CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Interfaces: Integrating Product Design and Process Engineering in Manufacturing and Construction

By

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Summary: **Technical Report Number 50**

Title: **Interfaces: Integrating Product Design and Process Engineering in Manufacturing and Construction**

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Abstract: Manufacturing and construction have been traditionally regarded as fundamentally separate industries, producing different products for dissimilar markets. In response to intense competitive pressures for shorter development times, lower costs and higher quality, progressive manufacturers are now integrating product design and process engineering. This trend towards integrating the two functions is often termed concurrent product and process design. Construction's current equivalent, constructibility improvement, is both less developed and less a force for integration. However, the increasing complexity of the constructed product, the diversity of possible construction methods, and the sequential nature of the traditional approach to design and construction indicate that the application of integrated manufacturing approaches may be an effective approach to the delivery of constructed projects. The purpose of this research was to understand and describe the integrated manufacturing environment and to assess the extent of similar attributes in a selected group of construction projects. The findings indicate that managerial priorities for integration precede the effective use of technical tools and the project manager plays a key role.

Subject: The subject of this research was comparison of integrated product and process design in manufacturing with design-construction integration on facility projects and developing conclusions and recommendations regarding ways to increase integration.

Objectives/Benefits: The purpose of this research was to understand and describe the integrated manufacturing environment and to assess the extent of similar attributes in a selected group of construction projects.

Methodology: This research began with the induction of a framework composed of twelve variables that describe the integrated manufacturing environment. This framework guided data collection on a series of eight cogeneration projects. Each of the eight construction projects was then ranked on the degree of conformance to each of the twelve framework variables. The resulting matrix of conformance values formed the basis for quantitative data analysis using cluster and factor analysis methods.

Results: The results of the analysis support five conclusions regarding integration on the group of cogeneration projects. These conclusions support the validity of the framework, present the concept of project integration curves, and provide insights into mechanisms that may drive projects to higher levels of integration. The conclusions also indicate areas of evolutionary and revolutionary change, describe the engineering-construction interface, and identify the project manager as the focal point for change.

Research Status: This project is complete. The valuable insights gained from this research indicate that CIFE may obtain further benefits from future investigations that build on the knowledge gained from integration in manufacturing.

EXECUTIVE SUMMARY

Manufacturing and construction have been traditionally regarded as fundamentally separate industries, producing different products for dissimilar markets. In response to intense competitive pressures for shorter development times, lower costs and higher quality, progressive manufacturers are now integrating product design and process engineering. This trend towards integrating the two functions is often termed designing for manufacturability, simultaneous engineering, concurrent product and process design, or simply integrated manufacturing.

Construction's current equivalent, constructibility improvement, is both less developed and less a force for integration. However, the increasing complexity of the constructed product, the diversity of possible construction methods, and the sequential nature of the traditional approach to design and construction indicate that the application of integrated manufacturing approaches may be an effective approach to the delivery of constructed projects. This research examines fundamental mechanisms of project integration in both sectors of the economy.

The purpose of this research was to understand and describe the integrated manufacturing environment and to assess the extent of similar attributes in a selected group of construction projects. This research began with the induction of a framework composed of twelve variables that describe the integrated manufacturing environment. This framework guided data collection on a series of eight cogeneration projects.

Each of the eight construction projects was then ranked on the degree of conformance to each of the twelve framework variables. The resulting matrix of conformance values formed the basis for quantitative data analysis using cluster and factor analysis methods.

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This research would not have been possible without the participation of the firms that provided access to the projects I studied. Project time is always at a premium, yet sixty professional engineers and managers generously shared their time and experience to play a fundamental role in this research. Opening the doors to their projects reflects their dedication to the industry and their commitment to the educational process, and I thank them for their enthusiastic participation.

I would also like to acknowledge the contribution to this research of my academic advisory committee, Ray Levitt, Boyd Paulson, Paul Teicholz, and Steve Wheelwright, and in particular, my principle advisor, Bob Tatum.

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CHAPTER 1

INTRODUCTION AND RESEARCH OBJECTIVES

INTRODUCTION

Manufacturing and construction together account for one third of the United States' annual gross national product. These two giant and diverse sectors of the national economy have been traditionally regarded as independent industries, which produce different products for dissimilar markets. Responding to intense competitive pressures for shorter development times, lower costs and higher quality, progressive manufacturers are now integrating product design and process engineering.

This trend towards integrating the two functions is often termed designing for manufacturability. Construction's current equivalent, constructability improvement, is both less developed and less a force for integration. But the complexity of the constructed product, the diversity of possible construction methods, and the many different project participants all indicate that the application of integrated process engineering may be an effective approach to the delivery of complex constructed products.

There are indications that construction and manufacturing are actually growing closer together, both in the nature of their products and in the processes through which these products are created. Traditional parameters that differentiate the constructed and the manufactured product, such as size, complexity, immobility, consequences of failure, and fabrication locale, are becoming less and less distinct. In addition, both the procedural and the physical processes by which these products are designed, fabricated and assembled are growing more similar.

While construction seeks the benefits of mass production and the economies afforded by the production of multiple units, manufacturing is moving towards flexible systems that permit economic assembly of smaller batches of different products. As the two sectors have evolved from their traditional roles, they have responded to market forces by developing new approaches to creating small batches of complex products, both more quickly and more efficiently. This research examines fundamental mechanisms of project integration in these two sectors of the economy.

This introductory chapter begins with a brief discussion of competitive strategies in manufacturing and construction. These lead to the fundamental problem addressed in this research, the organizational fragmentation of the design and construction process and the subsequent decline in competitive advantage. I then briefly describe integrated manufacturing and the use of observed attributes that form an integrated manufacturing environment as a guide for the study of similar environments in construction. The next sections list the objectives and the point of departure of this research. The chapter closes with a reader's guide to the thesis.

COMPETITIVE STRATEGIES

The construction industry's share of the U.S. gross national product, although still substantial, has been declining steadily for the past 15 years, from over 10% in the early 1970's to just over 4% in 1985. During this same period, American engineering and construction firms have seen their share of the international market decrease as well. Perhaps even more significant is the steady increase in construction contracts won by foreign firms in the United States. The Office of Technology Assessment (O.T.A.) identifies three primary factors that affect international competitiveness in the Engineering and Construction industry: costs, financing and technical capability. The O.T.A. also reports that American firms are losing ground to foreign competitors on all three (Office of Technology Assessment, 1987).

Conventional competitive strategies, such as Porter's generic strategies of cost leadership, differentiation and focus (Porter, 1980), may not be sufficient in today's changing marketplace. Takeuchi and Nonaka (1986) consider high quality, low cost and differentiation to be basics, but also stress the importance of speed and flexibility in bringing new products to market.

The Office of Technology Assessment describes two technology-based strategies to improve U.S. construction competitiveness: development of new products, and development of new management technologies and construction methods. The O.T.A. concludes that "an aggressive strategy based on strengthening the infrastructure for technology development offers the best hope for maintaining competitiveness over the long run." (Office of Technology Assessment , p. 121)

However, Putnam (1985, p. 139) points out that "investing in new technology will not alone ensure the competitiveness of U.S. industry." Similarly, Hayes, Wheelwright, and Clark argue that "if one's goal is to develop a sustainable competitive advantage, one's efforts must be directed . . . toward the development of specific organizational competences and relationships that are difficult for competitors to match over the long term." (1988, p. 20)

Stalk makes a persuasive argument for the use of time as a competitive strategy. Shorter lead times in getting new products to market can result from the use of "structurally different methods to develop, manufacture and introduce new products." (Stalk, 1988, p. 45) Honda used new methods, such as cross functional factory teams, to develop new models more quickly than its competition and emerged as the premier motorcycle manufacturer in Japan.

The development and, just as significantly, the management of new technologies and project environments offer promise as competitive weapons. And, as Clark and Fujimoto (1988a, p. 7) point out, "it seems likely that product development (its speed, the quality of design) will be a critical dimension of competition in the years ahead." Product and process design activities during the development of a new manufactured product are similar to the design/construction planning process in construction, even though the nature of the manufactured and constructed products may be be quite dissimilar. The integration of product and process engineering provides an opportunity for the assimilation of new product and process technologies into both the manufactured and the constructed project. The concept of integrating product design and process planning offers promise as a mechanism for providing new products more quickly and efficiently than traditional sequential development.

PRODUCT AND PROCESS INTEGRATION

An integrated approach to product and process design has proven to be an effective competitive weapon in the manufacturing sector. The dictionary defines integrate as "to make whole or complete by adding or bringing together parts" and as "the organization of various traits or tendencies into one harmonious personality." (Webster's, 1979, p. 953) Putnam defines integrated manufacturing as "the simultaneous collaboration of specialized functions." (1985, p. 140) Both definitions apply to the integration of product and process design in manufacturing.

The concept of integrating product and process engineering functions means more than merely integrating vertically to house the two functions under the same organizational roof. It also is more than interconnecting all the project players electronically. True integration means the sharing of common resources to achieve progress towards common goals, from positions of equal power and status within the firm. It includes the appropriate structuring of a project team to insure congruent high level goals while recognizing that lower level goals may differ. To support high level goal congruence, cross-functional collaboration and transparent communications at all levels can build an atmosphere of perceptual congruence, which supports a uniform and unbiased view of the project by all participants.

Integration also includes the use of tools, knowledge, experience, and technologies that support the integrated effort. However, while the use of specific technologies to promote project integration can be crucial, their use does not in and of itself guarantee integration. As Rooks points out, "It is becoming increasingly evident that a major stumbling block to the implementation of assembly automation is more managerial than technological. . . . One of the critical managerial factors is the integration of the product design process with the manufacturing process." (1987, p. 69)

Product development can be described both as "a sequence of information processing activities" (Clark, 1988a, p. 4) and as "a system of problem solving cycles." (Clark and Fujimoto, 1988b, p. 2) Cooper offers a more formal description of the new product process "as a goal directed stepwise process, involving a series of information acquisition activities and evaluation points." (1983, p. 3) From each of these perspectives, product development is very similar to the evolving process of engineering design and construction planning. Insights gained by examining the process of integrated manufacturing can be used both as a guide and as a framework for the examination of similar circumstances in the design-construct sector.

RESEARCH OBJECTIVES

The purpose of this research is to describe the existing integration environment on a series of construction projects and compare the attributes of integration in the observed sample to the current state of integration in manufacturing.

This research takes a unique exploratory tack by offering a new approach to defining and measuring integration in construction. The definition of construction integration that guides this research is the degree of similarity to the existing integrated manufacturing environment described in the manufacturing literature. The measure of integration is the degree of conformance to a framework of twelve variables that describe the integrated manufacturing environment.

The following four objectives guided this research towards its goal. The chapter of this thesis that addresses each objective is listed in parentheses.

1. Develop a framework to synthesize current knowledge regarding the factors that support integrated product design and process engineering in new product development. (See Chapter 3 - Literature Review and the Integrated Manufacturing Framework)
2. Evaluate the extent to which the conditions described by the framework are present on a selected, similar group of engineering and construction projects. (See Chapter 5 - Analysis)
3. Describe characteristics of project organization and management that would increase the integration of plant design and construction planning. (See Chapter 6 - Conclusions)
4. Describe needs for future research involving design-construction integration. (See Chapter 6 - Conclusions)

The attainment of these objectives resulted in multiple research contributions that consisted of new knowledge and insights, innovative research methodologies, and opportunities for future research.

RESEARCH APPROACH AND GUIDE TO THE REPORT

(Reader's Note: This Technical Report is based upon the thesis I submitted to the Department of Civil Engineering at Stanford University. It does not include the case studies, but maintains the same chapter and appendix nomenclature scheme as the original thesis; therefore, the appendix numbers are not consecutive. The thesis in its entirety can be found in the Stanford University Library.)

In order to accomplish the objectives of this research, I developed a research methodology that provided structure to the study, yet allowed a degree of flexibility for the research to evolve as it progressed. Methodological issues and the research methodology I selected are discussed in Chapter 2.

