

"Onsite preassembly" involves preassembly of components at the construction site and subsequent erection of the building frame as preassembled units rather than individual components. This section discusses the use for onsite preassembly and provides an example. Increased use of onsite preassembly can be developed for the construction of building frame systems as follows:

Use conventional shop fabrication: Use the customary shop fabrication process of conventional construction for structural member preparation (i.e., cutting, drilling, bolting, painting, etc.).

Preassemble building frames and floor systems at ground level onsite: Preassemble steel building frames and reinforced concrete or composite steel-concrete building floor systems onsite, complete with columns, connections, and service (i.e., electrical, plumbing, mechanical, insulation) systems.

Increase safety by working at ground level: Increase the use of ground level preassembly of components to create a safer construction environment by reducing safety and height-related concerns.

Work in parallel and increase productivity by working at ground level: Assemble a number of units simultaneously, and increase productivity by working at ground level where workers are more comfortable and equipment is more accessible.

Increase quality by working at ground level: Increase the quality of the work by performing the assembly at ground level where workers are more comfortable and equipment is more accessible.

Reduce the transportation costs: Reduce the transportation costs associated with modular construction by assembling modules at or near the construction site.

Acknowledge disadvantages: Acknowledge the disadvantages of onsite preassembly to reduce their impact. Some of the disadvantages include: (1) increased planning, and design and engineering effort, and (2) increased handling and erection equipment capacity.

An example that illustrates some of the uses of onsite preassembly is discussed here. As indicated in Section 4.3.1.4, one individual interviewed in the industry survey discussed the use of onsite preassembly for the construction of industrial plants in which steel preassembled units are assembled onsite at ground level. The preassembled units consist of complete floor levels including bracing, equipment, platforms, stairs, handrails, columns, and so on. Once the floor levels are assembled, each is handled and erected onto the lower floor level and connected into final position. Patented safety pinhole connections are used to joined the preassembled units. These connections are discussed in the next section. This construction method takes advantage of onsite preassembly by: (1) using safer construction practices by constructing floor levels of a plant at ground level, and (2) reducing the transportation costs typically associated with modular construction.

Onsite preassembly can also be used for the construction of commercial buildings. Modules for low-rise buildings made of steel frames and/or reinforced concrete (or composite steel-concrete) floor systems could be fabricated by conventional methods and assembled efficiently at ground level onsite. These modules, however, may require wider spans (i.e., for the placement of windows, architectural features, etc.) than the modules for industrial plants. The platforms and plant equipment such as vessels, pumps and piping, that are placed in industrial preassembled units are not needed for a commercial building. However, building service systems could be installed. The assembly, handling, and erection of these commercial building modules could be similar to that of the industrial plant example above.

7.2.2 Self-Aligning and/or Self-Locking Connections

"Self-aligning and/or self-locking connections" can simplify the onsite erection process and enable the building frame systems to be erected more efficiently and cost effectively. This section discusses increased use of self-aligning and/or self-locking connections, and provides examples. Increased use of self-aligning and/or self-locking connections can be developed for the construction of building frame systems as follows:

Use self-aligning connections: Use patented safety pinhole connections created by Ralds Industries, Inc. or the ATLSS connection created by the Center of Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University. Self-aligning connections can reduce the erection time and promote safer erection and assembly practices. Self-aligning connections could be used to connect preassembled modules onsite.

Use conventional shop fabrication: Use the customary shop fabrication process of conventional construction for structural member preparation (i.e., cutting, drilling, bolting, painting, etc.).

Use self-locking connections: Use connections which are self-seating or locking without bolting or welding to reduce the effort required to assemble building frame systems. The ATLSS connection has this feature. Self-locking connections could be used for ground level preassembly of modules as well as the final connections between preassembled modules.

Acknowledge disadvantages: Acknowledge the disadvantages of self-aligning and/or self-locking connections to effectively reduce their impact. The disadvantages include: additional design and engineering effort, additional fabrication effort to produce connections, tighter tolerance requirements, and use of additional material in the connections.

Examples that illustrate some of the uses of self-aligning and/or self-locking connections are discussed here.

- **Example No. 1 (Ralds Industries safety pinhole connection):**

As mentioned in the discussion of onsite preassembly, patented safety pinhole connections can facilitate the use of onsite preassembly. As previously discussed, preassembled units can be erected to their final positions and connected by these connections that splice the columns just below the bottom of the beams. The pinhole connection uses two horizontal plates. One with a vertical pin and the other with a hole to guide the pin. The pin is part of the lower plate, and the hole is part of the upper plate. The connection holds the columns in place until permanent bolting is performed. The tolerance for the connection is 1/8 inch.

- **Example No. 2 (ATLSS connection):**

Another self-aligning connection is the ATLSS connection. "The ATLSS connection concept is based on using a tapered tenon piece on the beam which slips into a mortise guide mounted on the column" [Fleischman et al, 1993]. In concept, a self-aligning and/or self-locking connection should have specific features such as "(1) the connection must be able to guide the beam toward the proper location once the tenon and mortise pieces make contact, (2) the tenon piece can not jam or catch on the mortise guide, nor can it pull out horizontally once it engages, (3) the connection must allow for misalignment and have the ability to be adjusted easily when the building is being plumbed, and (4) the connection must be stable during erection and carry the intended design loads during the life of the building" [Fleischman et al, 1993].

