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# A review and analysis of modular construction practices

Mayra L. De La Torre  
*Lehigh University*

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**AUTHOR:**

**De La Torre, Mayra L.**

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Modular Construction  
Practices**

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**A REVIEW AND ANALYSIS OF  
MODULAR CONSTRUCTION PRACTICES**

by

Mayra L. De La Torre

A Thesis

Presented to the Graduate and Research Committee

of Lehigh University

in Candidacy for the Degree of

Masters of Science

in

Civil Engineering

Lehigh University

This thesis is accepted and approved in partial fulfillment of the requirements for the Master of Science.

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Date

Dr. Richard Sause  
Thesis Advisor

---

Dr. Le Wu-Lu  
Chairperson of Department

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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 thesis achieves the first objective of this research project.

The thesis has two objectives: (1) to study of 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 were identified from using current modular construction practices. The following advantages were 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 were identified from this study 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 more complex than conventional construction activities because of the interdependency among the activities, and because many of the activities are performed earlier in the project.

Essential characteristics of successful modular projects were also identified in this research. The characteristics were categorized within three areas: (1) project management, (2) design and engineering, and (3) fabrication. An example of a project management characteristics includes obtaining a module task team; an example of a design and engineering characteristics includes designing the modules early; and an example of a fabrication characteristics includes using standardization in fabrication shop fabrication and assembly.

Opportunities to advance modular construction technology and methodology are identified. They are presented as several areas requiring future development to take further advantage of modular construction practices.

# **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 the objectives of: (1) identifying opportunities for using modular construction methods for building frame systems, and (2) developing 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, issues, and opportunities, (2) 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, (3) study the application of current modular construction practices to opportunities identified in Task 2, (4) develop new modular construction concepts (technology and methodology), and (5) develop methods for selecting appropriate levels of prefabrication and preassembly and for designing prefabricated and preassembled components. This study addresses Task 1 of the research project.

### **1.2 RESEARCH OBJECTIVE**

The objective of this thesis is to complete the first task 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 joined 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-scaled 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: (1) bridge, (2) industrial, (3) light industrial/commercial, (4) prison, (5) residential, and (6) ship; and from a variety of perspectives, including: (1) fabricator, (2) project manager, (3) architect, (4) structural engineer, (5) engineer, (6) erector, and (7) manufacturer. The purpose of the investigation is to report on the state of modular construction practices 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 both 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 six different types of construction: (1) bridge, (2) industrial, (3) light industrial and commercial, (4) prison, (5) residential, and (6) ship. Examples of modular construction projects and general modular construction practices are identified from the interviews. The companies that are interviewed ranged 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 those of conventional construction to identify important differences in a project's planning 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 thesis consists of 8 chapters, which report on the state of modular construction practices. This 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 consisting of 31 interviews conducted with selected industry representatives. 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; it discusses the technology and methodology that should be developed in order to exploit some existing opportunities in modular construction. Chapter 8 presents a summary of this report, its conclusions, and provides a discussion of future research work.

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 the design and construction of 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 Liquefied 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.

**Table 2.1**  
**Potential Broad Advantages and Disadvantages**  
**of Modular Construction**

<b><u>ADVANTAGES</u></b>	<b><u>DISADVANTAGES</u></b>
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

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.

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 also 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) performing the design and procurement simultaneously, (2) working 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, the design and procurement activities usually overlap. This overlap is possible because the general contractor of a modular construction project is involved at an early point in the project, during the design and engineering phase, rather than becoming involved later, such as 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 to 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 of activities, (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 Construction Effort**

The need for additional construction 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 conventional construction project [Mullet, 1984a].

The additional design and engineering activity is needed to avoid later design changes, because an assembled module must have sufficient strength, stiffness, and stability to withstand the transportation, handling, and erection loads, and possibly because of the connections needed 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 of Activities**

As the interdependence of construction activities increases, the need for communication and control mechanisms between activities increases. For example, 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.

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.

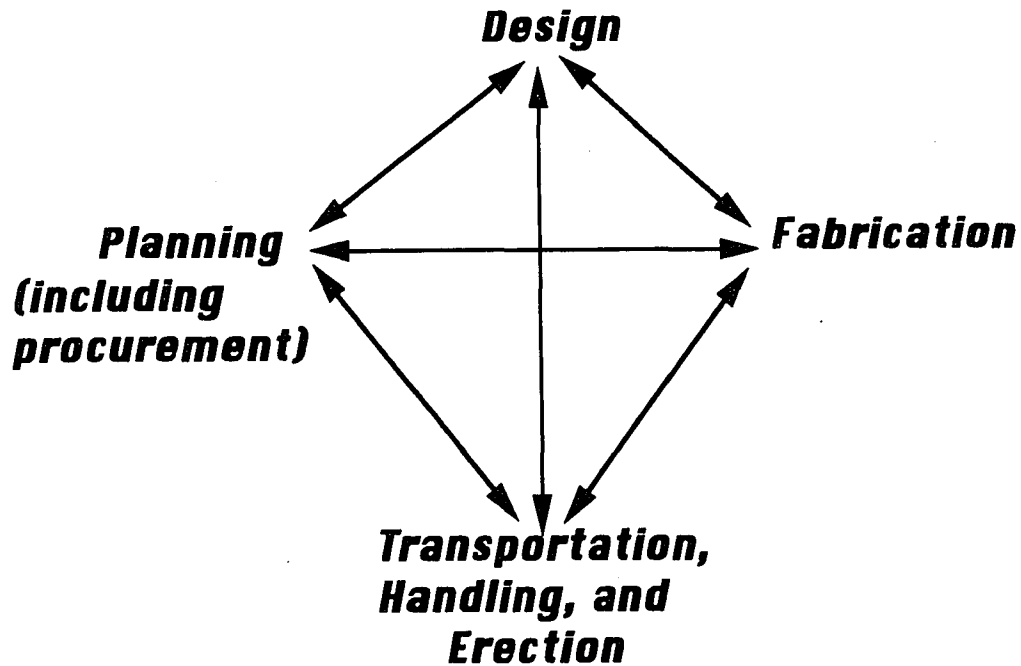


Figure 2.1 Coordination among Modular Construction Activities

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 sets 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].

The coordination between the module fabrication and transportation is also important. The means of transportation, for example, must be available upon completion of module fabrication. The coordination between the transportation, handling, and erection increases because the handling equipment used in modular construction 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 foreign inspection. 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 (to approximately \$100,000), 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. Hesler [1990] states that the first modular design by a particular team "can be 50-60% more than conventional construction design, particularly if the job is done well. This, of course, is only 50-60% more (than conventional construction design) or 12% of the total installed cost."

### **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 must 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 all modular projects, and (2) the advantages and disadvantages unique to specific modular projects.

The advantages common to all modular projects can include: (1) improved safety, and (2) reduced social and environmental impact. The disadvantages common to all modular projects can include: (1) the need for additional material, (2) the need for additional construction effort, (3) the need for additional coordination of activities, and (4) the increased risk of modular construction. The advantages unique to specific modular projects can include: (1) reduced cost, (2) reduced schedule, (3) increased quality, and (4) increased possibility of construction; and a disadvantage unique to specific modular projects can include 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 investigations of modular construction technology and methods must be made to ensure that the project will be among the successful modular construction projects.