I first reviewed the existing literature to establish the point of departure for this work, and to develop a descriptive framework of the integrated manufacturing environment. I summarize the literature and present the framework in Chapter 3.

The framework provided the basis for collecting data and organizing the data in a series of eight case studies of construction projects. The interview guide is included as an appendix to this report. Chapter 4 presents an overview of cogeneration and describes the sample of eight cogeneration projects included in this research.

Analysis of the case data took place in two phases. The first phase was the assignment of a conformance ranking for the case study data for each framework variable. The case data are summarized in Appendix L. The formulation and subsequent analysis of the eight by twelve conformance matrix is presented in Chapter 5. I discuss the details of the multivariate methods I used in Appendix M.

In addition to collecting case data through site visits and interviews, I collected project performance data after the interviews using a questionnaire submitted to the project manager of each project. Appendix N discusses the results of regressing the project performance data against the degree of project integration, as measured by the conformance rankings.

The analysis of the case data led me to formulate several conclusions about the process of integration on the projects I studied. These conclusions, as well as the overall research contribution, are presented in Chapter 6.

CHAPTER 2

METHODOLOGY

INTRODUCTION

This research is an exploratory effort at comparing aspects of two industries, the integrated approach to product and process design in manufacturing, also known as concurrent or simultaneous engineering, and the approach taken in the delivery of a selected group of power projects from the construction industry.

This research consists of multiple, exploratory case studies. It is qualitative in nature, and uses multiple data collection methods, primarily personal interviews. It makes use of a framework that was developed from an examination of the manufacturing literature to provide structure to data collection and analysis. The unit of analysis is the construction project, and the case study method provides and excellent opportunity to capture the richness of the project environment from a qualitative perspective.

This chapter first presents a discussion of issues related to research methodology in general, and then focuses on the specific methods that I employed during the course of this study. The first section is a description of methodological issues. These issues include exploratory approaches, the unit of analysis, qualitative and quantitative perspectives, inductive and deductive methods, the use of case studies, sample selection, data collection and validity.

The second section of this chapter is a detailed description of the process by which the specific methodology for this work evolved and the study itself was carried out. The principal activities included formulating the descriptive framework of integrated manufacturing, selecting cogeneration cases and collecting data, and analyzing the data in order to derive conclusions. The final section of the chapter describes possible sources of error.

METHODOLOGICAL ISSUES

The literature on research methodology is overwhelming and at times confusing. There are a number of schema for classifying research methods and delineating the attributes of quality research, but no apparent universally accepted, global taxonomy. Most research efforts focus on a generic strategy, while incorporating some defensible combination of characteristics from other methodologies. The specific approach must be tailored both to the particulars of the problem under investigation and the predilections of the investigator.

Basic research versus applied research

One of the fundamental classifications of research is the distinction between pure and applied research. O'Brien and Woodhead (c. 1985, p. 9) provide an intriguing global definition of research as "a functional operator which can be applied to a field in an endeavor to answer questions," and note that the operator "is neutral as to the field to which it can be applied." (c.1985, p. 10) From this perspective, the issue of applied versus basic research is merely semantic. However, they also note a lack of standard nomenclature and offer eight different variations on the definition of basic research.

Basic research is often categorized as the effort to seek knowledge for knowledge's sake, or "the pursuit of underlying structure, deep structure or the essence of things." (O'Brien and Woodhead, c. 1985, p. 13) In the United States, this form of research is predominantly the domain of the academic sector, although often funded by government agencies. It is often characterized by an attempt to discover fundamental relationships or create new theory in a field. One source (Simon and Burstein, 1985, p. 3) notes that "'pure' research, . . . can be defined as research motivated primarily by the desire to understand something without regard to immediate economic or social payoff." However, pure, or basic, research does indeed benefit the society in which it is performed by providing a better understanding of the universe, world and systems in which we all reside, and by creating a platform to launch new fields of inquiry. For example, Hayes, Wheelwright and Clark (Dynamic Manufacturing, 1988, p. 9) describe basic research as "the kind that leads to new products, markets, and industries."

Applied research, on the other hand, is characterized by a problem solving or solution generating perspective. One difference between applied and pure research is the time frame for 'social payback.' Simon and Burstein (1985, p. 3) describe "'applied' social research, which is oriented towards answering practical questions with an eye to short term payoff." Research activities performed by private industry as well as by various government laboratories, notably those affiliated with the military, generally are more applied in nature.

This research leans more towards the applied end of the spectrum. It focuses on ongoing processes in one industry, manufacturing, as means for increasing understanding of similar processes in another industry.

Exploratory approach

The first activities in the scientific method are those of observation and classification. The "first description is important because it serves to focus subsequent studies." (Simon and Burstein, 1985, p. 37) Exploratory research is a first attempt to focus on and describe phenomenae on a local scale and to develop theory, models, or hypotheses that are testable and generalizable during the course of further studies. As Hakim notes, "qualitative research may be used for preliminary exploratory work before mounting a larger scale or more complex work." (1987, p. 28) This sort of approach is often characterized by an inductive approach to knowledge building, rather than the formulation of specific testable hypotheses. However, there are inherent difficulties in exploring new territory. "The early descriptive researcher has great freedom, but such great freedom can be terrifying." (Simon and Burstein, 1985 p. 38) (This researcher found this observation particularly apropos.)

An exploratory approach is well suited in this case since it is a first effort to approach a new topic from a fresh perspective. Although this work builds upon previous studies, both in terms of methodology and content, (Tatum, Vanegas and Williams 1986, 1985; Vanegas 1988) it is a first attempt to describe design-construction integration using a framework developed from observations of similar processes in a distinctly different field.

Unit of analysis

As Georgescu-Roegen (in Simon and Burstein, 1985, p. 54) points out, "every scientist slices actuality in the way that suits best his own objective," much the same way that an engineer cuts a free body diagram of that portion of a complex system he or she wishes to isolate and analyze. There is no one appropriate unit. Broad based studies, such as industry wide surveys, provide perspectives of macro-economic forces or cyclical phenomenae. (See, for example, Office of Technology Assessment, 1987.) On the other hand, experimental research on timber truss design (Brungraber, 1985) leads to increased understanding of structural response to specific loading conditions using a given material. Judicious selection of the unit of analysis helps provide a focus on the issues of interest to the researcher.

For this research, I selected a free body diagram containing the project as the unit of analysis, but with close attention to the context in which the project is executed. Even though projects are by definition one time efforts of limited duration, the execution of a project, be it the development of a new product or the design and construction of a power plant, cannot be accurately viewed as a stand alone event. It takes place within the context of the operating firms, and is influenced by the existing culture, values, experience, knowledge and, most importantly, people that comprise the firms. This includes the principal project participants, the owner, the engineer and the constructor, and encompasses the different project phases, from definition of need through design, construction and operation. This research focuses on the relationship between the design and production functions during the early design and construction planning phases, as well as project execution.

Qualitative versus quantitative approaches

Quantitative research is that which defines and measures variables that can be represented by numbers. Qualitative research, on the other hand is descriptive in nature, and uses data that consist of words rather than numbers. It is often used for exploratory studies that are a first attempt to describe a new field of interest. The qualitative approach can provide a richer, more perceptive description of the cases it examines.

One strength of qualitative research is the internal validity of the data obtained. The data are collected directly from the people whose experiences are described. One weakness is that, even if care is taken to choose a representative cross section of the type of people who are the subjects of the study, the small sample size may lead to difficulties in generalizing the findings. That is, the external validity (described below) may not be as strong as studies that use quantitative methods on statistically significant samples of populations. There are measurable numbers associated with the case studies, such as project durations and project costs, years of experience of project personnel, and plant capacity, and in this case, these data were recorded where appropriate. However, this information generally contributes to the overall qualitative description of the conditions on the project at the time of the interviews, rather than providing any basis for external generalization.

Qualitative and quantitative approaches are not necessarily mutually exclusive. In the case of this research, the conformance values associated with each case (described in the second section of this chapter) were coded numerically to provide an opportunity to reorder the data. This numerical reordering resulted in a number of illuminating conclusions, supported by inspection and thoughtful qualitative analysis of the data.

Inductive versus deductive approaches

The development of knowledge or theory generally takes one of two forms. Eisenhardt describes induction as "a logic process for generating theory from data" and offers Mintzberg's observation that "induction is an iterative, two step process involving detective work and followed by creative leaps to general understanding." (Eisenhardt, 1988, p. 3) Simon and Burstein (1985) differentiate this from using a systematically organized body of theory to deductively produce testable hypotheses, or as Eisenhardt puts it, beginning "with assumptions which then logically lead to theory." (Eisenhardt , 1988, p. 3)

This research is exploratory in nature. As such, it uses a fundamentally inductive approach to collecting data in the form of case studies, which were then analyzed to help provide an understanding of design-construction integration on cogeneration projects. The use of a framework derived from observations of the integrated approach to new product development in manufacturing, while not providing a formal, testable set of hypotheses, served as a guide to structure the research.

Case studies

Yin offers a formal definition of a case study as an "empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used." (Yin, 1984, p. 23) Case studies can be either longitudinal, where one entity is examined in a dynamic temporal environment, or cross sectional, which provides a snapshot at a single instant of time.

This research closely fits Yin's definition in that it provides observations of ongoing projects within the context of the structure of the participating firms and the cogeneration industry, and uses multiple sources of data. The primary data collection mechanism was personal interviews. These were supplemented by site visits, telephone interviews, and reviews of project documents.

This research took an innovative approach to the application of case study methodologies to the comparison of similar aspects of two different industries, manufacturing and construction. The study utilized a conceptual framework constructed from examples of product and process design integration in new product development programs to examine the parallel processes of designing and constructing cogeneration plants. I conducted multiple case studies of cogeneration projects and used the studies to compare data across projects. Each case provides a snapshot of the project at the time of the project interviews, but also includes historical information regarding the early project environment. In addition, I used follow up questionnaires to capture post project performance data.

Validity

One measure of the appropriateness of a measurement is validity. "A measurement is valid if it really classifies or measures what you want it to classify or measure." (Simon and Burstein, 1985, p. 18) The concept of validity is usually expressed as two related issues, internal and external validity.

Internal validity is the accuracy with which the data describe the actual conditions at each project; that is, the element of truth. Simon and Burstein describe the related concept of reliability. "Reliability is roughly the same as consistency or repeatability." (Simon and Burstein; 1985, p. 19) However, they also point out that "An operational definition or measurement can be very reliable but still be invalid." (Simon and Burstein, 1985, p. 19) A simple example is that of a scale that has been calibrated incorrectly so that it is never correct but is consistently off by the same amount. Therefore, for an observation to be internally valid, it must contain both an element of truth and be repeatable by another observer.

The selected methodology of case studies based on personal interviews contributes to internal validity, and is supported by the overlapping data collection devices and by independent review. The richness of descriptive prose provides a more compelling and thorough description of observed phenomenae than do other, more quantitative methods. I reviewed the case data three separate times to insure consistency. In addition, each case was reviewed by both the project manager for accuracy, and by an independent reviewer for consistency.

External validity, the ability to extend or generalize the results to a larger population, is inherently a function of the nature of the sample studied. The sample of projects I selected is representative of the population of mid-size gas fired cogeneration plants, developed by independent power producers and delivered with fast track schedules under lump sum, turnkey contracts in the United States in 1990. The results of this research are strongly generalizable to other cogeneration projects of comparable size that are delivered under similar contract structures, with corresponding schedule pressures.

The results of this research can also be logically extended to other construction projects if these projects are also defined by extensive mechanical installations, delivered in a fast track or phased approach under significant time pressure, faced with powerful vendors, and coordinated over many internal and external interfaces. Examples might include other types of power projects, refinery work, aluminum and steel mills, and other process facilities.

The preceding discussion of methodology addressed some of the general issues related to research. These issues can be thought of as the general solution of the research "differential equation." The particular solution consists of the activities that I performed during the course of this project. These are described in the next section.