ATLSS connections were used on the construction of an addition to a building for a chemical plant [Fleischman et al, 1993]. One bay of the building addition was preassembled onsite at ground level using conventional connection. Upon completion of the 20 feet by 30 feet bay, the entire unit was erected and placed onto its final position with a boom crane and three workers. Erection and final placement of the bay took place by connecting the ATLSS connections on each corner of the bay to the columns. "The assembly on the ground took 20 minutes, the attachment of the tenons to the corners of the bay took 5 minutes, and the lift took less than 2 minutes ... The total time of erection for the bay was 30 minutes. When compared with the more than one hour time to erect a similar bay in the adjacent span, a tremendous erection time savings was realized" [Fleischman et al, 1993].

7.2.3 Transportation-Efficient Building Designs

"Transportation-Efficient Building Designs" are innovative building designs that reduce the large transportation costs associated with modular construction. This section discusses the use of transportation-efficient building designs and provides some examples. Transportation-efficient building designs can be developed for building frame systems as follows:

Use conventional shop fabrication: Use the customary shop fabrication process of conventional construction for structural member preparation (i.e., cutting, drilling, bolting, painting, etc.). However, reduce the number of individual components that leave the fabrication shop by assembling certain components together, while still maintaining a module of appropriate size for easy transportation.

Take advantage of current highway regulations: Design 2- or 3-dimensional modules with dimensions and weights that allow them to be transported by truck.

Design foldable steel and/or concrete structural assemblies: Design foldable steel and/or concrete structural assemblies to allow them to be transported and handled efficiently. "Foldable" assemblies can reduce the transportation expenses, since the building assemblies can be transported as "stacked" 2-dimensional panels rather than 3-dimensional modules.

Acknowledge disadvantages: Acknowledge the disadvantages of transportation-efficient building designs to effectively reduce their impact. The disadvantages of this concept include: additional design and engineering effort, potentially complex connections, additional fabrication effort, and use of additional material.

Examples that illustrate some of the uses of transportation-efficient building designs are discussed here.

- **Example No. 1:**

Zhenqiang et al [1991] identify several public and industrial buildings in Honduras that took advantage of transportation-efficient building designs developed in China. These designs consist of precast prestressed foldable plate structures. The "precast prestressed folded plate roof elements are cast flat with hinges between panels; they are transported flat, then opened to the desired angle during erection, with joints formed and cast in place to unify the structure" [Zhenqiang et al, 1991]. When erected, the precast prestressed folded plates have a V-shape connection. The plates are fabricated, transported, and handled as 2-dimensional elements, making transportation by truck feasible. During the field erection phase, the plates are opened and adjusted to the required angle.

Zhenqiang et al [1991] indicated that this system has been used since 1988 for the construction of both commercial and industrial buildings, and provide examples that used the V-plate structural system. A commercial building, the Plaza de Sula Theater building, was constructed in San Pedro Sula, Honduras in 1989 with a V-plate structural roof system. Another project was the construction of the Good Shepherd Catholic Church, also located at San Pedro Sula. Zhenqiang et al [1991] state that "this fan-shaped roof for this church demonstrates the inherent flexibility of the precast prestressed V-plate system."

- **Example No. 2:**

Taking advantage of existing local highway regulations and codes is another means of providing efficient transportation methods. By designing modules that can be transported by truck, the transportation costs can be significantly reduced since barge or ship transportation can be expensive. For example, in Pennsylvania, the maximum transportable truck load size is 14 feet in width (except as authorized), 80 feet in length, and 12 feet in height. Thus, if modules are designed to "fit" the existing load limitations, trucks may be used effectively to transport components and modules. Systems that can be transported within the limitations include: (1) foldable roof systems, (2) foldable truss systems, (3) foldable floor systems, and so on.

7.3 MODULAR CONSTRUCTION METHODOLOGY

Advances in modular construction methodology can be made through development in several areas, including: (1) the planning, and design and engineering (i.e., decision-making) process, and (2) the fabrication, transportation, handling, and erection process.

- **Planning, and Design and Engineering:**

Computer programs are frequently used to assist users in determining the feasibility of using modular construction methods in the construction of industrial and chemical/process plants. Appendix B discusses and compares three current computer programs that assist in the decision-making process. Opportunities to advance the planning, design and engineering, and decision-making methodology for modular construction include:

(1) Develop procedures to determine an optimal conceptual design that takes advantage of modular construction by identifying the extent of modularization that will make the project successful from the owner's business and/or financial perspective. The methods for optimization should include the selection of the size, weight, and dimensions of modules considering fabrication, and transportation, handling, and erection.

(2) Develop procedures to evaluate the use of modular construction methods in the construction of building frame systems.

(3) Develop procedures for the selection of the best transportation method for modules that consider the module dimensions and weight, and transportation economics.

(4) Develop procedures for detailed economic analyses of modular and conventional construction approaches for a project.

(5) Create new concepts for innovative and productive management teams responsible for the planning and management of modular projects.

The first opportunity identified above is discussed here. To identify the most appropriate extent of modularization in an optimal design, considerations to be investigated include:

(1) What portions of the project are infeasible using conventional construction methods?

(2) What portions of the project need to be completed on a fast track schedule?

(3) Is sufficient financing available early in the project?

(4) What portions of the facility can be broken down into modules?