# Chapter 3

## Review of Modular Construction Activities

### 3.1 INTRODUCTION

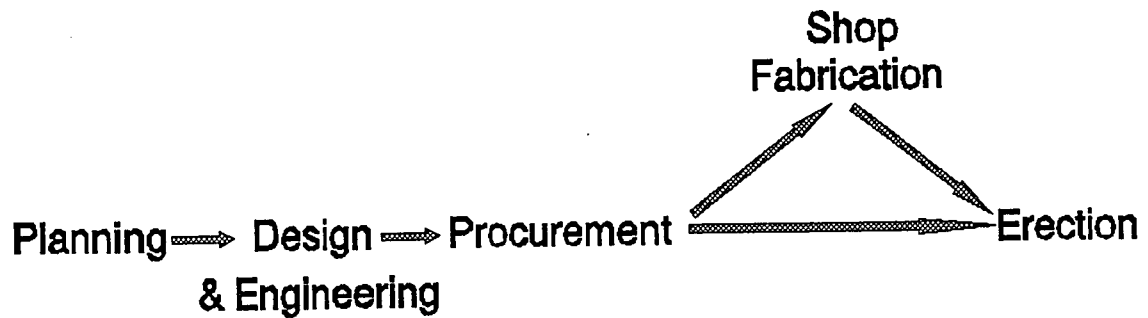
This chapter discusses five activities of modular construction projects: (1) planning, (2) design and engineering, (3) procurement, (4) fabrication, and (5) transportation, handling, and erection, as shown on Table 3.1. Of the five, planning is the most significant activity in a modular construction 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**

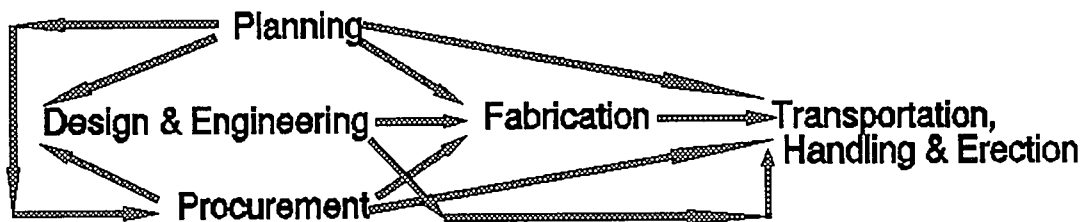
<b>MODULAR CONSTRUCTION</b>				
<b>Planning</b>	<b>Design &amp; Engineering</b>	<b>Procurement</b>	<b>Fabrication</b>	<b>Transportation Handling, &amp; Erection</b>

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 most of the design and engineering, and construction activities are performed in sequential order, the activities for modular construction involve additional interdependency since these activities can be performed in parallel in various fabrication shops and/or 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 discusses activities that show why 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 since minimizing costs is an objective of project control. 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 changes in costs involved in modular projects.

In addition to the elements shown in Table 3.1 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].

- ***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

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

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

**Legend**

- + costs that increase with modular construction
- costs that decrease with modular construction
- = costs that are apparently the same for both modular and conventional construction

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 & sea fastening
- 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.

**(1) 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.

**(2) 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 additional complexity, 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 they 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 (e.g., its location) 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 includes the shop location. The locations of the fabrication shops should complement the selected method of module transportation since an appropriate fabrication shop location can drastically reduce

transportation costs [Carreiro, 1968]. 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.

Important shop characteristics other than location include proper working conditions, appropriate shop equipment, and an adequate labor force. In addition, large assembly (i.e., working) 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 are significantly interdependent and 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.

**(3) 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 efficiently 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.

**(1) 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.

**(2) 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].

Specific highway regulations, which set limitations on module dimensions, affect the transport of modules by land. Each state in the United States has its own specific highway regulations that regulate the transportation of large structures. For example, height restrictions reflect the potential conflicts with overhead utilities, bridges, and other common vertical barriers. These height restrictions affect the modular housing industry by establishing a limit on the height of modular homes. As a result, many modular homes have flat roofs to stay under this height limitation. However, these height regulations 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 and regulations, 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 route [Sullivan et al, 1980]. Although all states have their own transportation restrictions, states are working with the modular housing industry to allow for the transport of larger modules on highways.

- *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 module size restrictions, highway restrictions, and other concerns including overhead utilities, bridges, vertical barriers, slopes, and so on. 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 performed. For example, helicopters not only deliver 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 used two of the three transportation methods to deliver modules from the fabrication shops to the construction site; these examples typically involved fabrication shops that were at close proximity to water, and a construction site that was inland. Thus, both water and land methods were required.

**(3) 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                      | · Piling requirements    |
| · Pile cap construction           | · Construction drainage  |
| · Underground piping connections  | · Electrical connections |
| · Site appearance & accessibility | · 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. The management of design and engineering activities in a modular construction project is affected by: (1) design sequence, and (2) design 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 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.

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) loading points, (2) acceleration forces, and (3) weight and stiffness. The loading 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."

Three aspects of fabrication are discussed below: (1) fabrication and assembly, (2) quality control, and (3) testing.

### **3.4.1 Fabrication and Assembly**

Fabrication and assembly can be categorized into two areas: (1) management, and (2) 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 can 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

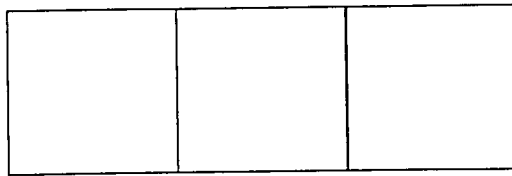
in conventional construction because most of the work is conducted in fabrication shops. The labor force in a fabrication shop can be trained and controlled more efficiently and effectively than in the field. The labor force in a shop environment tends to be permanent, and can be more skillful and stable 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/processing 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 as opposed to its upright 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 on 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."

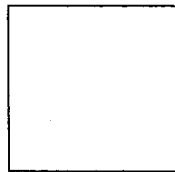
- *Working in Parallel:* Fabrication and assembly can benefit from performing work in parallel rather than in series as in conventional construction. Working in parallel provides the opportunity for fabrication and assembly to occur at various fabrication shops for the same project. In addition, various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



**PLAN VIEW**

(module on its side)

\* All work is performed at ground level



**PLAN VIEW**

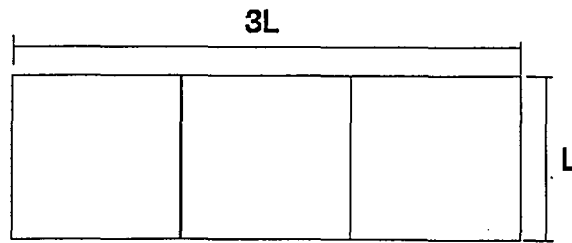
(module in an upright position)

\* 1/3 of the work is performed at ground level

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

**3.4.2 Quality Control and Module Testing**

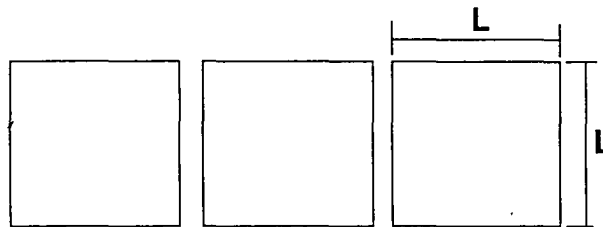
Quality control and module testing is discussed in this section. When module assembly occurs in a fabrication shop, quality control can be provided as the modules advance through the assembly phases. Shop fabrication and assembly can enhance the quality of a project by: (1) using module inspectors continuously in the fabrication shops, (2) taking advantage of the more controlled environment in fabrication shops, (3) using



**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)

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. These tests can



be performed before the completed modules leave the fabrication shops. 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 should be permanently connected to conclude the construction of the structure. 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 design modules with sufficient structural integrity during transportation, handling, and erection, and possibly because of the connections needed 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 et al [1994a] provide a detailed presentation of the

information gathered from these thirteen companies.