RESEARCH ACTIVITIES

Yin (1984, p. 29) describes a research design as a research blueprint that deals with four questions; what questions to study, what data are relevant, what data to collect, and how to analyze the results. Or, as he more succinctly puts it, the research plan is "an action plan for getting from here to there." (Yin, 1984, p. 28)

The research plan that guided this work consisted of several distinct steps. Although each successive step ultimately is predicated on the preceding steps, the activity flow is not linear sequential. In a fashion similar to that described by the integrated approach to product and process design that this research describes, the research effort is itself an iterative process.

Research activities included reviewing the literature, building the framework, selecting projects, collecting data, writing case studies, assigning conformance values, analyzing the data, and generating conclusions.

Review the literature

All research builds upon previous work. The first activity in any new research undertaking is to establish a point of departure from current knowledge. This research contributes to the knowledge base of project level experience in construction and to the comparison of two industries at the project and firm level. I described the point of departure for this research in Chapter 1.

In order to develop a framework to describe integrated manufacturing and for use as a tool for data collection in construction, I explored the existing manufacturing literature. The literature review focused on descriptions of the integrated approach to manufacturing, also known as concurrent product and process engineering, or simultaneous engineering. This review took place at three levels ranging from industry based to firm or project oriented, and finally to the production workface itself.

I employed two mechanisms to discover the current state of knowledge in this area. The first was through informal networking with friends, colleagues, faculty and industry professionals. Although this is a less structured process than an on-line database search, it is very effective in pulling together a variety of preliminary information and in generating leads and keywords to direct a more rigorous database search.

For the more formal literature search, I utilized a number of different sources. These included the Stanford library system, course syllabi and papers, the Knowledge Index (Knowledge Index, 1991) on-line database, and other published materials. The Knowledge Index service, a division of the Dialog database service, was particularly useful. This service permits on line searching of a number of databases, including the Engineering

Index, all of which are updated on a regular basis. It was an excellent source of timely information.

Although literature review is an ongoing activity during the course of a research effort, the major portion of the literature review was completed prior to beginning data collection. The literature review activity resulted in the formulation of a framework that describes the dominant elements of the integrated approach to manufacturing. A review of the literature and the framework are presented in Chapter 3.

Build the framework that describes integrated manufacturing

The focus of this background analysis was the integrated product development team that exists within a specific firm or division that is bringing a product to market. The firm or division contains a number of distinct functional groups, two of which are product engineering and manufacturing. Much has been written describing the interaction of these two groups in an integrated environment. However, I found no structure or classification to the descriptions in the literature. In order to create a useful comparative tool for data collection, it was necessary to structure the various findings from management research and anecdotal descriptions of the integrated environment. Furthermore, in order to build a tool useful in collecting data in a different industry, I had to induce a series of higher level variables that were expressed as the attributes of integrated manufacturing described in the literature.

After reviewing the literature, I extracted the salient characteristics of the project environment, the project team, and the individual team members that contribute to an integrated approach in manufacturing. The framework I developed is a compendium of characteristics from the manufacturing literature as practiced by many different firms. As such, it is a composite picture of current industry practice regarding integrated product and process design. However, that picture was composed of a large number of descriptions of different characteristics of the integrated environment. Not only was there no structure to the descriptions, there was the added difficulty of making direct comparisons to a different process, the design and construction of cogeneration plants.

It gradually became clear that there was an intermediate level of description necessary in order to enable me to make a valid comparison with the construction projects I would study. The entire concept of measuring variable values in two different industries requires that a neutral descriptor be developed that captures each general characteristic of the integrated effort. This required synthesizing a higher level set of variables that were inferred from the observed values in manufacturing literature. These same high level or general variables were used as a basis for data collection on the cogeneration cases; the specific variable values for manufacturing were extracted from the literature. The specific variable values for construction were measured on the construction projects by collecting data during field interviews.

The development of the framework of variables was a dynamic, iterative process. This is described in the following series of steps:

1. Collect examples of attributes of integrated manufacturing from the literature.
2. Induce the nature of the higher level descriptive variables that the attributes describe.
3. Select and name an appropriate number of variables that capture most of the salient attributes.
4. Use the framework to guide collection of data on construction projects.

An example from this research is the use of concurrent or simultaneous engineering in manufacturing. A similar, although not identical, effort in the construction sector is fast track construction. Therefore, in order to make comparisons of these similar efforts, it was necessary to induce a higher order variable that I have called "Timing of product and process engineering." This descriptor is a variable that takes on different values in the manufacturing sector and the construction sector. By measuring characteristics of the two industries at this level, I was able to make meaningful comparisons between them.

Ultimately, there had to be sufficient variables to capture the complexity of the integrated manufacturing environment. However, too many variables would make data collection and analysis more laborious and time consuming with decreasing marginal value.

The structure of the final framework, which consists of twelve variables, is outlined below. For convenience, I initially organized the twelve variables into four groups of three variables each. I labeled the four groups Context, Organization, Process, and Content.

Context Variables

Variable 1-A Project development environment
Variable 1-B Timing of product and process engineering
Variable 1-C Management perspective of integration technologies

Organization Variables

Variable 2-A Project team attributes
Variable 2-B Engineering-production interface
Variable 2-C Vendor interactions

Process Variables

Variable 3-A Communication patterns
Variable 3-B Engineering generalist
Variable 3-C Computer integration

Content Variables

Variable 4-A Production input to design
Variable 4-B Development of process plan
Variable 4-C Electronic data exchange

These four variable groups are based on the general characteristics of the variable values from the manufacturing sector. We shall see later that there is another more appropriate grouping of variables based on the analysis of the construction case data.

Select the project sample

With the framework in place, the next step along the research path was to select a group of construction projects for study. I focused the case study portion of this research exclusively on cogeneration projects, for several reasons. There is a trend in power generation in the U.S. towards smaller, more standardized designs. As this trend continues, there will be more of a premium placed on the ability of firms to deliver a high quality product in a shorter time frame. Cogeneration plants are often delivered under a design/construct contract, which presumably offers a greater opportunity for the integration of design and construction than a conventional general contractor approach.

Combined purpose power plants are proliferating in the United States, therefore there is a reasonable population from which to select projects. The plants are physically small, and although relatively sophisticated technically, are also small in terms of project size and organization. The relatively small scope makes these projects suitable for descriptive case study research.

I selected specific cogeneration projects based on several criteria. In order to maintain a sense of technical or product consistency across the projects, I selected only gas fired cogeneration plants, all but one of which are combined cycle units. See Chapter 4 for a description of the projects. The projects were all in the mid-range market segment terms of capacity, ranging from 47 MW to 356 MW. All the projects were delivered under lump sum, turnkey contracts, the standard or typical project delivery format for this industry. The projects were geographically dispersed, located on both coasts of the United States, and were delivered by different firms. Appendix A lists the firms that participated in this research, and Appendix B lists the people who participated in interviews.

I also selected ongoing projects at different stages of completion, ranging from projects that had just begun detailed engineering to recently completed projects in the startup stage. The inclusion of currently active projects improved the quality and timeliness of the data and helped to offset problems of selective recollection by the interviewees.

A final important criteria for project selection was accessibility. This included availability of key project personnel and open access to project data. Since accessibility to project data was crucial, I could only include projects that agreed to participate in a frank and open manner. This necessarily precluded the selection of a random sample. However, random sampling is only one method of obtaining a representative sample of a population. By selecting projects with similar technical and contractual characteristics, yet delivered by different firms in different regions, I developed a representative sample of this segment of the cogeneration industry.

Collect project data

Project data collection focused on interviews with key project participants, review of project documents and direct observations at both design offices and project sites. The interviews with representatives of the owner, designer and constructor were all used to build a qualitative description of the project. Interviews also included members of the different functional groups, as well as management and field personnel.

I used the framework developed from the manufacturing literature to prepare an interview guide to structure the interviews. The interview guide is attached as Appendix C. This provided a consistent method for gathering data that could be compared across the projects. I also allowed time for an unstructured portion of the interviews to pursue interesting and relevant issues unique to the project.

The interviews were supplemented with reviews of project documents such as organization charts, project plans, drawings, and memos. Direct observation of the design environment and the project sites provided the opportunity for an appraisal of actual conditions on the project. These observations generally corroborated the statements of the project participants. The use of multiple interviews, coupled with a thorough review of project documentation and personal observations by the researcher provided a rich description of each project's development and execution.

I transcribed the extensive interview notes and incorporated the project data into a case study for each project. Each case is structured by the variables in the framework, and includes a section on both data and discussion for each variable. In the interest of brevity, the cases are not included here; Appendix L provides a summary of the case data. The turn-key project manager for each project reviewed the finished case for his project and I incorporated his comments and clarifications into each case.

The final data collection instrument was a follow-up questionnaire that I mailed to each of the project managers on the eight projects. The questionnaire was designed to capture two specific sets of data. The first was a list of project performance parameters as defined by the project manager. I asked each manager to list the parameters that he used to determine the success of his project. I also asked him to rank his project on each of those parameters on a scale from low, or poor performance, to high or very good performance. A sample questionnaire and the response data are included in Appendix M.

Assign conformance values

The first step in the analysis of the project data was to assign a conformance value to each of the twelve variables for each construction case. In other words, I compared the data from each case for each variable against the value of the same variable in the manufacturing sector. Ranking the eight projects on each of the twelve variables resulted in a matrix of 96 conformance values representing the twelve variables observed on the eight cases.

The conformance value is the fundamental mechanism for comparing the cases to the framework and analyzing the project data. As such, a somewhat detailed description of how these values were assigned is merited at this point.

The structure of the framework, as previously tabulated, consists of the four variable groups, each of which is composed of three variables. Each variable is in turn composed of several elements. The variable elements represent the values of the variable in the given context, either from manufacturing or from the individual construction cases. In the case of the manufacturing framework, the variable elements represent the composite characteristics of integrated manufacturing as currently practiced and described in the literature. In the case of the individual construction projects, the variable elements correspond to the data collected that relates specifically to that variable. The conformance values were assigned at the variable level. But the underlying support for the assignment was based on an examination and comparison of each variable, at the element, or variable value, level.

The process of assigning values to each of the variables was an intense, subjective activity, due to the fact that the elements of each variable did not correspond exactly between the manufacturing framework and the construction cases. I took a combined approach and looked not only for <u>congruent</u> features, that is identical elements, but also for <u>similar</u> approaches. For example, in assigning the conformance values for Variable 2-B, the engineering-production interface, there were few explicit examples of construction being perceived as the customer of product design. However, in most cases, the construction schedule drove the detailed engineering schedule, so that construction was the de facto customer. There were also few examples of either formal liaison groups or designated producibility experts. But there were examples of construction personnel assigned to the design offices to provide constructability input and to build sound working relationships with the design group. These projects ranked higher in conformance due to the similarity of the variable elements, rather than their absolute congruence.

The project case studies are structured by variable and each variable section contains three parts. The first part contains the data obtained from interviews and other sources. A discussion of this data forms the second section. This discussion considers conformance of the project regarding the elements that make up the variable. The third part gives the conformance value selected for the project regarding the variable and the major rationale for selection of this value. Many aspects of the data influence selection of the assigned conformance value and the process involved a subjective consideration of the relative strengths of these influences.

The assignment of the conformance rankings took place in three stages. This was to insure that the conformance values not only were a representative comparison of the data from the cases to the manufacturing framework, but also to maintain a sense of internal consistency among the projects.

The first assignment occurred when the data from each case were written up into the preliminary case draft. While writing each section, I assigned a value of low, medium or high to the variable for that case. I then returned the draft cases to the project managers for the turnkey contractors on the projects that I studied. However, I did not include the conformance values in the cases that I sent out for review. I felt that the values might be misinterpreted by project personnel. I wanted to avoid any possibility that they might slant their responses to try to achieve what they might have perceived as a higher or somehow "better" ranking, thinking that they or their projects had been scored on some arbitrary scale against the other projects I studied. Indeed, there were a number of requests for information on "how we stacked up" against the other projects. I responded to these by noting that I was not able to discuss any of the cases until all the reviewed versions had been returned, approved for publication.