(5) Can these modules be transported, handled, and erected considering the dimensions and weight of the largest module?

(6) Will there be adequate design and engineering expertise available?

(7) What additional material will be required to provide the module with sufficient strength, stiffness, and stability during transportation?

- **Fabrication, Transportation, Handling, and Erection:**

Modular construction can be used to reduce the environmental impacts of a construction project. For example, modular construction methods could allow buildings to be assembled and used, and then disassembled and relocated without producing significant demolition-related waste. Opportunities to advance fabrication, transportation, handling, and erection methodology include:

(1) Create more convenient methods to disassemble and relocate facilities without demolishing them.

(2) Develop construction methods that assemble the modules as close as possible to, but not necessarily at, the construction site to reduce transportation effort.

(3) Develop construction methods to increase the use of onsite preassembly of components prior to erection.

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Appendix A

List of Companies, Descriptions, and Addresses

(1) **AIR PRODUCTS AND CHEMICALS, INC.** is an international supplier of industrial gases and related equipment, chemicals and environmental & energy systems.

Location: 7201 Hamilton Boulevard
Allentown, Pennsylvania 18195-1591
(215) 481-4911
Contact: Scott F. Baer

(2) **ALLENTOWN APPLICATORS & ERECTORS** provides full services for the erection of pre-engineered metal buildings.

Location: 508 South Fawn Street
Allentown, Pennsylvania 18103
(215) 797-0816
Contact: Gino Demyan

(3) **ALLIED STEEL PRODUCTS CORP.** is a fabricator of ferrous and non-ferrous materials and related equipment.

Location: 500 Water Street
Newport, Delaware 19804
(302) 994-0933
Contact: Robert L. Parrish

(4) **BATH IRON WORKS CORPORATION** provides services to the shipbuilding and industrial construction industries. Bath Iron Work's facilities include fabrication plants and assembly and pre-outfit buildings.

Location: 700 Washington Street
Bath, Maine 04530
(207) 442-2828
Contact: William Peterson

(5) **BE & K - DELAWARE** is an engineering, procurement and construction company specializing in heavy industrial manufacturing facilities.

Location: P.O. Box 8255
242 Chapman Road
Newark, Delaware 19714-8255
(302) 452-9127
Contact: Henry L. Ritchie

(6) **BERKUS GROUP, ARCHITECTS** is an architectural and planning firm with experience in the mobile and modular housing industries.

Location: 223 E. De La Guerra Street
Santa Barbara, California 93101
(805) 963-8901
Contact: Barry A. Berkus, AIA

(7) **BUTLER MANUFACTURING COMPANY, INC.** is a manufacturer of pre-engineered metal buildings.

Location: 400 No. Weaber Street
Annville, Pennsylvania 17003
(717) 867-3214
Contact: Jim Badger

(8) **EASTERN EXTERIOR WALL SYSTEMS, INC.** provides services in design, manufacturing, and installation of prefabricated exterior wall systems.

Location: 3135 Schoenersville Road
Bethlehem, Pennsylvania 18015
(215) 868-5522
Contact: Robert A. Handschue

(9) **ENVIRONMENTAL RESOURCES MANAGEMENT, INC.** is a consulting firm that provides engineering and consulting services to industrial firms in environmental and wastewater treatment.

Location: 855 Springdale Drive
Exton, Pennsylvania 19341
(215) 524-3500
Contact: Carl Petrus

(10) **FALCON STEEL COMPANY, INC.** is a structural steel fabricator and erector specializing in highrise structures and bridges.

Location: P.O. Box 1567
Wilmington, Delaware 19899
(302) 571-0890
Contact: Brett S. Paddock

(11) **FOSTER WHEELER CONSTRUCTORS, INC.** **(Foster Wheeler USA Corporation)** provides engineering, procurement and construction services to the construction, petroleum, chemical, energy and pharmaceutical industries.

Location: Perryville Corporate Park
Clinton, New Jersey 08809-4000
(908) 730-6739
Contact: John E. Donnelly

(12) & (13) **FOSTER WHEELER ENERGY, LTD. & TEXACO, LTD.** Information from these companies was obtained from a video (video no. VC-109) produced by the Construction Industry Institute (CII). The name of the video is "Modularization Video from CII/Case Study/Pembroke Hydrotreater Project/Wales, U.K."

The speakers in this video were Michael Beaumont of Foster Wheeler, and Ken Hamilton of Texaco Ltd (Houston).

(14) **GATE CONCRETE PRODUCTS** is a manufacturer specializing in precast, prestressed concrete.

Location: 402 Heckscher Drive
Jacksonville, Florida 32218
(904) 757-0860
Contact: Pietro Leo Van Dyke

(15) **HALLA ENGINEERING & HEAVY INDUSTRIES, LTD.** provides a range of heavy industrial machinery and construction equipment and services.

Location: Washington D.C. Office
1001 No. 19th Street, Ste# 1020
Arlington, Virginia 22209
(703) 243-7222
Contact: Moon Ki Kim

(16) **IHI, INC.** (Ishikawajima-Harina Heavy Industries Company, Ltd., Japan) is a company that provides technology-oriented products and services ranging from space development to shipbuilding.

Location: 280 Park Avenue, West Building, 30th Fl
New York, New York 10017
(212) 599-8121
Contact: Shigeo (Sam) Matsuyama

(17) **INGALLS SHIPBUILDING** is a shipbuilding company.