**Table 4.1**  
**Companies that Provided Information on Specific Projects**

<b>COMPANY (PROJECT NAME)</b>	<b>ROLE</b>
(1) Falcon Steel Company, Inc. ("Tribeca" Bridge)	Fabricators
(2) Allied Steel Products Corporation (Steam Stripper)	
(3) Eastern Exterior Wall Systems, Inc. (EEWS, 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. (ERM, Inc.) (Steam Stripper)	
(1) Pierce-Goodwin-Alexander-Linville (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.

**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. (ERM, Inc.)
	1	Eastern Exterior Wall Systems, Inc.
	1	Quickway Metal Fabricators, Inc.
Prison		Gate Concrete Products
		Pierce-Goodwin-Alexander-Linville
		Sverdrup Civil, Inc.
	1	The Consulting Engineers Group, Inc.
	1	Tindall Concrete Virginia, Inc.
<b>TOTAL</b>	9	

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

**Table 4.3**  
**Companies that Provided General Information on Modular Construction**

<b>COMPANY (SPECIFIC TYPE OF CONSTRUCTION)</b>	<b>ROLE</b>
(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)	

LEGEND

MCPC            Modular Chemical Plant Construction  
PEMB            Pre-Engineered Metal Building

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 et al [1994b] provide a detailed presentation of the information gathered from these eighteen

companies.

**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

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.

## **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 included: (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**

<b>TYPE OF CONSTRUCTION</b>	<b>PROJECT SPECIFIC</b>	<b>GENERAL</b>	<b>TOTAL</b>
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
<b>TOTAL</b>	<b>13</b>	<b>18</b>	<b>31</b>

**Table 4.6**  
**Roles of the Companies/Individuals Interviewed**

<b>ROLE</b>	<b>PROJECT SPECIFIC</b>	<b>GENERAL</b>	<b>TOTAL</b>
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
<b>TOTAL</b>	<b>13</b>	<b>18</b>	<b>31</b>

### **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 unswayed construction difficult because of rough terrain and severe weather, and there was a lack of skilled labor.

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 unswayed. 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. The type of construction that the two individuals discussed were 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 company's proximity to water, and the traffic control expenses that would have been required to truck the module through downtown New

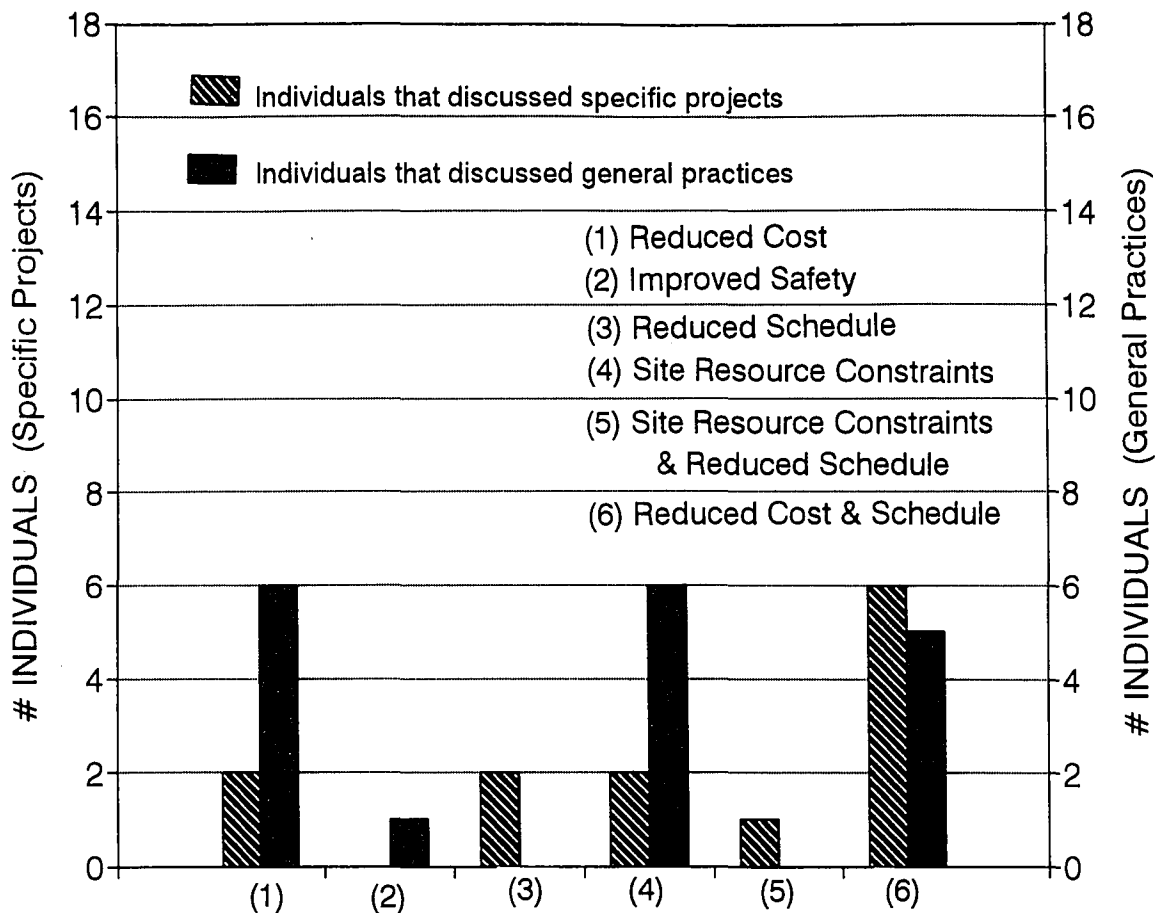


Figure 4.1 Individuals that Identified Driving Forces

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 Greenville 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 general modular construction practices. 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 modules, 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.

#### **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 et al [1994a, 1994b] include a more detailed discussion of these specific benefits.

**Table 4.7**  
**Relationships Between Driving Forces and Construction Types**

Type of Construction	DRIVING FORCES					
	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
<b>TOTAL</b>	31					