Each project manager reviewed his case for accuracy and content, and also distributed it to other persons involved in the project to provide an opportunity for input and review. When the case was returned to me, I incorporated the comments from the marked up case and from telephone conversations with the project managers into a final draft case. When the final drafts were complete, I again assigned conformance values to each variable on each case. There were a total of 22 changes to the original values. Five values were downgraded to the next lower value, for example from a high ranking to a medium ranking. Seventeen values were upgraded, for a net difference of 12 ranking points. These changes were primarily the result of incorporating the clarifications by the project managers.

Finally, when I wrote the draft version of Chapter 5, which discusses the findings from the cases, I reviewed the conformance values one final time, primarily as a check of the consistency of assigning values across the cases. This time I broke each case into twelve sections, representing the twelve variables, and compared the sections from each of the eight cases that related to each of the variables. This process of comparison across the cases resulted in changing only one value, from a ranking of high to medium, which indicates a high degree of consistency in the ranking process.

Analyze the data and report conclusions

Data analysis began with the assignment of the conformance values. Measuring twelve variables on eight projects resulted in 96 individual conformance values. I arranged these in an 8 x 12 matrix and this matrix formed the basis for further analysis of the project data.

The purpose of manipulating the conformance values was to discover or illuminate relationships within the data not readily apparent through inspection. (Thoughtful inspection of the data, however, proved to be a valuable tool in itself.) Data analysis proceeded in four general areas, plotting distributions of conformance values, transposing or reordering the conformance matrix, grouping variables and projects using cluster and factor analysis methods, and regressing the conformance values against the performance ratings from the project manager questionnaires.

I plotted the distribution of high, medium and low conformance values for each variable across the project sample, a total of 12 plots of eight values each. The different characteristics of the histograms yielded insights towards a new classification system for the variables. See Chapter 5 for the results of these analyses.

Transposing rows and columns of the conformance matrix allowed me to order the projects and the variables based on average values across the sample. This provided one mechanism for grouping both projects and variables into new related clusters, or dimensions. The use of grouping algorithms in an applied cluster analysis approach bolstered the results of the project groupings based on average value.

I also computed pairwise correlations for all the variables across the eight cases. One might expect that since the variables were all designed to measure some portion of the integrated environment, they would tend to move together. This was indeed the case, as the resulting correlation coefficient histogram was strongly positively skewed. The correlation coefficients also formed the basis for a principle components factor analysis of the variables, which led to the discovery of three underlying variable groups, or dimensions. See Appendix N for a detailed description of this process.

Finally, I regressed the project conformance values against the measures of project performance from the follow-up questionnaires. This was an attempt to discover any relationship between the two sets of data that might give the conformance values some measure of predictive power. The results of the regression analysis did not reveal any significant relationship between the degree of conformance and the degree of performance. These results are presented in detail in Appendix M.

The analysis of the project conformance data is described in detail in Chapter 5 and the results of the multivariate analysis and the regression on the performance data are discussed in Appendices M and N. The project data analysis resulted in a series of conclusions that are reported in Chapter 6. The conclusions include high level abstractions, practical implications for managers, and opportunities for future research.

POSSIBLE SOURCES OF ERROR

I identified four potential sources of error in this research. These include the sensitivity of the conformance values, non-response bias, temporal bias, and interviewee bias. This section describes these possible sources of error and describes the actions I took to mitigate their impact on the validity of the study.

Conformance value sensitivity

The use of a three-tiered ranking scale and a small sample results in average conformance values for projects and variables that are fairly sensitive to changes in individual conformance values. This means that if there is an error in assigning a conformance value to one variable on one project, the average value for the project or for the variable will change markedly.

One way to mitigate this impact would be to use a ranking scale with more degrees of freedom. However, the apparent greater degree of precision this would impart would probably not be valid given the subjective nature of the data. Given the qualitative nature of the variables and the characteristics of the data that each captures, a ranking scale with more than three tiers would be difficult to apply, and would impart a higher degree of precision than is warranted.

I reviewed the conformance values three separate times. The first assignment was made as each case was written. There were some revisions to the values during the second iteration, based on the clarifications and comments by the project managers. The third pass focused on internal consistency as well as consistency against the manufacturing framework, and resulted in only one change. The fact that there was only one change during the last iteration supports my position that the ranking criteria were applied consistently. Consistent ranking leads to greater accuracy in assigning conformance values.

Non-response bias

One possible source of bias in the project selection procedure stems from the fact that access to the firm and the project was a necessary and important attribute. Therefore, one might argue that there is a non-response bias since I only collected data from projects that "responded" or willingly participated. That is, those firms that declined to participate may have done so if their management felt that there were some reason to not make public information about a particular project. The argument follows that the sample might be skewed towards more successful projects.

However, the data collected from the follow-up questionnaire to the project managers tends to refute this argument. When asked to define performance measures and rank their projects on those measures on a scale of one to ten, the responses ranged in value from four to ten. These responses are plotted in **Figure 2-1**, and as might be expected, are skewed towards the high end. After all, every project was indeed successful in that it finished and produced electricity, and there is undoubtedly a personal response bias when ranking one's own project. However, the variation in the response values not only indicates that the project managers were frank in their responses, but that the sample is not systematically biased due to non-response.

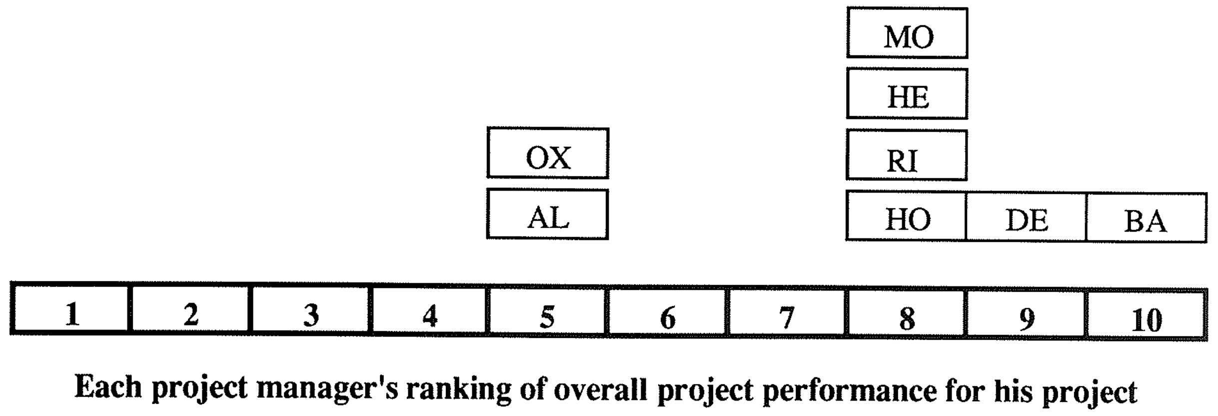


Figure 2-1

Project manager questionnaire response data

Temporal bias

Another possible source of error stems from the fact that each case study is a snapshot in time. It is conceivable that there might be a systematic bias in data collection based on the project phase. Projects in the early phases might be learning organizationally or be in the process of team building. The nature of the interactions between project participants changes as the project progresses. Data from projects in the later stages might be selectively filtered by hindsight or by the euphoria of start-up and successful operation.

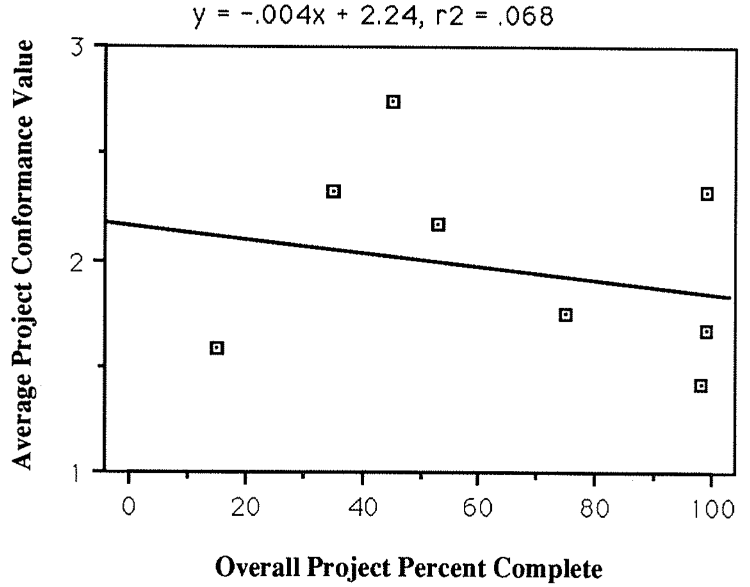
In order to obtain a representative perspective of conditions during the life of cogeneration projects, I specifically selected projects at different phases for inclusion in this study. They ranged from projects that had not broken ground to projects that were in the start-up phase and substantially complete. If there were a systematic bias to project data based on the timing of the interviews, one might expect to see the bias reflected in some correlation between the project conformance value and the degree of project completion.

Meaningful comparative data on the degree of overall project completion were difficult to obtain, primarily due to different tracking and reporting mechanisms on the different projects. As a measure of overall completion, I used an average value of the percent complete for engineering and for construction at the time of the interviews.

Figure 2-2 is a plot of a regression of project percent completion against project average conformance value. The flat slope of the regression line and the correlation coefficient of 0.068 indicate that there is no apparent relationship between a project's assigned conformance value and the project phase during which data was collected.

Interviewee bias

One source of error in collecting the raw data is individual or personal bias on the part of the interviewee. This may be the result of incomplete information, personal feelings, filtering due to the passage of time, lack of experience, or other factors. The best safeguard against individual bias is to interview a number of different people on each project. Other measures include reviewing project documents to substantiate interview data, observations of the site and the office environment, and the experience base of the the interviewer.



Project	MO	BA	HE	AL	DE	OX	RI	HO
Average of %E & %C completion	45%	99%	35%	53%	75%	99%	15%	98%
Average project conformance value	2.75	2.33	2.33	2.17	1.75	1.67	1.58	1.42

Figure 2-2

Project percent complete plotted against average conformance value

I talked to a total of 59 people on the eight projects I visited. The number of interviewees on each project ranged from six to nine. They also represented a range of positions and perspectives, from project managers to field engineers to owner's representatives. In most cases, the information from the different sources was complementary. In the few instances where there was a conflict in the data, I generally relied on the information provided by the project manager. This was based on the assumption that he had access to the best project information and had the best overall project perspective.

This chapter addressed methodology issues in a general sense and described the particular activities that transpired during the course of this research, as well as potential sources of error. One of the key elements of the research methodology was the development of the framework of integrated manufacturing. The next chapter presents the literature that provided the basis for the framework, and introduces the reader to the framework variables.

CHAPTER 3

LITERATURE REVIEW AND THE INTEGRATED MANUFACTURING FRAMEWORK

INTRODUCTION

This chapter presents a review of the integration literature and the structure of the framework of integrated manufacturing that I developed from the manufacturing literature.

Chapter 1 provided an an introduction to the concepts of integrating product and process engineering. Chapter 2 described the methodology used in this research, including the approach I used to building the framework of integrated manufacturing described in this chapter.

This chapter begins by defining the point of departure for this research. It then presents an overview of integrated manufacturing and a discussion of the reported benefits of the approach. Finally, this chapter presents the framework that I developed to organize the attributes of the integrated manufacturing environment.

POINT OF DEPARTURE

Research related to integration can be segmented in a number of ways. **Figure 3-1** illustrates two parameters that differentiate integration research, the industry studied and the level of granularity, and also presents a third parameter, the concept of comparative studies between industries. The following sections present an overview of integration research at the three levels of granularity, industry studies, firm or project studies, and integration tools. The sections are organized by industry, manufacturing and construction, and also discuss inter-industry comparative work.

Manufacturing research

There is a large body of literature in the manufacturing sector that addresses integration. At the industry level, Porter (1980) offers a schema for classifying competitive strategies.