Location: P.O. Box 149
Pascagoula, Mississippi 39568-0149
(601) 935-3904
Contact: Tom Rakish

(18) **JACOBS APPLIED TECHNOLOGY, INC.** is an engineering and construction organization that provides services to hydrocarbon, chemical processes, pharmaceutical, and other related industries.

Location: 1525 Charleston Highway
P.O. Box 1327 29116-1327
Orangeburg, South Carolina 29115
(803) 534-2424 (513) 595-7500
Contact: Linda G. Davis

(19) **KEYSTONE STRUCTURES, INC.** provides services for the pre-engineered metal building industry.

Location: 130 Route 202
P.O. Box 939
Chadds Ford, Pennsylvania 19317-0939
(215) 558-0900 (800) 525-1567
Contact: Michael Dougherty

(20) **LEHIGH VALLEY BUILDING SYSTEMS, INC.** is a contractor specializing in pre-engineered building systems.

Location: P.O. Box 3454
330 Schantz Road
Allentown, Pennsylvania 18106
(215) 398-1343
Contact: Stephen A. Shaver

(21) **LOVE HOMES** is a modular housing manufacturer.

Location: 4325 Hamilton Boulevard
Allentown, Pennsylvania 18103
(215) 398-1111
Contact: Todd Schwepfinger

(22) **NANTICOKE HOMES, INC.** is modular housing manufacturer.

Location: P.O. Box F
Greenwood, Delaware 19950-0506
(302) 349-4561
Contact: Tonda L. Parks

(23) **PIERCE-GOODWIN-ALEXANDER-LINVILLE, ARCHITECTS** provides architectural services.

Location: 2701 No. Rocky Point Drive Ste# 500
Tampa, Florida 33607
(813) 289-3313
Contact: Paul Mathews

(24) **PORTA-KING BUILDING SYSTEMS, INC.** provides services for the pre-engineered metal building industry.

Location: 4133 Shoreline Drive
Earth City, Missouri 63045
(800) 456-5464
Contact: Jim Aquado

(25) **QUICKWAY METAL FABRICATORS, INC.** is a fabricating company that specializes in metal forming and welding.

Location: P.O. Box 472
Monticello, New York 12701
(914) 794-1900
Contact: Marc Lerner

(26) **RALPH M. PARSONS COMPANY** is an engineering and construction company that provides services to the construction and other industries.

Location:
100 West Walnut Street
Pasadena, California 91124
(818) 440-2000
Contact:
Joseph Szlamka

(27) **ROTONDO/PENN-CAST** is a manufacturer of precast concrete products.

Location:
514 Township Line Road
P.O. Box 210
Telford, Pennsylvania 18969
(215) 257-8081
Contact:
Michael A. Grapsy

(28) **SVERDRUP CIVIL, INC.** provides civil and structural engineering services.

Location:
1650 Prudential Drive
Suite 200
Jacksonville, Florida 32207
(904) 399-1902
Contact:
John A. Unterspan

(29) **THE CONSULTING ENGINEERS GROUP, INC.** is a structural consulting firm that specializes in precast/prestressed concrete.

Location:
2455 No. East Loop 410 Ste# 125
San Antonio, Texas 78217
(210) 637-0977
Contact:
Walter Korkosz

(30) **THE PROSSER COMPANY, INC.** is an engineering and construction company that provides services to the chemical processing industry.

Location:
5234 Glen Arm Road
Glen Arm, Maryland 21057
(410) 592-6271
Contact:
Joseph L.Prosser, Jr.

(31) **TINDALL CONCRETE VIRGINIA, INC.** is a producer of structural and architectural precast, prestressed concrete products with in-house engineering and design capabilities.

Location:	P.O. Box 711 Petersburg, Virginia 23804 (804) 861-8447
Contact:	Greg Force

Appendix B

Computer Programs for Determining the Utility of Modular Construction and the Controlling Factors Considered

B.1 INTRODUCTION

This appendix reviews and analyzes three computer programs that are available to assist in determining if modular construction methods are appropriate for a given industrial or chemical process plant project. The purpose of the analysis is to identify controlling factors that are considered by these programs. The three programs are: (1) Modularization Decision Support Software (MODEX); (2) Advanced Construction Technology (ACT) Expert System; and (3) Module Assessment Program (MAP). MODEX was written by the Modularization Task Force of the Construction Industry Institute (CII) [CII, 1992]. ACT was written by Jacobs Applied Technology, Inc., a member of Jacobs Engineering Group [Jacobs Applied Technology, Inc., 1991]. And MAP was written by The Prosser Company, Inc. [The Prosser Company, Inc., 1992].

This appendix contains five additional sections. Three sections discuss each program in terms of the controlling factors it considers. Another section reviews, analyzes, and compares the controlling factors considered by all the programs, and presents common factors considered in determining the utility of modular construction methods for industrial and chemical/process plant projects. The last section summarizes the chapter.

B.2 MODULARIZATION DECISION SUPPORT SOFTWARE (MODEX)

MODEX is a computer program that assists the user in a decision making process that compares modular construction with conventional construction for industrial and chemical/process plants. It was written by the Modularization Task Force of the Construction Industry Institute (CII) [CII, 1992]. MODEX is intended for use early in the project by individuals who assist the owner in selecting construction methods for a specific project. MODEX poses a series of multiple choice questions on construction-related issues. The user answers the questions based on preliminary information about the project. The questions are answered on a scale of 0 to 100%. A higher number implies a higher confidence level for using modular construction methods.