LEGEND

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

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

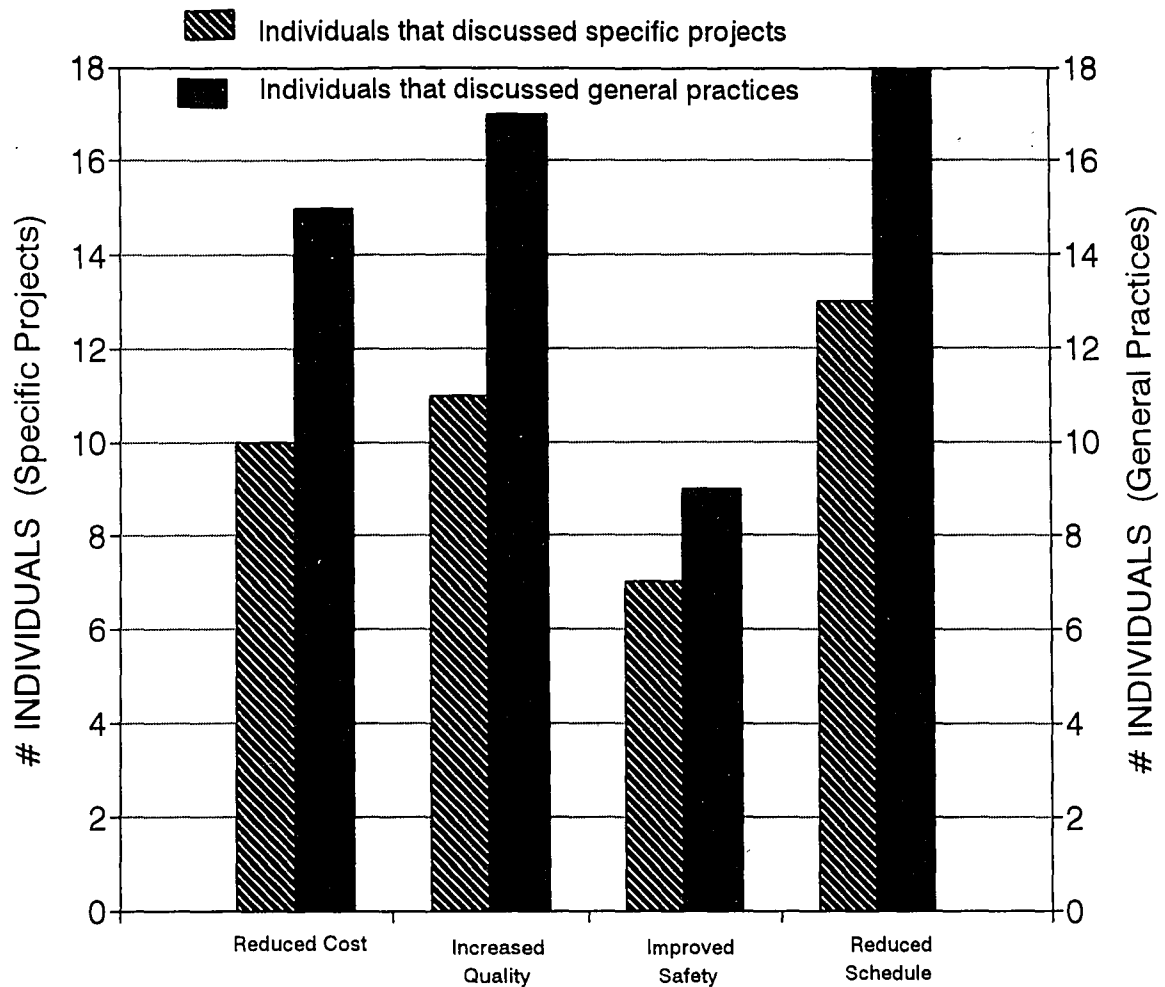


Figure 4.2 Individuals that Identified Broad Advantages

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.

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, which allows 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 the 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 construction activity, 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 Construction Activity**

The need for additional construction activity was considered to be a broad disadvantage of modular construction methods by all of the 31 individuals interviewed. The specific activities that increase in scope 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 for their projects increased because of a need for more effort in: (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 interviewed 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).

One individual mentioned that an increase in the procurement activity was needed

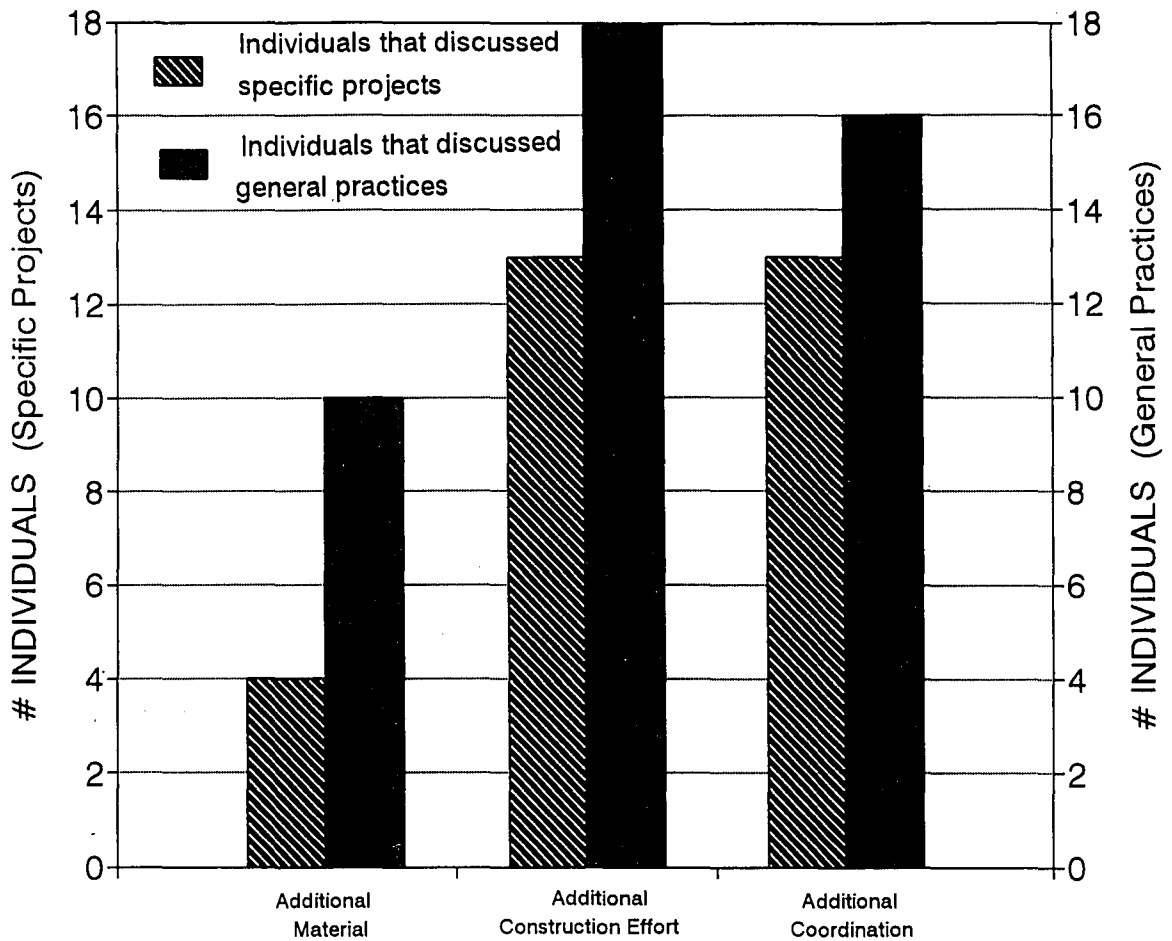


Figure 4.3 Individuals that Identified Broad Disadvantages

due to the additional fabrication and assembly activities and vendors involved. He stated that it is essential to know each vendor'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 hookups for 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.

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 4.8**  
**Relationships Between the Number of Major Dimensions and Transportation**

CONSTRUCTION TYPE	TRANSPORTATION MODE			
	PROJECT SPECIFIC		GENERAL	
	LAND	WATER	LAND	WATER
Bridge	3-D			
Industrial	3-D		3-D	
Light Industrial/Commercial	3-D		2-D	
	2-D			
	3-D			
Prison	3-D		3-D	
Residential			3-D	
			3-D	
Ship			3-D	

Table 4.9 shows the relationship between the transportation mode and the construction type 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.