Integration Research

	Manufacturing	Comparitive Research	Construction
Industry Studies	Porter (1980, 1985) Hayes, Wheelwright (1984) Hayes, Wheelwright, Clark (1988) Riggs (1983) Gunn (1987) Jaikumar (1986) Rubinstein and Ginn (1985)	Office of Technology Assessment (1987) Sanvido and Medeiros (1989)	Business Roundtable (1982) Construction Industry Institute (1986) Tatum (1988)
Firm or Project Studies	Schonberger (1987) Ampex (1987) Sun (1988) Plus (1986) Deere (1988) Leuenberger (1986)		O'Connor, Rusch and Schultz (1987) Vanegas (1988) Williams (1987)
Integration Tools	Cutkosky and Tenenbaum (1989) Allen (1987) Donovan (1989) Skevington (1984) Teicholz and Orr (1987)	CAD systems Knowledge based systems Simulation systems Paulson (1985)	Howard and Rehak (1986) Tommelein et al. (1987) Cleveland (c. 1989)

Figure 3-1

Classification of integration research

Hayes and Wheelwright (1984), and Hayes, Wheelwright and Clark (1988), discuss the concept of creating competitive advantage through improved manufacturing capabilities, including closer interaction between product and process engineering. Riggs (1983) describes management issues such as team building in high technology firms, and Adler (1988a) offers an excellent guide to the Technology Strategy literature. Other authors discuss the general topics of designing for manufacturability and integrating the efforts of research and development, or engineering, and manufacturing. (See Clark, 1988b; Dwivedi and Klein, 1986; Etienne, 1981; Fischer, 1982; Gold, 1986; Gomory, 1989; Hales, 1986; Hounshell, 1988; Koenig, 1981; Rubinstein and Ginn, 1985; Schonberger, 1987; Shapiro, 1977; and Weinrauch and Anderson, 1982.)

Numerous case studies of individual firms or development projects within firms are provided by the Harvard School of Business Administration and the Stanford Graduate School of Business. (See Ampex, 1987; Sun, 1988; Plus, 1986; or Deere, 1988.) Advocates of design for manufacturability describe efforts at incorporating manufacturing "know how" into a firm's product design process. (See Atkinson, 1985; Avishai, 1989; Clark and Fujimoto, 1988a, 1988b, and 1991; Donovan, 1989; Ettlie and Reifeis, 1987; Hayes and Wheelwright, 1979; Heidenreich, 1988; Jaikumar, 1986; Magaziner and Patinkin, 1989; Rooks, 1987; and Whitney, 1988.)

At the level of integration tools, the manufacturing industry is leading the way in the development and use of automated technologies such as computer aided manufacturing (see Teicholz and Orr, 1987 for an overview) and computer aided design that are shared resources for both product and process engineering. (See Cutkosky and Tenenbaum, 1989; Skevington, 1984; "Smart Factories", 1989.)

Construction research

The Business Roundtable's "Construction Industry Cost Effectiveness Project" was a seminal work that resulted in a series of "grey books" describing the impacts of project management, construction technology, labor, training and regulations and codes on the construction industry. One report specifically addressed integration and identified constructability as an important mechanism for incorporating construction knowledge and experience into engineering (Business Roundtable Report B-1, 1982). The Construction Industry Institute (CII) sponsors research in a number of areas identified by the Business

Roundtable, including constructability and engineering-construction integration (see "Constructability: A Primer," 1986).

Construction integration research at the project or firm level has focused on constructability improvement at different phases in the project life cycle, (see Tatum, Vanegas and Williams, 1985; O'Connor, Rusch and Schultz, 1987) and on the use of specific methods to aid constructability (Tatum, Vanegas and Williams, 1986). Tatum (1983) used project case studies to explore organizational decision making in structuring project organizations, and later (1988) provided a concise overview of constructability and construction integration research. Vanegas (1988), and Williams (1987) used case studies of construction projects as a method of investigating constructability issues.

The Center for Integrated Facility Engineering at Stanford University has sponsored extensive research in the area of developing integration tools. This research includes an investigation of using constructability knowledge during preliminary design of reinforced concrete structures (Fischer, 1991). This project focused on identification of constructability knowledge, representation in an expert system, and evaluation of constructability using project data from a linkage with a CAD database. Related work includes integrated database systems (see Howard and Rehak, 1986), knowledge based systems for incorporating construction preferences into site layout (see Tommelein et al., 1987), and the use of computer integration to reduce fragmentation in the architectural, engineering, and construction industry (see Howard et al., 1989).

Comparative research

There is less in the way of comparative research between the manufacturing and construction industries. At the industry level, comparative statistics such as those provided by the Office of Technology Assessment provide an overview or summary of data such as the volume of work or number of employees. Sanvido and Medeiros (1989) discuss opportunities for "cross fertilization," or learning across the two industries, and Paulson (1985) describes opportunities for the application of automation technologies in the two industries.

At the level of integration tools, there is considerable overlap in the development of automation tools that can foster integration, such as computer-aided design, discrete-event simulation, and knowledge-based systems, but this work rarely focuses on direct comparisons of applications in the two industries.

This research builds upon previous work, both in manufacturing and in construction, and addresses specific gaps in the structure of integration research as indicated by the empty box in **Figure 3-1**. It is a case-based approach to understanding issues and mechanisms of integration in both industries, and offers insights into the existing state of integration in manufacturing and on a selected sample of construction projects.

Examples of Integrated Manufacturing

There are numerous descriptions of integrated manufacturing in the literature. Wheelwright and Hayes developed the concept of a manufacturing strategy and identified four stages in the evolution of the strategic role of manufacturing (1985, p. 396). These describe an evolutionary process in the strategic role of manufacturing in a firm, as it moves from a Stage 1 "internally neutral" organization that merely reacts to designs passed down from engineering, to the goal of a Stage 4 "externally supportive" organization where the manufacturing function is regarded as an integral part of the firm's competitive strategy. Characteristics of the world class, fourth stage manufacturing organization include linking product design and manufacturing process design with an emphasis on "the parallel and interactive development of both products and processes." (Wheelwright and Hayes, 1985, p. 106)

General Electric's dishwasher development program emphasized the concurrent development of product and process design in an iterative and interactive fashion. In this case, both cost targets and high quality specifications drove engineering and manufacturing together, and management found that "it was necessary to coordinate product and process development, rather than separating them as had been the traditional practice." (Hayes and Wheelwright, 1984, p. 404)

Another Stage 4 firm, IBM, stressed the interaction of product and process technologies and emphasized "activities that facilitate, encourage, and reward effective interaction between manufacturing and both marketing and engineering." (Wheelwright and Hayes, 1985, p. 108)

Takeuchi and Nonaka (1986) describe a holistic approach to new product development that is analogous to a rugby match where the ball is passed back and forth as the team moves down the field. In addition to expediting the delivery of new products, this team approach can act as an agent for change as well as providing opportunities for the introducing new ideas and technologies. In a similar fashion, Stalk (1988) argues that reducing product development times can act as a source of competitive advantage, and describes the Japanese practice of using factory cells during product development. These cells are structured as cross-functional factory teams instead of the independent functional entities that traditionally perform sequential development.

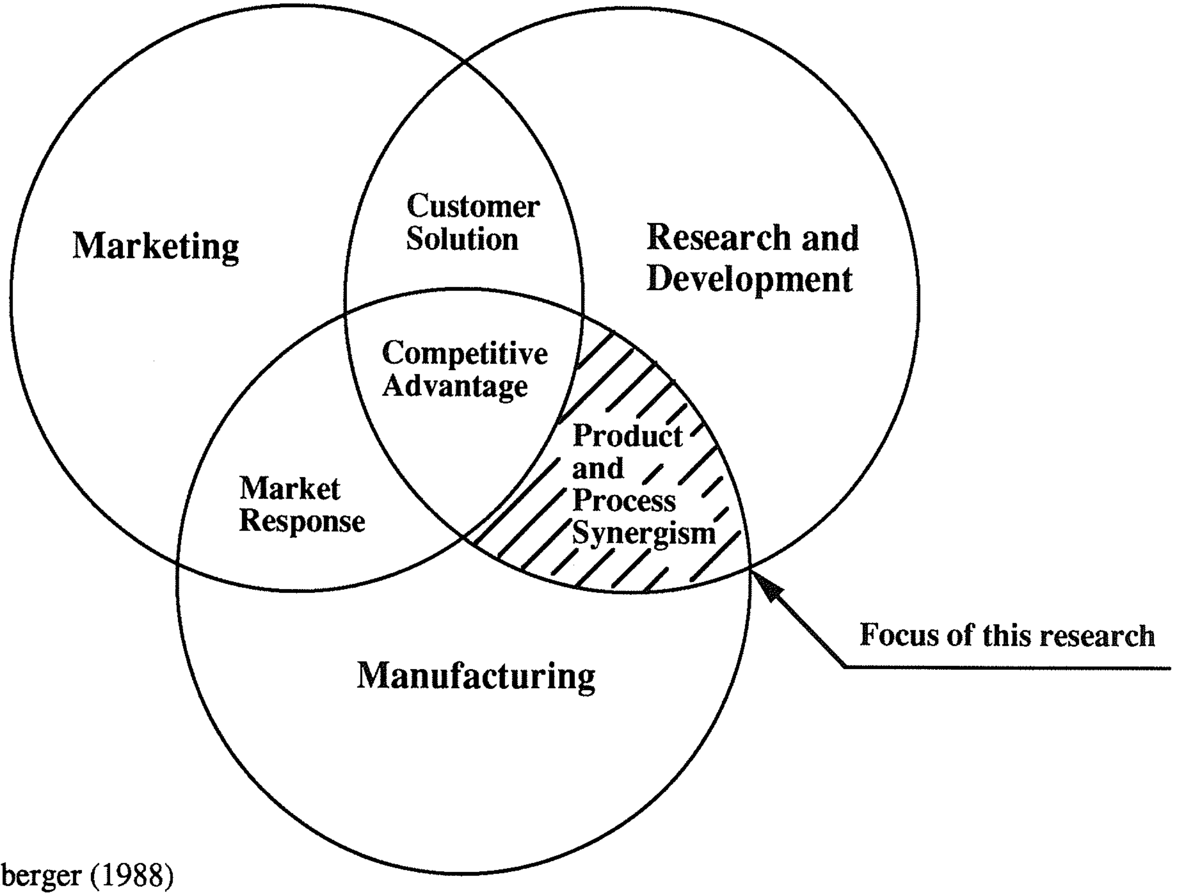
Hewlett-Packard's Sunnyvale Personal Computer Operation established the goal of creating a competitive advantage through the development of a world class manufacturing capability. Their philosophy of incorporating manufacturing as an integral member of their business team is illustrated in **Figure 3-2**. The firm applied its manufacturing philosophy during successive generations of its personal computer, resulting in a substantially simpler and more manufacturable product.

Benefits of Integrated Manufacturing

New product development projects face extreme pressure to shorten overall development cycle times. The use of a concurrent or integrated approach to product and process design affords an opportunity to shorten overall development times while, in addition, providing a framework for improved product quality, better manufacturability, and the opportunity to incorporate new process technologies.

The design and construction of projects ranging from buildings to complex industrial facilities also face similar project pressures. Schedule pressure is often the driving project constraint. The conventional paradigm of managing a series of independent, linear activities has traditionally been perceived as the optimum method of minimizing project costs. However, an integrated product and process development approach to the delivery of the constructed product may provide similar opportunities for project improvement to those observed in the manufacturing sector.

Commonly cited benefits of a concurrent approach to product and process design are the reduction in the lead time required to launch a new product, flexibility in producing new



(Adapted from Leuenberger (1988)

Figure 3-2

Hewlett Packard's manufacturing strategy:
Incorporate manufacturing as an integral and equal member of the business team

products, and delivery of higher quality products. Other benefits include the opportunity for innovation by encouraging trial and error and challenging the status quo. The holistic approach "stimulates new kinds of learning and thinking within the organization at different levels and functions," and can "act as an agent of change for the larger organization." (Takeuchi and Nonaka, 1986, p. 138)

Putnam (1985, p. 140) reports that "the advance thinking (integration) encourages about manufacturability, testability and serviceability contributes mightily to the goal of making things right the first time." Fewer engineering changes, more realistic specifications for tolerances, more certainty about quality and yield, and more complete specifications and controls are all benefits of integration that contribute to getting it right the first time.