MODEX conducts three types of analyses: (1) initial prescreening, (2) detailed analysis, and (3) economic analysis. After completing each analysis, MODEX recommends whether modular construction should be used on the project. This program summarizes: (1) the user's answers to the questions from the three analyses, (2) MODEX's final recommendation, and (3) it's level of confidence in its recommendation. The three analyses are discussed below.

B.2.1 Prescreening Analysis

The prescreening analysis considers controlling factors in the following categories: (1) plant location; (2) environmental/organizational; (3) plant characteristics; (4) project risks; and (5) labor-related factors. The analysis uses a weighted factor approach in which controlling factors are assigned a weight. If the total weighted score is less than a specified percentage (25%), MODEX recommends that conventional construction methods be used for the project and ends the analysis. If the total weighted score is greater than the specified percentage (25%), MODEX recommends that the user continue with a detailed analysis of the project's potential use of modular construction methods.

B.2.2 Detailed Analysis

The detailed analysis determines the most appropriate design and construction methods for the project. The analysis reviews the same five categories of controlling factors considered in the prescreening analysis. Example questions from the detailed analysis include:

(1) **Plant Location Factors:**

Transportation Equipment (this question is 13% of category value). Modules usually require specialized transport equipment. One must consider the availability of this equipment for transporting and setting modules from the fabrication location to the project site.

THE AVAILABILITY OF MODULE TRANSPORT EQUIPMENT NEAR THE SITE IS? CHOICES: High, Normal, Low

(2) **Plant Characteristic Factors:**

Project Design Evolution (this question is 6% of category value). If the plant design is to be modified many times during the project, it is an evolving type of process, which is not a very good candidate for modularization. Modularization requires an early freeze in design to take advantage of parallel construction (versus sequential construction using conventional methods).

THE PROJECT'S DESIGN PROCESS IS EXPECTED TO BE?
CHOICES: Non Evolving, Somewhat Evolving, Evolving

(3) **Labor-Related Factors:**

Jobsite Labor Force Impact (this question is 20% of category value). Modularization normally has the advantage over conventional construction of a reduced jobsite labor force, both in size and length of time the labor force is there.

HOW IMPORTANT IS THE REDUCTION OF THE JOBSITE LABOR FORCE IMPACT TO YOUR PROJECT?
CHOICES: Very Important, Somewhat Important, Unimportant

B.2.3 Economic Analysis

The economic analysis, which follows the detailed analysis, is important because economic and financial aspects of a modular construction project vary significantly from those of a conventional construction project. For example, the cash flow pattern for a modular project is different from that of a conventional project in that more expenses are incurred upfront because of the increased design and engineering, fabrication, and transportation effort. This analysis provides answers to questions related to the potential cost savings and reductions in schedule; and allows the user to create and maintain economic data tables to be used and modified as the project's economic evaluations change.

B.3 ADVANCED CONSTRUCTION TECHNOLOGY (ACT) EXPERT SYSTEM

The ACT Expert System is a computer program that assists the user in a decision making process that considers the use of complete or partial modular construction, and conventional construction. The ACT Expert System was written by Jacobs Applied Technology, Inc., a member of Jacobs Engineering Group [Jacobs Applied Technology, Inc., 1991]. It is intended for individuals who assist the owner in selecting construction methods. The ACT Expert System asks questions using a multiple choice format. It considers approximately 20 factors related to the project, the construction of the project, and the business aspects of the project. By analyzing the user's responses and an internal knowledge base, ACT evaluates the project, decides whether or not to use modular construction, and provides justifications for its decision. ACT is intended to be used with a book entitled "Advanced Construction Technology: Modular Design and Construction in Today's Process Industries" [Clement et al, 1989].

The ACT Expert System contains three sections, which include: (1) instructions and introduction, (2) evaluation and analysis, and (3) utilities. Section 1, Instructions and Introduction, provides instructions on the proper program operation and describes what the program can do and its importance within the industry. Section 3, Utilities, allows the user to register himself/herself as a program user. Section 2, Evaluation and Analysis, is the main section of the system; and it is the only section discussed here. Based on input from the user, ACT recommends the extent to which modular construction should be used on the project. The controlling factors considered in the evaluation and analysis can be placed into five categories: (1) plant location, (2) environmental /organizational, (3) plant characteristics, (4) project requirements, and (5) labor-related factors. Note the similarities between the ACT and MODEX categories.

Approximately 20 factors that are related to the project, the construction of the project, and the business aspects of the project are categorized into the five categories. Examples of factors with their corresponding category are listed below.

(1) The "plant location" category includes factors such as: (1) the "onsite land conditions" of the construction site (i.e., the availability of land, topography, etc.), and (2) the "onsite weather conditions."

(2) The "environmental/organizational" category includes factors such as: (1) "determining the work performed in shops," which refers to the percentage of the plant that is suitable for fabrication and assembly in fabrication shops, and (2) "reducing the time for onsite work," which refers to the possible reduction of time for onsite work enabled by: (1) transferring most of the onsite work to fabrication shops, and (2) postponing the required field mobilization.