**Table 4.9**  
**Relationships Between the Modules and the Transportation Methods**

CONSTRUCTION TYPE	TRANSPORTATION MODE			
	PROJECT SPECIFIC		GENERAL	
	LAND	WATER	LAND	WATER
Bridge	1S			
Industrial	3 S		1G*	
			5G	
Light Industrial/Commercial	2S		5G	
	1S			
	1S			
Prison	1S		1G**	
	4S		1G	
Residential			1G	
			2G	
Ship			2G	
<b>TOTAL</b>	<b>13</b>		<b>18</b>	

LEGEND

- 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 and vendors 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. The project 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) review of advantages and disadvantages of modular construction, (2) review of modular construction activities, (3) review of current modular construction practices, and (4) a review of the essential characteristics of successful modular projects.

### 6.2 ADVANTAGES AND DISADVANTAGES OF MODULAR CONSTRUCTION

Several advantages and disadvantages were identified from reviewing modular construction activities. This section summarizes the advantages and disadvantages of modular construction identified in Chapter 2, and shows that they are consistent with the findings from the interviews in Chapter 4.

· *Advantages:* A broad advantage is one of the general benefits derived from using modular construction. Six broad advantages 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. For example, reduced cost was derived from: (1) the ability to work indoors in fabrication shops in a more controlled environment, rather than onsite where unfit construction conditions may be present, and (2) the ability to reduce the cost of 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. Based on the interviews, increased quality is a broad advantage that is possible because the majority of the fabrication and assembly work is performed indoor in a more controlled environment.

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.

Table 6.1 shows the relationship between the broad advantages and the specific benefits that lead to these broad advantages, based on the industry survey.

*Disadvantages:* A broad disadvantage is a drawback that results from the use of modular construction. Six broad disadvantages were identified from the literature and industry survey (interviews): (1) the need for additional material, (2) the need for

**Table 6.1**  
**Broad Advantages and their Specific Benefits**

<u>SPECIFIC BENEFITS</u>	<u>BROAD ADVANTAGES</u>			
	<u>RC</u>	<u>IQ</u>	<u>IS</u>	<u>RS</u>
Working in a more controlled environment	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>
Reducing the fabrication and assembly schedule	x			<b>X</b>
Providing for increased quality		<b>X</b>		x
Reducing the cost of fabrication and assembly	<b>X</b>			
Using a single responsible source in contracting				<b>X</b>
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                   |                        |
| <b>X</b> Specific benefits that are primary contributors to the broad advantages |                        |

additional construction 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 need for additional construction effort and coordination appears to be more prevalent, as approximately 90% of the individuals interviewed identified them as drawbacks to modular construction. The need for additional construction effort arises from the need for effort 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: (1)

the interdependency of activities, and (2) the need for additional construction activities. Many activities in modular construction are performed in parallel rather than in series as in conventional construction. Thus, 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 disadvantages, they did not emphasize them as broad disadvantages of modular construction. 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 modular 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 additional design effort is needed to provide modules with structural integrity for transportation, handling, and erection. The design effort is also increased because of the connections needed for modular construction. The design and engineering activities that increase in complexity include: (1) tolerances and connections, (2) designing for stability, and structural integrity, and (3) satisfying 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 to the 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**

<u>SPECIFIC CHANGES IN FABRICATION</u>	<u>DEGREE OF CHANGE</u>
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	"
Onsite construction labor	"
Temporary labor force (onsite)	"
Onsite fabrication and assembly	"

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

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**

<u>SPECIFIC CHANGE IN ERECTION</u>	<u>DEGREE OF CHANGE</u>
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 CURRENT DRIVING FORCES OF MODULAR CONSTRUCTION**

This section summarizes the information on the driving forces of modular construction identified from the industry survey. Driving forces of modular construction were identified by the individuals interviewed in the industry survey. Six driving forces were identified by the individuals interviewed: (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, many construction projects are forced to use modular construction methods to reduce the cost, or reduce both the cost and schedule of the project. Many projects use modular construction methods to overcome a deficiency of site resources such as space, labor, and an appropriate construction environment. These projects may not be feasible with conventional construction.

## **6.5 ESSENTIAL CHARACTERISTICS OF SUCCESSFUL MODULAR CONSTRUCTION PROJECTS**

In order for modular construction to be implemented with success, the modular projects 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 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**

### **7.1 INTRODUCTION**

This chapter identifies opportunities to advance modular construction technology and methodology. Current examples of modular construction technology and methodology are presented in De La Torre et al [1994c]. "Modular construction technology" refers to: (1) new systems and components for constructed facilities, and (2) 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 are discussed below. In order 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 OPPORTUNITIES TO ADVANCE MODULAR CONSTRUCTION TECHNOLOGY**

Advances in modular construction technology can be made from development of:

(1) new modules and components for constructed facilities, and (2) new construction equipment. In general, advances can be made by developing concepts for new, larger modules and components that can be shop-fabricated, transported, and erected; and by developing improved transportation, handling, and erection technology for large modules and components. This section identifies opportunities to advance technology in several different industries including: (1) ship, (2) bridge, (3) residential, and (4) building frame construction. It also discusses opportunities for advancing technology in the placement of underground utilities.

• ***Ship Construction:*** The shipbuilding industry takes advantage of modular construction technology by means of "block" construction techniques. Tatum et al [1987] state that "the concept is essentially the same as modularization: move major sections of the work to where it is most efficiently performed, then moved the product of the work to the facility site, be it a gas plant, an offshore platform, or a ship."

Okayama [1982] indicates that "shipbuilding methods have consistently become more productive during the past three decades because of the change from traditional system-oriented processes to the following zone-oriented processes: (1) hull block construction method, (2) zone outfitting method, and (3) zone painting method." Opportunities to advance modular construction technology for shipbuilding include:

(1) Increasing modularization by requiring vendors/suppliers to provide less individual components, and more complete modules.

(2) Increasing the use of fabrication in controlled environments rather than inside ships where conditions may not be conducive to safe and efficient work.

• **Bridge Construction:** Bridge construction currently takes advantage of some modular construction. Many bridges use precast prestressed concrete I girders, prefabricated plate girders, prefabricated steel cables, prefabricated steel truss systems, and so on, which are fabricated and assembled in fabrication shops. The use of such prefabricated elements in bridge construction can significantly reduce onsite work. Opportunities to advance modular construction technology for bridge construction include:

(1) Increasing the use of mass-produced prefabricated components that are fabricated in "manufacturing" environments (e.g., standardized "manufactured" plate girders or bridge decks).

(2) Creating larger modular components, within the limitations of available transportation methods.

(3) Creating modular components that allow for efficient use of space during transportation (e.g., fabricating modules that can "stack" efficiently on a truck).

• **Residential Construction:** Residential construction frequently takes advantage of modular construction methods. The modular housing industry has successfully provided modular homes that resemble conventionally-built homes. Some modular homes use innovative "pop-out" roof designs to avoid noncompliance with highway height limitations. By transporting the home with a flat "pop-out" roof, and then on delivery, unfolding the roof, the home is made as attractive and functional as a conventionally-built home with a sloped roof. One opportunity to advance modular construction technology for residential construction is to:

(1) Develop home/building designs that do not waste space during

transportation by increasing the use of stackable 2-dimensional building components.

• ***Building Frame Construction:*** Building frame systems, such as those in industrial, light industrial, commercial, and prison construction, 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:

(1) Prefabricating extensive 3-dimensional modules for building frame systems rather than 1-dimensional (i.e., fabricated beams, columns, and braces) or 2-dimensional components (such as those used in pre-engineered metal buildings).

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

(3) Reducing the number of onsite connections and decreasing erection time.

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

(5) Increasing modularization by integrating the service (i.e., electrical, mechanical, plumbing, insulation, etc.) systems and building frame systems in the fabrication shops.

(6) Developing new building frame systems specifically for exploiting onsite preassembly methods.