Simpler products and processes also can result. Hewlett-Packard reported substantial decreases in the number of parts in its line of personal computers as well as fewer labor hours to assemble them (Leuenberger, 1986). General Electric's efforts at creating an integrated manufacturing environment included a focus on concurrent product and process design, which contributed to measurably better quality (in terms of reduced service calls), lower unit costs, higher throughput, lower reject rates, and greater productivity (Hayes and Wheelwright, 1984).

However, another perspective is offered by Ettlie and Reifeis (1987, p. 65), who describe their efforts at collecting longitudinal data on "the deployment of advanced manufacturing technologies in domestic plants," and make the argument that "the performance outcomes of adopting administrative innovations to enhance design-manufacturing integration have not yet been determined. Therefore, these results are preliminary and can best be used to generate propositions rather than to test models of effective integration."

THE FRAMEWORK OF INTEGRATED MANUFACTURING

After extensive review of the manufacturing literature and discussions with industry practitioners and academic researchers, I extracted a number of characteristics or attributes of the integrated manufacturing environment.

I aggregated the various attributes of integrated manufacturing into a series of 12 variables, each capturing a distinct aspect of the integrated environment. I further organized the 12

CONTEXT VARIABLES

Variable 1-A Project development environment
Variable 1-B Timing of product and process engineering
Variable 1-C Management perspective of integration technologies

ORGANIZATION VARIABLES

Variable 2-A Project team attributes
Variable 2-B Engineering - production interface
Variable 2-C Vendor interactions

PROCESS VARIABLES

Variable 3-A Communication patterns
Variable 3-B Engineering generalist
Variable 3-C Computer integration

CONTENT VARIABLES

Variable 4-A Production input to design
Variable 4-B Development of process plan
Variable 4-C Electronic data exchange

Figure 3-3

Integrated manufacturing framework variables

variables into four general groups: context, organization, process, and content. **Figure 3-3** presents an overview of the framework structure.

The manufacturing variables do not represent any one specific project; rather, they are aggregate values compiled from a review of current practice in integrated manufacturing. The context variables describe the environment in which the development effort takes place. The organization variables capture attributes of the structure of the product development group. The process variables delineate the mechanisms by which the various group members communicate and exchange information. The content variables describe the types of information that flow among the team members. This section describes each variable and presents the attributes of each variable as manifested in the manufacturing literature.

CONTEXT VARIABLES

Although most development projects are unique, there are a number of contextual factors that generally characterize new product development efforts. These include the project work environment, the temporal relationship between product and process design, and management's attitude towards integration technologies. The integration variables related to context and their associated attributes are summarized in **Figure 3-4**.

Variable 1-A Project development environment

The project environment in which the integrated development effort takes place is characterized by several traits. These include goal congruence, an open work environment, an emphasis on teamwork, and an overiding sense of time pressure.

Ettlie and Reifeis (1987, p. 72) describe a philosophical shift necessary to support a committed DFM program and report instances where firms are "resolving the problem of integrating design and manufacturing with a commitment to design for manufacturing (DFM) at higher levels in the business unit or the corporation." Whitney (1988, p. 85) reiterates this concept when describing the application of multifunctional teams and states that "top executives should make their support and interest clear."

Dwivedi and Klein (1986, p. 54) describe techniques for DFM/A (Design for manufacturability/assembly) and stress that "top management's commitment to automation and support of DFM/A principles is essential."

Integration Variable	Variable Elements
Variable 1-A Project development environment	• Overall project level goal congruence • Open environment that supports learning and is tolerant of mistakes • Emphasis on teamwork and problem solving • Time pressure to get the product out
Variable 1-B Timing of product and process engineering	• Concurrent or simultaneous product and process engineering • Overlapping development phases
Variable 1-C Management perspective of integration technologies	• Management takes long term time perspective • Management has strategic perspective of integration technologies

Figure 3-4

Integrated manufacturing framework - context variables

An open environment with clear communication of overall project goals is critical. When the two functions are isolated, product and process engineers may work towards different goals. "Where departmental barriers are high . . ., design engineers will attempt to maximize product performance and manufacturing engineers will try to redesign the product to reduce its cost." (Riggs, 1983, p. 130)

Takeuchi and Nonaka (1986, p. 143) emphasize the importance of an open environment that anticipates and is tolerant of mistakes, and they quote a 3M executive as saying "I believe we learn more from mistakes than from successes." However, they point out that "the key lies in finding the mistakes early and taking steps to correct them immediately."

The integrated environment is one in which learning takes place both across multiple levels in the organization and across multiple functions. In addition, learning takes place across disciplines and across projects. Takeuchi and Nonaka (1986, p. 143) term this "multilearning." Adler (1988b) also identifies five distinct levels at which learning occurs in the development organization: skills, procedures, structure, strategy, and culture.

Wheelwright and Hayes describe a four stage process by which firms progress to a point where they pursue a manufacturing-based competitive advantage by improving the link between product design and manufacturing process design. (1985, p. 104) They found that in the more progressive "Stage 4" firms, "the dominant approach to the work force must be in terms of teamwork and problem solving, not command and control."

New product development efforts generally take place in a high pressure environment to shorten lead times to get new products to market more quickly. Stalk (1988, p. 49) stresses the importance of reducing new product development cycle times and asserts that "unless U.S. companies reduce their new product development and introduction cycles . . . Japanese manufacturers will easily out-innovate and outperform them."

The attributes that describe this variable are overall project level goal congruence, an open environment that supports learning and is tolerant of mistakes, an emphasis on teamwork and problem solving, and time pressure to get the product out.

Variable 1-B Timing of product and process engineering

The traditional approach to product development is that of a linear, sequential series of activities with manufacturing the downstream user of information developed by product design. This commonly culminates with product design "throwing the design over the wall" to manufacturing after most major design decisions have been made. Changing the temporal relationship between product and process design is a key aspect of integrated manufacturing. This is demonstrated by the implementation of simultaneous product and process development efforts; that is, the activities take place concurrently. The simultaneous effort is also characterized by overlapping development phases. The activities associated with each phase support each other in an interactive fashion rather than sequentially.

Characteristics of the world class, fourth stage manufacturing organization include linking product design and manufacturing process design with an emphasis on "the parallel and interactive development of both products and processes." (Wheelwright and Hayes, 1985, p. 106)

As an example, they cite General Electric's dishwasher development program in 1983, which emphasized the concurrent development of product and process design in an iterative and interactive fashion. In this case, cost targets and high quality specifications drove engineering and manufacturing together, and management found that "it was necessary to coordinate product and process development, rather than separating them as had been the traditional practice." (Hayes and Wheelwright, 1984, p. 404)

Examination of another Stage 4 firm, IBM, found that it stressed the interaction of product and process technologies and emphasized "activities that facilitate, encourage, and reward effective interaction between manufacturing and both marketing and engineering." (Wheelwright and Hayes, 1985, p. 108)

Hewlett-Packard found that "it is the design of your products that determines the fundamental characteristics of your manufacturing operations." (Leuenberger, 1986) Three requirements that Hewlett-Packard identified for a successful concurrent design effort are a recognized need, management commitment to the design process, and engineering focus on maximizing synergy between product and process designers.

Takeuchi and Nonaka (1986) argue that the traditional sequential approach of passing product designs from engineering to production is inappropriate for firms that require both speed and flexibility in new product development. Rather than the traditional sequential approach to passing product designs to manufacturing, which they liken to passing a baton in a relay race, they describe a holistic approach to new product development that is likened to a rugby match where the ball is passed back and forth as the team moves down the field. An important characteristic of the holistic approach is overlapping, rather than sequential, developmental phases.

Similarly, Stalk (1988) described reduced product development times as a source of competitive advantage, and observed the Japanese practice of using factory cells during product development. These firms use cross functional factory teams, rather than sequential development by functional teams. In addition, the Japanese often use decentralized product development scheduling, as opposed to the Western approach of highly centralized scheduling and tracking.

Billatos (1988, p. 165) presents a series of guidelines for manufacturability and maintains that the "essence of the DFM (Design for Manufacturability) is, therefore, the integration of product design and and process planning into one common activity."

Cutkosky and Tenenbaum (1989, p. 19) describe a spectrum of approaches to design and manufacture. At one end is the "traditional approach in which design and manufacturing are virtually decoupled, and complete designs are 'thrown over the wall' to the production department." The other end of the spectrum is fully concurrent design and process planning facilitated through the use of CAD and expert systems to facilitate sharing information from common databases.

The attributes that comprise Variable 1-B are concurrent or simultaneous product and process engineering and overlapping development phases.

Variable 1-C Management perspective of integration technologies

The project environment is not the only environment in which the development process takes place. The firm, division, or business unit also has a unique culture and set of attitudes. One important aspect of this culture is the perceived value of new technologies, in particular those computer and automation technologies that support and enhance the integrated effort. This is reflected in a long term perspective regarding the acquisition of new technologies, and an appreciation of the strategic value of those technologies in supporting a level of competitiveness that insures the firm's survival and success.

Wheelwright and Hayes (1985, p. 103) cite one characteristic of the Stage 4 manufacturing firm as anticipating "the potential of new manufacturing practices and technologies and seek(ing) to acquire expertise in them long before their implications are fully apparent." This is representative of a long term commitment to developing expertise in new technologies with the perceived benefits accruing to the firm as a whole over the long term, not just to projects in progress.

The Budd Company, a supplier to Ford Motor Company, worked with Ford to interconnect their computer systems with Ford's in order to exchange design information more quickly on the development of a new automobile front end suspension part. Budd viewed the project a success based not only on the results for the specific project, but primarily by "allowing the company to develop a fully computerized design and manufacturing system essential to future competitiveness." ("Re-inventing the wheel," 1989, p.79)

Hayes and Jaikumar (1989, p. 83) liken the investment in new manufacturing technologies to buying "table stakes" in the competitive game. Those firms that do not choose to enter the game by investing in the new technologies may not be at the table in a few years. They point out that traditional capital budgeting methods often exclude benefits from new technology's "increased operating flexibility, the novel products it might facilitate, or the knowledge that the computerized systems would generate–i.e., 'soft' benefits."

The two attributes that characterize Variable 1-C are the management characteristics of a long-term time perspective and a strategic perspective of integration technologies.

ORGANIZATION VARIABLES

The organization variables capture the structure of the new product development project and how the different members of the team are related. The organization variables include the attributes of the project team, the engineering/production interface, and external vendor and supplier relationships. These organization variables and their associated attributes are presented in **Figure 3-5**.

Integration Variable	Variable Elements
Variable 2-A Project team attributes	• Dedicated cross-functional teams • Heavyweight project manager or Tiger Team approach • Joint accountability and reward systems • Continuity of team members through the project
Variable 2-B Engineering-production interface	• Manufacturing is customer of product design • Use of formal liason group to expedite design production interface • Use of producibility experts or integrators
Variable 2-C Vendor interactions	• Early vendor involvement • Strong vendor relations based on partnering • Use of fewer suppliers

Figure 3-5

Integrated manufacturing framework - organization variables

Variable 2-A Project team attributes

The importance of structuring a dedicated development team to promote integration is stressed repeatedly in examples from the literature. Both the structure of the group and the composition of its members are critical elements. Characteristics of this variable include dedicated cross-functional teams, the use of heavyweight project managers or a Tiger Team approach, and joint accountability and reward systems.

Dean and Susman (1989, p. 30) describe the use of dedicated cross-functional teams as an integrating mechanism. "At a minimum, these consist of a designer and a manufacturing engineer, who work together throughout the whole process." Ettlie and Reifeis (1987, p. 65) describe one case study of design-manufacturing integration where "at the engineering level, manufacturing engineering and design engineering are required to work together as a 'coordinated team.'"