(3) The "plant characteristics" category includes factors such as the: (1) "equipment fit, grouping, and system density" which refers to whether or not: (1) the equipment can "fit" within the module frame, (2) similar equipment can be grouped together to fabricate the module more efficiently, and (3) there could be efficient long term maintenance of the module's equipment due to its density and its accessibility; modularization becomes very efficient if the system's density is high because many small individual parts and components are assembled in fabrication shops.

(4) The "project requirements" category includes factors such as: (1) the quality assurance, and (2) safety.

(5) The "labor-related" category includes factors such as the availability of onsite skilled labor.

B.4 MODULE ASSESSMENT PROGRAM (MAP)

The Module Assessment Program, MAP, is a computer program that assists the user in a decision making process that compares modular construction with conventional construction. MAP was created by The Prosser Company, Inc. [The Prosser Company, Inc., 1992]. MAP poses approximately 20 multiple choice questions to the user on construction-related issues. The user answers the questions based on preliminary information about the project. The questions are answered on a scale of -12 to 18. A higher number leads to a stronger recommendation to use modular construction methods.

MAP's evaluation and analysis is discussed here. MAP's evaluation and analysis considers several controlling factors that can be placed into four categories: (1) general site conditions; (2) plant characteristics; (3) project requirements; and (4) labor-related factors.

Approximately 20 factors that are related to the project, and its construction are categorized into the four categories. Examples of factors with their corresponding category are listed below.

(1) The "general site conditions" category consists of "plant location" and "environmental /organizational" factors such as: (1) the "adequate onsite lay-down area," which refers to the need for sufficient lay-down (i.e., working and/or temporary storage) area for the modules, and (2) the "ease of transportation," which refers to various items such as: (1) the simplicity of the selected transportation method (i.e., is the site inaccessible; is the required equipment accessible), (2) the simplicity of transporting the required bulk commodities for the construction of a plant in a remote location, and (3) the simplicity of transporting the required construction equipment to remote sites.

(2) The "plant characteristics" category includes factors such as: (1) the "possibilities of plant duplication and relocation," which refers to the possibilities of using the same plant design for several plants located at different locations; this factor questions whether or not the owner intends to relocate the plant in the near future. The factor also considers how much duplication (or repetitiveness) of modules is occurring within the construction of a plant.

(3) The "project requirements" category includes factors such as: (1) budget control which include the long-term maintenance costs and low fabrication shop costs, (2) safety, and (3) quality control.

(4) The "labor-related" category includes factors such as the: (1) "availability of onsite skilled labor," and (2) "size of local pool," which refers to the possible reduction of both the size and time the labor force is onsite.

Upon completion of the analysis, MAP recommends a construction method for the project. If the total score for all questions is between -12 and 57, MAP suggests that there is little potential for modular construction in the project; and thus, it recommends that conventional construction be used. If the total score is between 58 and 128, MAP suggests that there are potential advantages in using modular construction, but recommends that further analyses be performed to determine the extent of modularization. If the total score falls in the range of 128 to 198, MAP suggests that modular construction is advantageous for the project; and thus, recommends the use of modular construction.

B.5 COMPARISON OF MODEX, ACT, AND MAP

The previous three sections reviewed MODEX, ACT, and MAP. The review identified controlling factors involved in considering modular construction. Tatum et al [1987] identify several factors that should be addressed when considering modularization; these factors include: (1) plant location, (2) plant characteristics, (3) labor-related factors, (4) site infrastructure requirements, (5) project risks, and (6) owner's knowledge and acceptance of modular construction methods. The factors identified by Tatum et al. are similar to those considered by the three computer programs. The common factors between the three computer programs are categorized into five categories: (1) plant location, (2) environmental/organizational, (3) plant characteristics, (4) project requirements, and (5) labor-related factors. The following seven categories discuss the factors in these five categories as well as the factors in two other categories that only MODEX considers: (1) project risks, and (2) economic evaluation.

B.5.1 Plant Location Factors

Table B.1 lists specific factors in the "plant location" category. The first two factors are considered as controlling factors by all programs. The next two factors are considered by only MODEX and MAP; and the last factor is considered by only MODEX. Descriptions of these factors are presented below.

- The "onsite land conditions" factor refers to the need for flat, non-congested, and non-hazardous topography, which is required for onsite work. Both the availability and conditions of the land are factors. The existing buildings and their influence on the new construction are also considered.

- The "onsite weather condition" factor is important; if the onsite weather conditions are extremely hostile, modular construction is often used because conventional construction may not allow completion of the project within the specified schedule and budget.

- The "adequate onsite lay-down area" factor refers to the need for sufficient lay-down (i.e., working and/or temporary storage) area for the modules.

- The "ease of transportation" factor refers to various items: (1) the simplicity of the selected transportation method (i.e., is the site inaccessible; is the required equipment accessible), (2) the simplicity of transporting the required bulk commodities and construction equipment to the construction site in a remote location. If transporting the required bulk commodities for a conventional construction project is not feasible, modular construction can be a practical construction method. However, if transporting modules for a modular project becomes impractical or infeasible, modular construction is not the best construction method.

- The "preparation for accessing the site" factor refers to the site preparation required to deliver the modules onsite; at times, the construction of temporary access roads and/or the retrofit of existing bridges is required to deliver the module to its final destination.