• ***Placement of Utilities:*** The utility industries, to a certain extent, take advantage of modular construction practices in the placement of utilities. During site preparation work,

for example, many utility companies use prefabricated structures such as precast utility boxes, storm drain precast concrete manholes, prefabricated cable conduits, and so on. Standardization of these structures makes this prefabrication possible. Opportunities to advance modular construction technology for the placement of utilities include:

- (1) Increasing the standardization of required structures.
- (2) Creating more complete modules such as standardized concrete utility boxes that include the required conduit sections and cables in place.

### **7.3 OPPORTUNITIES TO ADVANCE 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) Developing methods and computer programs to evaluate the use of modular construction methods in the construction of light industrial and commercial facilities, housing, bridges, ships, prisons, etc.
- (2) Developing methods and computer programs to assist in the selection of

the best transportation method for modules that consider the module dimensions and weight and transportation economics.

(3) Developing methods and computer programs that perform detailed economic analyses of modular and conventional construction approaches for a project.

(4) Developing new concepts for innovative and productive management teams responsible for the planning and management of a modular project.

(5) Developing methods for identifying the extent of modularization that will make the project successful from the owner's business and/or financial perspective.

• ***Fabrication, Transportation, Handling, and Erection:*** Construction usually impacts the environment. Since modular construction transfers the majority of onsite work into fabrication shops, some of the environmental impacts can be reduced. For example, modular construction methods could allow buildings to be assembled and used, and then disassembled and relocated without producing demolition-related waste. In addition, opportunities to advance fabrication, transportation, handling, and erection methodology include:

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

(2) Fabricating and assembling the structure as close as possible to the construction site to reduce transportation effort.

(3) Increasing the use of onsite preassembly of components prior to erection.

## 7.4 SUMMARY

In summary, this chapter identifies opportunities to advance modular construction

technology and methodology. These opportunities can result in significant improvements in specific industries. For example, the building industry may be able to improve the cost, quality, safety, and schedule of building frame erection by developing and implementing advances identified here, such as the transportation of stackable components or increased use of onsite preassembly. Further work is needed to develop these potential advances.



# Chapter 8

## Summary, Conclusions, and Recommendations

### 8.1 SUMMARY

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 objective 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 methods were investigated for a wide variety of construction types, including: (1) bridge, (2) industrial, (3) light industrial/commercial, (4) prison, (5) residential, and (6) ship; and from a variety of perspectives, including: (1) fabricator, (2) project manager, (3) architect, (4) structural engineer, (5) engineer, (6) erector, and (7) 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 both 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, and reports, and books. The survey of industry included interviews with 31 companies within six different types of construction: (1) bridge, (2) industrial, (3) light industrial and commercial, (4) prison, (5) residential, and (6) ship. 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 those of conventional construction 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 Task 1.1 through 1.3.

Task 2 identified opportunities to advance modular construction technology and

methodology based on analysis of the findings from Task 1.

## **8.2 CONCLUSIONS**

### **8.2.1 Advantages and Disadvantages of Modular Construction**

Several advantages and disadvantages of modular construction were identified in Chapters 2 and 4. These are summarized in some detail in Chapter 6. Six broad advantages were 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 were identified from the literature and industry survey: (1) the need for additional material, (2) the need for additional construction 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 disadvantages, they did not emphasize them as broad disadvantages of modular construction.

### **8.2.2 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 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 among construction activities.

Planning is more involved and complex in modular construction than conventional construction because of the increased interdependency among construction activities. Design and engineering in modular construction is more complex because of the need to avoid the impact of design changes on the other construction activities, because additional design effort is needed to provide the modules with structural integrity for transportation, handling and erection, and because design effort is needed for the connections between modules. Procurement in modular construction is significantly interdependent with the other activities. In a modular project, procurement of design and engineering, fabrication, and 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 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. In one sense, erection may be less complicated, because the modules are often 100% complete upon delivery, and little onsite assembly is required. In another sense, erection may be more complicated in that larger, heavier, and more complex components are erected.

### **8.2.3 Driving Forces of Modular Construction**

Driving forces of modular construction were identified by the individuals interviewed in 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.

### **8.2.4 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.

## **8.3 RECOMMENDATIONS**

In Chapter 7, recommendations were made for further development needed to advance modular construction technology and methodology. "Modular construction

technology" refers to: (1) new systems and components for constructed facilities, and (2) 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.

### **8.3.1 Technology**

Advances in modular construction technology can be made through development of new modules and components for constructed facilities, and new construction equipment. The recommendations for advancing modular construction technology are organized according to the type of construction.

#### **• *Ship Construction:***

(1) Increasing modularization by requiring vendors/suppliers to provide less individual components, and more complete modules.

(2) Increasing the use of fabrication in controlled environments rather than inside ships where conditions may not be conducive to efficient productivity.

#### **• *Bridge Construction:***

(1) Increasing the use of mass-produced prefabricated components that are fabricated in "manufacturing" environments (e.g., standardized "manufactured" plate girders or bridge decks).

(2) Creating larger modular components, within the limitations of available transportation methods.

(3) Creating modular components that allow for efficient use of space during

transportation (e.g., fabricating modules that can "stack" efficiently on a truck).

• ***Residential Construction:***

(1) Develop home/building designs that do not waste space during transportation by increasing the use of stackable 2-dimensional building components.

• ***Building Frame Construction:***

(1) Prefabricating extensive 3-dimensional modules for building frame systems rather than 1-dimensional (i.e., fabricated beams, columns, and braces) or 2-dimensional components (such as those used in pre-engineered metal buildings).

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

(3) Reducing the number of onsite connections and decreasing erection time.

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

(5) Increasing modularization by integrating the service (i.e., electrical, mechanical, plumbing, insulation, etc.) systems and building frame systems in the fabrication shops.

(6) Developing new building frame systems specifically for exploiting onsite preassembly methods.

• ***Placement of Utilities:***

(1) Increasing the standardization of required structures.

(2) Creating more complete modules such as standardized concrete utility

boxes that include the required conduit sections and cables in place.

### **8.3.2 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:***

(1) Developing methods and computer programs to evaluate the use of modular construction methods in the construction of light industrial and commercial facilities, housing, bridges, ships, prisons, etc.

(2) Developing methods and computer programs to assist in the selection of the best transportation method for modules that consider the module dimensions and weight and transportation economics.

(3) Developing methods and computer programs that perform detailed economic analyses of modular and conventional construction approaches for a project.

(4) Developing new concepts for innovative and productive management teams responsible for the planning and management of a modular project.

(5) Developing methods for identifying the extent of modularization that will make the project successful from the owner's business and/or financial perspective.

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

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

(2) Fabricating and assembling the structure as close as possible to the



construction site to reduce transportation effort.

- (3) Increasing 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 a leading international supplier of industrial gases and related equipment, chemicals and environmental & energy systems.

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

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

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

- (3) **ALLIED STEEL PRODUCTS CORP.** is a fabricator of ferrous and non-ferrous materials and related equipment that has been in business for 47 years and has upheld a tradition in industry for on-time deliveries and quality.

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

- (4) **BATH IRON WORKS CORPORATION** is a company that provides full services to the shipbuilding industry (i.e. Navy) as well as the industrial industry. Some of Bath Iron Work's facilities include fabrication plants and assembly & pre-outfit buildings.

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

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

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

- (6) **BERKUS GROUP, ARCHITECTS** is a 25 year old architectural and planning firm based on Santa Barbara, CA. The firm has had extensive experience in the mobile and modular housing industries and has provided their services internationally.