Takeuchi and Nonaka describe the same sort of multi disciplinary, cross functional team and emphasize balancing the team between conservatism and radicalism, while closely monitoring shifts in group dynamics. They also (1986, p. 138) contrast the "rugby" approach to product development to the traditional "relay race" approach of sequential activities by a series of functional specialists. "Under the rugby approach, the product development process emerges from the constant interaction of a hand-picked, multidisciplinary team whose members work together from start to finish." Hayes, Wheelwright, and Clark (1984, p. 332) offer a "New Paradigm" for product and process development and identify the use of a "cross-functional team effort throughout."

Hayes, Wheelwright, and Clark (1984) describe four types of organizations for development projects: functional organization, lightweight project manager, heavyweight project manager, and "Tiger Team." The four organizational structures represent a spectrum that ranges from purely functional groups through strong and weak matrix structures to dedicated project teams. They conclude that the heavyweight project manager (weak matrix) and the Tiger Team (dedicated project team) are the most effective structures for the new, integrated approach to project execution. In a similar fashion, Putnam (1985, p. 143) describes the effectiveness of "small groups that work independently on projects (and) gradually shift employee's allegiance from specialized departments to interfunctional work teams." He also argues that the "final and most important step is organizational . . .

Organizations must eliminate the structural barriers that prevent team spirit from crossing departmental lines." (Putnam 1985, p. 144)

The tiger team approach in many ways resembles the Skunk Works described by Peters and Waterman as "bands of eight to ten zealots off in a corner, often outproducing product development groups that numbered in the hundreds." (1982, p. 201) The objectives of creating a skunk works environment are to "recapture the advantages of the small company: high motivation, focused purpose on a single product, system, or process, and intensive and informal communication with a minimum of organizational barriers." (Riggs, 1983, p. 133) Riggs gives three project criteria for creating a skunk works environment: input from a number of engineering disciplines; stringent manufacturability and cost requirements; and telescoping the design and product introduction stages.

Takeuchi and Nonaka (1986, p. 143) emphasize the importance of "establishing an evaluation and reward system based on group performance," and cite as an example one firm's application for patents on a development group basis. Wolff (1985, p. 10) also cites joint accountability as an important factor in establishing credibility among different groups, and quotes McHenry, "if the manufacturing person knows that his R&D counterpart has the same goals, that's certainly going to help the credibility problem."

Attributes of Variable 2-A include dedicated cross-functional teams, a heavyweight project manager or tiger team approach, joint accountability and reward systems, and continuity of team members throughout the project.

Variable 2-B Engineering-production interface

This variable describes several approaches to structuring the engineering-manufacturing interface to promote integration. Specific mechanisms include focusing on manufacturing as the customer of design, using organizational groups that facilitate interaction, and assigning individuals as producibility experts.

Heidenreich discusses methods for designing for manufacturability and notes that the design-manufacturing interface should be viewed differently than it has been traditionally, where designs are typically thrown over the wall to manufacturing. "The essential difference in this model is that manufacturing is now the primary customer of the product design." (Heidenreich, 1988, p. 41)

Graves and Poli (1987) describe an Advanced Manufacturing Technology organizational unit that provides technical assistance to both product designers and manufacturing engineers. Its purpose is threefold: assist product designers in assessing producibility implications of new products; assist manufacturing engineers in assessing new manufacturing technologies; and coordination of product and process design databases.

Similarly, Ettlie and Reifeis (1987, p. 66) describe the Advanced Automated Technology Systems Group (AATS) at General Electric's steam turbine division. "This group was created specifically 'to act as an integrating force between manufacturing and engineering.'"

Ampex Corporation created the Product Matrix Engineering Group to act as "a liaison effort between new product engineering and manufacturing." (Ampex, 1987, p. 9) Although the group was "envisioned as a natural buffer between manufacturing and engineering," it became an integrating force by promoting communication between the two groups.

Dean and Susman describe the role of the integrator, or producibility coordinator. "Integrators work with designers on producibility issues, serving as liaisons to the manufacturing group." (Dean and Susman, 1989, p. 29) Their concept of the integrator is that of a person who develops sufficient expertise or understanding of both disciplines that he can facilitate communication between the two. Even though the integrator is often an engineering generalist, he essentially becomes a producibility expert.

The attributes of Variable 2-B are manufacturing as the customer of product design, the use of a formal liaison group to expedite the design-production interface, and the use of producibility experts or integrators.

Variable 2-C Vendor interactions

In addition to product and process engineers within the firm, the integrated development team interfaces closely with outside vendors and suppliers. These interactions are characterized by early involvement of suppliers, strong vendor relations, and a reduced number of vendors with which the firm does business.

The process of integration is not limited to the internal project participants. Takeuchi and Nonaka (1986) describe involving suppliers early during design as a characteristic of the integrated approach. Leuenberger (1986) cites the establishment of strong relationships with suppliers of material, machinery and equipment as a lesson that Hewlett-Packard learned during the integrated approach to the development of its Vectra personal computer.

Plus Development Corporation developed the concept of "single sourcing" components with a small number of suppliers with whom it worked closely over a period of time. As differentiated from sole sourcing, Plus would typically arrange with one supplier to provide a specific component, while retaining the capability of sourcing that component through other suppliers if necessary. Plus reported that "strong vendor relations developed," (Plus, 1987, p. 10) due to its partnership approach to working with vendors.

The Economist ("Re-inventing the wheel," 1989, p. 78) reports that General Motors has also adopted a single sourcing approach. "Now almost all GM's parts are single-sourced." The firm has also shifted toward the concept of "'collective practice.' The idea is to establish longer term relationships with suppliers, and to involve them in product development much earlier - almost like internal departments of the company."

Ettlie and Reifeis (1987, p. 67) cite the example of Xerox, which reduced the number of suppliers with which it deals from over 5,000 to around 300 as part of an overall shift to an integrated approach to copier development.

Variable 2-C is characterized by three attributes. These include early vendor involvement, strong vendor relations based on partnering, and the use of fewer suppliers.

PROCESS VARIABLES

The process dimension describes the process of integration and the communication mechanisms on the integrated development project. Variables that characterize the process dimension include communication patterns, the role of the engineering generalist, and the implementation of a computer integrated manufacturing philosophy. These variables, as well as their attributes, are summarized in **Figure 3-6**.

Variable 3-A Communication patterns

An integrated approach to product development depends on effective communication, both between functional teams and between team members. This variable captures the nature of communication patterns within the integrated team, and includes such characteristics as full

Integration Variable	Variable Elements
Variable 3-A Communication patterns	• Full two way information exchanges between design and production • Direct horizontal (lateral) exchanges rather than vertical flows • Continuous, low level interaction that supports low level decision making • Extensive communication, both formal and informal • Manufacturing approval for design release or veto of engineering design
Variable 3-B Engineering Generalist	• Engineering generalists as team leaders • Experience in more than one discipline • Translator function between functional groups
Variable 3-C Computer Integration	• Applied automation technology in four areas, product design, process design, production, and information management • Integration of these distributed automation efforts • Direct linking of design tools and manufacturing systems using CIM network technologies • Common CAD database and model for product and process design permits mutual and concurrent access by design and manufacturing • MIS group as well as engineering takes active role in computer integration

Figure 3-6

Integrated manufacturing framework - process variables

two-way information flows, extensive horizontal communications, continuous low level communication among team members, and extensive formal and informal exchanges, and often some form of manufacturing approval for design releases.

Adler (1988b) describes tacit knowledge, design rules and functional strategies as examples of one-way, stilted one-way and two-way information flows, respectively. All of these modes can be effective in communicating manufacturing capabilities to design, depending on the project phase. However, concurrent design requires a full two-way communication pattern between design and manufacturing. Wolff (1985, p. 9) supports the concept of two way information flow and observes that "the manufacturing/R&D interface is healthy only when technology transfer occurs in both directions."

The traditional "command and control" manager described by Hayes and Jaikumar (1988, p. 82) often functions in a vertical hierarchy that requires that information and decisions flow up and down the hierarchy rather than across the organization at lower levels. Command and control managers also tend to rely on outside expertise that is "purchased" as necessary for the project rather than cultivating in-house people, equipment and systems experience. They maintain that "the interfunctionality engendered by the new manufacturing can mean much more informal cooperation at low levels in the organization—between engineers and market analysts, designers and manufacturers."

Wolff (1985, p. 10) also mentions the importance of keeping communications at a low level to prevent filtering. In a vertical hierarchy, "the needs won't be well stated as far as manufacturing is concerned and the requirements of the process won't be well stated as far as R&D is concerned."

The nature of the information flows is different with an integrated approach. Rather than transferring large portions of relatively complete designs, information flows continuously through "many smaller two-way exchanges throughout development," as described by Hayes, Wheelwright, and Clark (1988, p. 333).

Riggs notes that "extensive communication between engineering and production is critical to implementing the firm's technical policy." (1983, p. 129) He also emphasizes the importance of both formal and informal communications mechanisms, and comments that "much of the traditional tension between engineering and production turns on the problem of communication." (1983, p. 122)

Hayes and Jaikumar (1988, p. 82) point out that firms that have mastered the new manufacturing technologies "strive to build close horizontal relationships throughout the company, so that product designers work directly with manufacturing process designers . . . Decisions are pushed down to operating level."

Since manufacturing is typically the downstream user of, and therefore dependent upon, information generated by the design group, product designers are often in a position of power compared to their manufacturing counterparts. The integrated project shifts a portion of this power to the manufacturing group. This may take the form of a manufacturing signoff or conversely, production veto authority.

Dean and Susman (1989, p. 29) describe the concept of the manufacturing sign off, where "manufacturing engineers are given veto power over product designs, which cannot be released without manufacturing's approval."

Port cites the organizational changes that accompanied the integration of the B-2 development process. Production was involved in every step of the design process and could actually veto specific designs. "Manufacturing got veto authority over the design. . . . it was necessary for the downstream disciplines, especially manufacturing, to have access to the engineering information before it was released and veto it if they felt it would impede them." (Port, 1989, p. 143)

The attributes that characterize Variable 3-A are full two way information exchanges between design and production; direct horizontal (lateral) exchanges rather than vertical information flows; continuous low-level interaction that supports low-level decision making; extensive communication, both formal and informal; and either manufacturing approval for design release or manufacturing veto authority over engineering design.

Variable 3-B Engineering generalist

There is a growing recognition of the role that the engineering generalist can play as part of the integrated project team. This variable presents the concept of the engineering generalist as a team member with experience in more than one discipline, who can function both as a team leader and as a translator between different functional groups.

Hayes and Jaikumar (1988, p. 82) describe the traditional "command and control" style of manager that thrives "in hierarchical organizations in which the primary relationships between people are vertical." They contrast this style with that of the generalist that strives to "build close horizontal relationships throughout the company, so that product designers work directly with manufacturing process designers" to create an environment where "decisions are pushed down to the operating level."

Eaton describes attributes of the simultaneous engineering team. He notes that "The programme needs a single leader. Ideally, this leader would have a varied background from many disciplines." (Eaton, 1987, p. 188)

In addition to structuring the team, there is an emphasis on selecting the "right" people, who are characterized as top notch, hand picked, able to work under uncertainty, and able to put project goals above their own discipline goals. Although the functional specialists bring specialized discipline knowledge to the team, Hayes and Jaikumar (1988, p. 82) observe that "the companies that have mastered the new technologies prize generalists."

This was reflected in one of the criteria for participating the Product Matrix Engineering Group at Ampex Corporation. This group acted as a liaison group between engineering and manufacturing during new product development. One criterion for staffing the group was the "'green beret' principle–each (member) must have experience in more than one function." (Ampex, 1987, p. 9)

Ettlie and Reifeis (1987, p. 73) make note of the role of the producibility engineer and describe this person as an engineering generalist who illustrates the "evolution of a new breed of engineer needed to integrate design and manufacturing, . . . quite different from the more narrowly trained and narrow task assigned engineers typical in many firms today." Based on a series of nine case studies, they conclude that both "DFM and engineering generalists . . . are likely to be adopted in all successful cases of design-manufacture integration."