Table B.1
Plant Location Factors

PLANT LOCATION FACTORS	MODEX	ACT	MAP
Onsite land conditions	X	X	X
Onsite weather conditions	X	X	X
Adequate onsite lay-down area	X		X
Ease of transportation	X		X
Preparation for accessing the site	X		

B.5.2 Environmental/Organizational Factors

Table B.2 lists specific factors in the "environmental/organizational" category. The three programs consider eight controlling factors in this category. Only two of these factors are considered by more than one program. The remaining six are considered by only one program. Descriptions of these factors are presented below.

- The "ability to freeze the design" factor refers to committing to a module design in order to maintain the construction schedule. Modularization is more efficient if the design can be "frozen;" the design should not continue to evolve throughout the project.

- The "obtaining benefits from an early startup" factor refers to whether or not the project can benefit from starting early; the possible benefits derived from an early startup should be identified. In many conventional projects, construction work begins after the permits have been acquired. However, in a modular project, one can begin fabrication of the modules before or concurrent to permit acquisitions. Starting a project early can equate to early completion of the project, which in turn, can provide a better rate of return on investment.

- The "constructing for current needs" factor refers to the capability of reducing the project scope and building only what is currently in need. Not constructing for future building needs can equate to: (1) savings in cost, and (2) elimination of under-utilization of plants for the first few years.

Table B.2
Environmental/Organizational Factors

ENVIRONMENTAL/ORGANIZATIONAL FACTORS	MODEX	ACT	MAP
Ability to freeze the design	X		X
Obtaining benefits from an early startup	X		X
Constructing for current needs			X
Determining work to be performed in shops		X	
Reducing the time for onsite work		X	
Identifying the possible delays		X	
Identifying the restraints on foreign labor	X		
Owner's understanding of modular construction	X		

- The "determining work to be performed in shops" factor refers to the percentage of the plant that is suitable for construction in fabrication shops.

- The "reducing the time for onsite work" factor refers to the possible reduction of time for the required onsite work by: (1) transferring most of the onsite work to fabrication shops, and (2) postponing the required field mobilization.

- The "identifying possible delays" factor refers to the possible delays that can occur during the project, and the potential costs of these delays.

- The "identifying the restraints on foreign labor" factor refers to the fact that some governments may require the use of local labor because it stimulates their economy; some governments may also place restrictions on the amount of onsite work because of the potential pollution and other environmental impacts.

- The "owner's understanding of modular construction" factor refers to characteristics of modular construction that the owner should be aware of: for example, modular construction: (1) introduces innovative construction methods, (2) involves more detailed planning, (3) imposes design constraints early in the project, (4) requires that the owner be involved with both the engineering and construction firms throughout the project, and so on.

B.5.3 Plant Characteristics Factors

Table B.3 lists specific factors in the "plant characteristics" category. The three programs consider eight controlling factors in this category. The first two are considered by all the programs. The next factor is considered by two of the programs; and the remaining factors are considered by at least one program. Descriptions of these factors are presented below.

Table B.3
Plant Characteristics Factors

PLANT CHARACTERISTICS FACTORS	MODEX	ACT	MAP
Possibilities of plant duplication & relocation	X	X	X
Equipment fit, grouping, and system density	X	X	X
Plant height	X	X	
Piping size and metallurgy		X	
Characteristics of the module enclosure		X	
Physical design constraints	X		
Protection of proprietary design	X		
Quality requirements during fabrication	X		

- The "possibilities of plant duplication and relocation" factor refers to the possibility of using the same plant design for several plants located at different locations; and also refers to whether or not the owner intends to relocate the plant in the near future. This factor considers how much duplication (or repetitiveness) of modules occurs in the construction of the plant.

- The "equipment fit, grouping, and the system density" factor refers to whether or not: (1) the equipment can "fit" within the module frame, (2) similar equipment can be grouped together to fabricate the module more efficiently, and (3) there could be efficient long term maintenance of the module's equipment due to its density and its accessibility. Modularization becomes very efficient if the system's density is high.

- The "plant height" factor refers to how high the plant is expected to be. Modularization can be advantageous if the height of the module is moderately high because it can transfer most of the high work to ground level.

- The "piping size and metallurgy" factor refers to the fact that modularization may be more advantageous if the piping is small since components can be assembled offsite more efficiently; the piping metallurgy is a factor because some piping material is more easily fabricated indoors in a controlled environment rather than onsite.

- The "characteristics of the module enclosure" factor refers to the module enclosure that is required.

- The "physical design constraints" factor refers to the possibility of having equipment arrangements that are not suited for modularization (i.e., large equipment at very high elevations).

- The "protection of proprietary design" factor refers to the fact that a plant's proprietary design would be fabricated more securely in fabrication shops rather than on an open construction site.

- The "quality requirements during fabrication" factor refers to the degree of quality and cleanliness that is required during the fabrication process.

B.5.4 Project Requirements Factors

Table B.4 lists specific factors in the "project requirements" category. Although a "project requirements" category is not included in the MODEX package, the three factors in Table B.4 are considered by MODEX within other categories of controlling factors. For example, cost factors are addressed in the "labor-related" category; and quality and safety factors are addressed in the "project risks" category. These MODEX factors are shown here to simplify the comparison with ACT and MAP. Thus, all of the programs considered the three factors included in this category. The programs also consider more specific factors within the cost area, as shown in the table.