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

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

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

- (8) **EASTERN EXTERIOR WALL SYSTEMS, INC.** is a manufacturing company that provides full services in design and installation of prefabricated exterior wall systems.

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

- (9) **ENVIRONMENTAL RESOURCES MANAGEMENT, INC. (ERM)** is an environmental consulting firm that provides full engineering and consulting services to industrial firms to assist them in solving environmental and wastewater treatment concerns. ERM, Inc. also performs design, construction and contract operations of site remediation work as well as wastewater treatment work.



Location: 855 Springdale Drive  
Exton, PA 19341  
(215) 524-3500  
Attn: 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, DEL 19899  
(302) 571-0890  
Attn: Brett S. Paddock

- (11) **FOSTER WHEELER CONSTRUCTORS, INC.**, which is an active part of **Foster Wheeler USA Corporation**, is a companies that provides full services in the engineering, procurement and construction areas and other related areas to the construction, petroleum, chemical, energy and pharmaceutical industries.

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

- (12&13) **FOSTER WHEELER ENERGY, LTD. & TEXACO, LTD.** It should be noted that these companies were not interviewed in person nor by phone. A modularization video was used to obtain information on a specific project. The modularization video (i.e., a case study of a modular project) came from the Construction Industry Institute.

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

The video name is: Modularization Video from CII/Case Study/Pembroke  
Hydrotreater Project/Wales, U.K.

- (14) **GATE CONCRETE PRODUCTS** is a manufacturer specializing in the precast/prestressed concrete industry.

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

- (15) **HALLA ENGINEERING & HEAVY INDUSTRIES, LTD.** is a company that provides a full range of heavy industrial machineries and construction equipment and services from their various specialized offices in Seoul, Korea.

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

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

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

- (17) **INGALLS SHIPBUILDING** is a leading company in the shipbuilding industry.

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

- (18) **JACOBS APPLIED TECHNOLOGY, INC.**, a member of Jacobs Engineering Group, is an engineering and construction organization that provides full onsite and offsite services to hydrocarbon and chemical processes, the pharmaceutical industries and other related industries. They recently were awarded the National Business RoundTable Award for Safety.

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

- (19) **KEYSTONE STRUCTURES, INC.** is a company that provides services for the pre-engineered metal building industries.

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

- (20) **LEHIGH VALLEY BUILDING SYSTEMS, INC.** is a building contracting company specializing in pre-engineered building systems including single story non-residential construction.

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

- (21) **LOVE HOMES** is a modular housing manufacturer that provides full services for acquiring quality alternatives for living accommodations and other services including financing and contracting.

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

- (22) **NANTICOKE HOMES, INC.** is leading modular housing manufacturer that provides for quality sectional homes.

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

- (23) **PIERCE-GOODWIN-ALEXANDER-LINVILLE** is a company that provides full architectural services.

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

- (24) **PORTA-KING BUILDING SYSTEMS, INC.** is a company that provides full services for the pre-engineered metal building industries.

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

- (25) **QUICKWAY METAL FABRICATORS, INC.** is a fabricating company that specializes in metal forming and welding and provides full services to the construction industries.

Location: P.O. Box 472  
Monticello, NY 12701  
(914) 794-1900  
Attn: Marc Lerner

- (26) **RALPH M. PARSONS COMPANY** is an international engineering and construction group that provides full services to the construction industry as well as the energy, natural resources, transportation, environmental, space and defense industries.

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

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

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

- (28) **SVERDRUP CIVIL, INC.** is a company that provides full civil and structural engineering services.

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

- (29) **THE CONSULTING ENGINEERS GROUP, INC.** is a consulting firm that specializes in the precast/prestressed concrete industry and provides full structural services to the construction related industries.

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

- (30) **THE PROSSER COMPANY, INC.** is an engineering and construction company that has been in business for over 30 years and provides the chemical processing industry full services ranging from process design & control and budget management to procurement and start-up.

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

- (31) **TINDALL CONCRETE VIRGINIA, INC.** is a leading producer of precast, prestressed concrete products in the southeast that manufactures structural and architectural components for institutional, commercial and industrial markets and provides for in-house engineering and design staff.

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

# **Appendix B**

## **The Feasibility of Modular Construction**

### **B.1 INTRODUCTION**

This appendix identifies controlling and influencing factors that are considered in deciding to use modular construction methods rather than conventional construction methods. The factors are identified by reviewing and analyzing three computer programs that currently assist in determining the feasibility of modular construction methods for the construction of industrial and chemical/process plants. The three programs are: (1) Modularization Decision Support Software (MODEX); (2) Advanced Construction Technology (ACT) Expert System; and (3) Module Assessment Program (MAP).

The sources that created the programs, and the number of analyses that each program conducts to identify the important factors in deciding to use modular construction, are discussed here. MODEX was written by the Modularization Task Force of the Construction Industry Institute (CII) [CII, 1992]; and it conducts three types of analyses. ACT was written by Jacobs Applied Technology, Inc., a member of Jacobs Engineering Group [Jacobs Applied Technology, Inc., 1991]; and this expert system conducts one analysis. MAP was written by The Prosser Company, Inc. [The Prosser Company, Inc., 1992] and it conducts one analysis.

In addition to this section, this chapter contains five sections. Three sections discuss each program in terms of important factors it identifies in deciding to use modular

construction. Another section reviews, analyzes, and compares the factors identified by all the programs and presents the common factors in determining the feasibility of modular construction methods for the construction of industrial and chemical/process plants. The last section consists of a summary of the chapter. The sections discussing each program are presented below.

## **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 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 influencing 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 categories of influencing factors considered in the prescreening analysis. These factors are reviewed in detail with the following overall weights used for each category: (1) plant location (27%); (2) environmental/organizational (28%); (3) plant characteristics (19%); (4) project risks (18%); and (5) labor-related factors (24%). 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) **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"

(3) **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"

### **B.2.3 Economic Analysis**

The economic analysis, which follows the detailed analysis, is important because the finances and economics of a modular construction project vary significantly from those of a conventional construction project. For example, the cash flow patterns for a modular project are different from those of a conventional project in that more expenses are incurred upfront because of the increased design and engineering, fabrication, and transportation efforts. 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 complete or partial modular construction, and conventional construction in the chemical process industry (CPI) and the hydrocarbon process industry (HPI). 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 weighs 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 influencing 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 what percentage of the plant is suitable for construction in fabrication shops, and (2) "reducing the time for onsite work," which refers to the possible reduction of time for onsite work required 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 conducts an evaluation and analysis based on input from the user. The program evaluates and analyzes the users responses, and recommends the extent to which modular construction should be used. MAP's evaluation and analysis is discussed here. MAP's evaluation and analysis considers several influencing factors that can be placed into four categories: (1) general site conditions; (2) plant characteristics; (3) project requirements; and (4) labor-related factors. Note the similarities between the MAP, ACT, and MODEX categories.

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 an adequate construction method for the project. If the total score for all questions is between -12 and 57, MAP assesses 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 assesses 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 assesses 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 three computer programs that assist in the decision making process for using modular construction. The review identified important factors involved in considering modular construction. Tatum et al [1987] identifies 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 evaluations.

### **B.5.1 Plant Location Factors**

Table B.1 lists specific factors in the "plant location" category. The first two factors are identified as important factors by all programs. The next two factors are identified by only MODEX and MAP; and the last factor is identified 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 impacts due to the new construction methods should also be 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 module 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**

<u>PLANT LOCATION FACTORS</u>	<u>MODEX</u>	<u>ACT</u>	<u>MAP</u>
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 identify nine important factors in this category. Only two of these factors are identified by more than one program. The remaining seven are identified by only one program. Descriptions of these factors are presented below.