Table B.4
Project Requirements Factors

PROJECT REQUIREMENTS FACTORS	MODEX	ACT	MAP
Cost			
· long-term maintenance costs			X
· low-cost assembly labor	X		X
· field labor rates	X	X	
· transportation costs		X	
Quality	X	X	X
Safety	X	X	X

B.5.5 Labor-Related Factors

Table B.5 lists specific factors in the "labor-related" category. Some "labor-related" factors (e.g., assembly labor costs, field labor costs) were discussed in the "project requirements" category to simplify the comparison. However, other specific factors that the programs consider are shown here. All the factors are considered by at least two programs. Descriptions of these factors are presented below.

Table B.5
Labor-Related Factors

LABOR-RELATED FACTORS	MODEX	ACT	MAP
Availability of onsite skilled labor	X	X	X
Size of labor pool	X		X
Amount of assembly labor	X		X

- The "availability of onsite skilled labor" factor refers to whether or not there is an adequate force of skilled labor onsite to construct the project, while still maintaining the required: (1) quality in the work, and (2) project schedule.

- The "size of labor pool" factor refers to the possible reductions of both the size of the labor force and the time that the labor force is onsite.

- The "amount of assembly labor" factor refers to the degree of detailed assembly labor required for piping, and electrical systems; instrumentation, and so on. Modularization can be advantageous if the project requires significant detailed and assembly work because it can be performed in more controlled conditions in fabrication shops.

B.5.6 Project Risks Factors

MODEX considers several specific factors in the "project risks" category. Two "project risks" factors (e.g., safety and quality) were discussed earlier within the "project requirements" category. Other factors that MODEX considers in the "project risks" category are: (1) "work in parallel," (2) "additional requirements in planning," (3) "equipment testing in fabrication shops," and (4) the "amount of experience fabricating, engineering, and construction." The definitions of these factors are presented below.

- The "work in parallel" factor refers to the amount of work that can occur simultaneously in the fabrication shop as well as onsite.

- The "additional requirements in planning" factor refers to measuring how much additional upfront planning is required for activities such as: (1) transportation, (2) design and engineering, and so on.

- The "equipment testing in fabrication shops" factor refers to how much equipment can be tested in the fabrication shops.

- The "amount of experience in fabricating, engineering, and construction" factor refers to the amount of experience that the fabricator and the selected engineering and construction firms have in modular construction. Because of the complexity of modular construction projects, the fabricators and the engineering and construction firms involved must have a thorough understanding of modular construction practices.

B.5.7 Economic Evaluation Factors

MODEX considers a specific factor in the "economic evaluations" category. The description of this factor is presented here.

- The "knowledge of the construction schedule and cost" factor refers to the fact that both the conventional construction schedule and cost as well as the modular construction schedule and cost should be known in order to compare the possible benefits in reducing the schedule and cost.

B.6 SUMMARY

This chapter has identified the controlling factors that are considered by three computer programs, MODEX, ACT, and MAP, that are used to assess the use of modular construction for industrial and chemical/process plants. The following is a summary of these controlling factors:

(1) **Plant location factors** include the following: (1) the onsite land conditions, (2) the onsite weather condition, (3) the adequate onsite lay-down area, (4) the ease of transportation, and (5) the preparation for accessing the site.

(2) **Environmental/organizational factors** include the following: (1) ability to freeze the design, (2) obtaining benefits from an early startup, (3) constructing for current needs, (4) determining work to be performed in shops, (5) reducing the time for onsite work, (6) identifying possible delays, (7) identifying the restraints on foreign labor, and (8) owner's understanding of modular construction.

(3) **Plant characteristics factors** include the following: (1) the possibilities of plant duplication and relocation, (2) the equipment fit, grouping, and the system density, (3) the plant height, (4) the piping size and metallurgy, (5) the characteristics of the module enclosure, (6) the physical design constraints, (7) the protection of proprietary

design, and (8) the quality requirements during fabrication.

(4) **Project requirements factors** include the following: (1) cost, (2) quality, and (3) safety.

(5) **Labor-related factors** include the following: (1) the availability of onsite skilled labor, (2) the size of local pool, and (3) the amount of assembly labor.

(6) **Project risks factors** include the following: (1) the work in parallel, (2) the additional requirements in planning, (3) the equipment testing in fabrication shops, and (4) the amount of experience in fabricating, engineering, and construction.

(7) **Economic evaluations factors** include the following knowledge of the construction schedule and cost.

Glaser et al [1983] stated that "each modularization project will have its own peculiar characteristics which must be evaluated in reaching a 'go or no go' decision." Careful evaluation and analysis of each project's individual factors can ensure a good decision based on specific project information. MODEX, for example, focuses on "three major issues: (1) if the plant can be modularized, (2) if the plant should be modularized, and (3) the potential savings of modularization" [Fisher et al, 1992]. Focusing on these issues can assist the owner in selecting appropriate construction methods.

Although these computer programs have been developed for the construction of industrial and chemical/process plants, these programs can be used, to a certain extent, for other types of construction as well. If the type of construction is something other than industrial construction, some controlling factors will not be applicable, such as the questions from the plant characteristics category. But the questions from other categories such as plant location, project risks, labor-related factors, and so on can apply to non-industrial projects. Industrial construction has clearly taken advantage of modular construction. Zambon et al [1982] stated "there is no doubt that the large-scale modular approach has found a permanent place in the process industry."