- The "being able to stop design temporarily" factor refers to temporarily ending the 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.



**Table B.2  
Environmental/Organizational Factors**

<u>ENVIRONMENTAL/ORGANIZATIONAL FACTORS</u>	<u>MODEX</u>	<u>ACT</u>	<u>MAP</u>
Being able to stop design temporarily	X		X
Obtaining benefits from an early startup	X		X
Constructing for current needs			X
Determining the work performed in shops		X	
Reducing the time for onsite work		X	
Identifying the possible delays		X	
Evaluating a project for modular construction		X	
Identifying the restraints on foreign labor	X		
Determining the owner's understanding of modular construction	X		

- 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 equate to 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. This option is available if constructing with modular

construction methods.

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

- The "reducing the time for onsite work" factor refers to the possible reduction of time in 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 being aware of the possible delays that can occur during the project (i.e., can one accept the penalty for being delayed).

- The "evaluating a project for modular construction" factor refers to when the project is evaluated for modular construction methods. This is critical since a modular project should be evaluated early in order for it have the potential of success.

- 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 can also place restrictions on the amount of onsite work because of The potential pollution and other environmental impacts.

- The "determining the owner's understanding of modular construction" factor refers to the fact that owners should understand that modularization: (1) introduces innovative construction methods, (2) involves more detailed feasibility studies, (3) identifies design constraints early in the project; these constraints should not be changed, (4) requires that the owner be involve with both the engineering and construction firms throughout the project, etc.

### **B.5.3 Plant Characteristics Factors**

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

**Table B.3  
Plant Characteristics Factors**

<u>PLANT CHARACTERISTICS FACTORS</u>	<u>MODEX</u>	<u>ACT</u>	<u>MAP</u>
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 possibilities of using the same plant design for several plants located at different locations; and it 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 due to many small individual parts that require assembly.

- 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 working with some piping material is more suitable indoors in a controlled environment rather than onsite where weather conditions may prevent efficient use of exotic material.

- The "characteristics of the module enclosure" factor refers to what type of module enclosure is required (i.e., can the module be enclosed with sidings or does it need a separate building to enclose it completely).

- 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 what degree of quality and cleanliness is required during the fabrication process.

#### **B.5.4 Project Requirements Factors**

Table B.4 lists specific factors in the "project requirements" category. All of the programs identify the three factors in this category. The programs identify more specific factors within the cost area, as shown in the table.

**Table B.4  
Project Requirements Factors**

<u>PROJECT REQUIREMENTS FACTORS</u>	<u>MODEX</u>	<u>ACT</u>	<u>MAP</u>
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 Considerations Factors**

Table B.5 lists specific factors in the "labor-related" category. The programs identify three factors in this category. All the factors are identified by at least two programs. Descriptions of these factors are presented below.

- The "availability of onsite skilled labor" factor refers to whether or not there is adequate labor force onsite to construct the modular project, while still maintaining the required: (1) quality in the work, and (2) project schedule. If an inadequate onsite labor exists, management must consider the transfer of a labor force onsite; and such a transfer

of labor may not be welcomed in all countries.

**Table B.5**  
**Labor-Related Factors**

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

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

- The "amount of assembly labor" factor refers to the degree of detailed intensive (assembly) labor required such as that in piping, electrical, instrumentation, etc. Modularization can be advantageous if the project requires significant detailed and intensive work because it can be performed in more controlled conditions.

#### **B.5.6 Project Risks Factors**

MODEX identifies four specific factors in the "project risks" category: (1) "work in parallel," (2) "additional requirements in planning," (3) "equipment testing in fabrication shops," and (4) the "amount of experience in 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 simultaneous 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, etc.

- The "equipment testing in fabrication shops" factor refers to how much equipment can be tested in the fabrication shops before it leaves the 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 and the new organization of the project.

#### **B.5.7 Economic Evaluations Factors**

MODEX identifies a specific factor in the "economic evaluations" category: (1) knowledge of the construction schedule and cost. 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 and influencing factors that are considered in deciding to use modular construction methods rather than conventional construction methods. Three computer programs: (1) Modularization Decision Support

Software (MODEX); (2) Advanced Construction Technology (ACT) Expert System; and (3) Module Assessment Program (MAP) have been reviewed and analyzed to determine what factors are important in determining the feasibility of modular construction methods for the construction of industrial and chemical/process plants.

The following are results of the program comparisons:

**(1) The decision making process** to use modular construction rather than conventional construction for industrial and chemical/process plants involves many categories of factors; these categories include: (1) plant location, (2) environmental and organizational, (3) plant characteristics, (4) project requirements, (5) labor-related factors, (6) project risks, and (7) economic evaluation.

**(2) The "plant location" category** includes the following factors: (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."

**(3) The "environmental/organizational" category** includes the following factors: (1) "being able to stop design temporarily," (2) "obtaining benefits from an early startup," (3) "constructing for current needs," (4) "determining the work performed in shops," (5) "reducing the time for onsite work," (6) "identifying possible delays," (7) "evaluating a project for modular construction," (8) "identifying the restraints on foreign labor," and (9) "determining the owner's understanding of modular construction."

**(4) The "plant characteristics" category** includes the following factors: (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."

**(5) The "project requirements" category** includes the following factors: (1) "cost," (2) "quality," and (3) "safety."

**(6) The "labor-related" category** includes the following factors: (1) the "availability of onsite skilled labor," (2) the "size of local pool," and (3) the "amount of assembly labor."

**(7) The "project risks" category** includes the following factors: (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."

**(8) The "economic evaluations" category** includes the following factor: (1) the "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 for using modular construction. The three programs are effective programs to determine the important factors in deciding to use modular construction; MODEX, for example, focuses on "three major issues: (1) if the plant can be modularize, (2) if the plant should be modularize, and (3) the potential savings of modularization" [Fisher et al, 1992]. Focusing on the issues above can greatly assist the owner in selecting adequate construction methods.

Although the discussion of these programs has been identified for the construction of industrial and chemical/process plants, these programs can be used, to a certain extent, in the decision making process for the construction of projects in other types of construction as well, since most sites will have similar controlling factors. If the type of construction is something other than industrial construction, some questions of these programs will not be applicable such as the specific questions from the "plant characteristics" category. But the questions from other categories such as "plant location," "project risks," "labor-related factors," etc. can apply to non-industrial projects. The decision making process in using modular construction for the construction of industrial and chemical/process plants has definitely been used effectively. 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."

## Vita

Mayra L. de La Torre was born at Tijuana, Mexico, Baja California, Mexico on October 26, 1963. Mayra obtained her Bachelors of Science degree in Civil Engineering on March, 1986 from California Polytechnic State University, San Luis Obispo, in San Luis Obispo, California.

Mayra has approximately seven years of practical civil engineering experience. Upon graduation, Mayra began to work with the California Department of transportation (CalTrans), where she obtained experience in the Hydraulics, Project Studies, Project Development, and Construction Inspection departments. Later, she was employed with the City of Thousand Oaks where she worked at the Department of Public Works. Mayra was later employed by Village Engineering, a private civil engineering firm at Westlake Village, California, where she managed civil engineering land development projects ranging from the construction of small single family dwellings to the construction of large pharmaceutical buildings.

Mayra began her program at Lehigh University in January, 1993; and is expected to graduate with a Masters of Science degree in Civil Engineering in June, 1994.

**END**

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