Variable 3-B attributes include engineering generalists as team leaders, generalists with experience in more than one discipline, and team members who perform a translator function between functional groups.

Variable 3-C Computer integration

The implementation of sophisticated computer and machine tools in manufacturing has often proceeded haphazardly, leading to "islands of automation" or "islands of information." Integrated approaches to connecting these islands include applying automation technology in four distinct areas, integrating distributed automation efforts, directly linking design tools and manufacturing systems using network technologies, using common CAD databases and models for both product and process design, and corporate MIS groups taking an active role in computer and CAD integration.

The development of electronic communications conduits is the focus of considerable project automation efforts. New tools such as CAD (Computer Aided Design), CAE (Computer Aided Engineering) and CAM (Computer Aided Manufacturing) all address issues concerning more efficient information conduits. These and other automation technologies are grouped under the common sobriquet of computer integrated manufacturing, or CIM.

CIM is defined by Teicholz and Orr (1987, p. 1.26) as the "use of database and communication technologies to integrate the design, manufacturing, and business functions that comprise the automated segment of the facility." Their vision of CIM is broadly composed of four areas that are tied together by a central common database, engineering design, manufacturing engineering, factory production, and information management. Billatos (1988, p. 166) takes a complementary approach and breaks CIM into four similar areas. These include product design, manufacturing engineering, production, and manufacturing planning and control systems.

In a sense the elements of CIM are merely tools that expedite the flow of information between project participants. However, they are themselves an integrating force on a project, and can change the nature and the timing of the information content that flows through them.

"Integrated manufacturing smooths the adoption of such advances as CAD/CAM and group technology and ensures that important information is shared. With integrated manufacturing, a company can realize the benefits of having a common database: engineering has access to information about processing at the same time manufacturing has access to data on standards and families of parts." (Putnam, 1985, p. 143)

Ettlie and Reifeis report on the use of common CAD systems for both engineering and manufacturing. "The division did not start out with two separate CAD systems–one for product design and one for tooling and fixturing or process design . . . They insisted on one common system–nothing solely home grown was allowed."

John Deere used Group Technology (GT) methods to provide a "foundation for computer integrated manufacturing (CIM) at Deere. GT's feature–based representation of parts provides a common neutral "language" to bridge computer aided design (CAD) and computer aided manufacturing (CAM), a fundamental requirement for CIM. With (its) system, the design database becomes the same base used for manufacturing." (Deere, 1988, p. 6)

Hayes and Jaikumar (1988, p. 81) point out that piecemeal implementation of automation technologies can be counter-productive. "No one component of a CIM network–a parts rationalization system, a CAD system, an FMS, a plant floor data collection and information system, or a customer communication system–may be able to meet as company's profitability requirements. The desired returns materialize only when all these advances are in place." But they also point out that "building such a system requires a strategic vision, lots of money up front, and a tremendous amount of patience."

In response to the issue of these "islands of automation," and in the absence of industry wide standards, General Motors developed it's own MAP or "manufacturing automation protocol." MAP is a "set of rules that govern how . . . machines of any make should communicate with each other." ("Factory of the Future," 1987, p. 10) Faced with similar fragmentation, but among "islands of information," Boeing developed its own communications standard, TOP (technical and office protocol) to facilitate the flow of information among different computer systems. ("Factory of the Future," 1987, p. 12)

Putnam (1985, p. 143) makes the point that an integrated approach actually facilitates the implementation of automation tools. "Integrated manufacturing smooths the adoption of of such advances as CAD/CAM and group technology and ensures that important information is shared. With integrated manufacturing, a company can realize the benefits of having a common database: engineering has access to information about processing at the same time that manufacturing has access to data on standards and families of parts."

Rosenthal and Ward (1985) point out that "manufacturing and planning and control systems have traditionally have been developed by EDP specialists in the corporate MIS group who work with manufacturing groups to define applications. CAD/CAM, in contrast, has emerged in most companies as an engineering function."

Ettlie and Reifeis also describe the use of a common reporting position for computerization. (Ettlie and Reifeis, 1987, p. 71-72) They relate four instances where "a common, consolidating, organizational reporting relationship was installed to integrate design, manufacturing, and other functions in the business unit." They go on to say that "this adaptation illustrates a structural solution to the growing conflict between the management information system (MIS) and the computerized integrated manufacturing (CIM) function."

The five attributes of Variable 3-C are: the use of applied automation technology in four areas, product design, process design, production, and information management; the integration of these distributed automation efforts; direct linking of design tools and manufacturing systems using CIM network technologies; common CAD database and models for product and process design that permit mutual and concurrent access by design and manufacturing; and the active participation of the MIS group as well as engineering, in implementing computer integration.

CONTENT VARIABLES

The content dimension captures the nature of the information exchanged between the product and process design groups in the integrated environment. This includes production input to design, the development of the process plan, and electronic data exchange. These variables and their associated attributes are listed in **Figure 3-7**.

Variable 4-A Production input to design

This variable describes manufacturing input to product design. This input typically includes the identification of critical components, sharing experience with different vendors, details of manufacturing process capabilities, and feedback on manufacturability.

The Product Matrix Engineering (PME) group at Ampex was formed to act as an interface between engineering and manufacturing. The PME group spent considerable time identifying what it termed critical parts and determining the advance information that

Integration Variable	Variable Elements
Variable 4-A Production input to design	• Identification of long leadtime or critical components that can drive schedule • Vendor prequalification • Process capabilities • Feedback to design on manufacturability
Variable 4-B Development of process plan	• Use of a formal planning procedure resulting in documented process • Detailed material, labor, and equipment requirements for production • Detailed assembly sequences
Variable 4-C Electronic data exchange	• Dimensional and material characteristics of components • Process characteristics and requirements, expert knowledge of assembly methods • Optimal shop floor layouts, machine allocation and distribution, tooling requirements • Activity durations and cycle times • Direct feed to CNC machines and robots

Figure 3-7

Integrated manufacturing framework - content variables

manufacturing needed regarding these parts. The group focused on the "amount and quality of information that passed between engineering and manufacturing, especially discovering the advance information the factory needed about critical parts before the design was released." (Ampex, 1987, p. 10) The PME group defined critical parts as "those that had long lead times or were exceptionally difficult to procure either because there were a limited number of qualified suppliers, or because a part was unusually exacting in its specifications." (Ampex, 1987, p. 10)

External vendors and suppliers have already been identified as important members of the integrated team. (see Variable II-C - Vendor interactions) Riggs (1983, p. 131) emphasizes the importance of manufacturing input regarding prior experience with vendors. "Manufacturing should share with the design team its experience with present vendors and subcontractors as engineering is selecting sources for parts or processing for the new product or system."

Plus Development Corporation (Plus, 1988, p. 10) created a team to evaluate suppliers that included the vice president of manufacturing. The team developed a detailed six-point list of criteria for supplier selection that include issues such as trust, quality, delivery capability, pricing and the supplier's use of technology.

Process capabilities are another important factor that manufacturing communicates to design. Graves and Poli (1987) describe an advanced manufacturing technology (AMT) organizational unit that acts as an interface between product designers and manufacturing engineers. The AMT group's responsibilities include assessing the producibility implications of prototype product designs, assessing new manufacturing technologies, and the coordination of product and process design databases. Teicholz and Orr (1987, p. 2.116) describe the role of the process planner and note that his job "is to determine the sequence of operations and interpose the appropriate inspection and testing processes while taking into account such factors as availability of machine tools, deadlines, and present mix of jobs in the shop."

Feedback on manufacturability includes evaluating the ease of assembly of a product. Boothroyd and Dewhurst (in Stoll, 1986, p. 1361) devised a design for assembly evaluation procedure that consists of three evaluation criteria:

1. Does the part move relative to all other parts already assembled?

2. Must the part be of different material than or isolated from all other parts already assembled?

3. Must the part be separate from all other parts already assembled because otherwise necessary assembly and disassembly of other parts would be impossible?

Stoll (1986, p. 1356) points out that "design for manufacturing can be divided into a number of subareas. Design for fabrication involves the design of product components and parts in ways which are compatible with the method of fabrication."

Attributes of Variable 4-A include the identification of long leadtime or critical components, vendor prequalification, process capabilities, and feedback to design on manufacturability.

Variable 4-B Development of process plan

In manufacturing, the product and process functions are formally related by a process plan. This variable describes the attributes of the detailed process plan for manufacturing the product.

In manufacturing, the product and process functions are formally related by a process plan. As described by Logan (1983, p. 2) "the process plan–detailing at a minimum manufacturing sequences by work centres, cycle times of resource usage and tooling requirements–is a central requirement of a manufacturing system." He identifies the process plan as "the link between engineering and actual manufacture."

Logan (1983, p. 2) further describes the process plan as "the methodical translation of engineering requirements (contained in engineering drawings and specifications) into detailed manufacturing requirements of material, labour and equipment."

Teicholz and Orr (1987, p. 2.116) note that the process plan is "usually expressed in the form of a process sheet which lists the sequence of operations, the machines on which the operations are to be performed, the estimated time needed for each operation, and the required tooling."

Whitney (1988, p. 85) advocates "designing an assembly process appropriate to the product's particular character. This involves creating a suitable assembly sequence, identifying subassemblies, integrating quality control, and designing each part so that its quality is compatible with the assembly method."

Deere described process planning as "the link between design and manufacturing," and defined the production plan as "the specification of the manufacturing operations to be performed in the production of a given part." (Deere, 1988, p. 6) The production plan includes information about "how each feature should be produced, which machine to use, and what machine settings to apply."

Attributes of Variable 4-B include the use of a formal planning procedure that results in a documented process, detailed material, labor, and equipment requirements for production, and detailed assembly sequences.

Variable 4-C Electronic data exchange

The use of the automation tools described in the process Variable 3-C facilitates the transfer of geometric data, material characteristics, process characteristics and requirements, expert knowledge of assembly methods, shop floor layouts, machine allocation, distribution, and tooling requirements, as well as activity durations and cycle times.

Fundamental input to engineering from manufacturing deals with basic component parameters. Deere's Group Technology System provides a database of all existing manufactured parts for use by engineers. "The heart of our package is a classification and coding system designed to capture key geometric characteristics of a part." (Deere, 1988, p. 5)

Gunn (1987, p. 38) notes that "using CAD captures the geometry of the part in an electronic (computer-based) engineering data base. The geometric data serve as the basis for most manufacturing activities."

The Ampex Product Matrix Engineering team, established as an engineering-manufacturing interface group, developed "new procedures and documentation devices for Ampex," including a material status chart indicating the group's "confidence level concerning the likelihood of a part being used in the final design." (Ampex, 1987, p. 10)

Cutkosky and Tenenbaum developed "First Cut," a sophisticated tool that keeps the designer "continually in touch with manufacturing processes by providing manufacturing modes that capture process characteristics at an abstract level. Working in manufacturing modes is similar to feature based CAD except that features are promptly translated into process plans." (1989 page 3) The designer is advised on line of manufacturing options by linking a CAD tool with expert systems that advise the user on the manufacturability of the component as it is designed.

Stoll (1986, p. 1362) describes a simulation package that creates a model that "includes the size and variation of each component and accuracy of each assembly operation based on tolerances specified by the designer." The program then uses a Monte Carlo procedure to simulate a production run, and computes a population distribution of critical assembly parameters.

Gunn describes the use of work cells in the modern factory, and points out that group technology cells are a "fundamental premise of modern manufacturing. These are cells of production equipment dedicated to the production of a family of parts that share the same product or process design characteristics." Work cells include "production and assembly robots, machine tools or production equipment on the shop floor that (are) driven and connected by NC, CNC, or DNC" software. (Gunn, 1987, p. 42)

Teicholz and Orr describe computer assisted process planning systems that help process planners "to standardize process plans and to develop prefered routings for part families." The preferred routing is "the optimal routing for the part; it is based on the experience of process planners and the tools available to do the job." (Teicholz and Orr, 1987, p. 2.108) They also point out that, based on analyses of historical data, it is possible to predict cycle times and machine usage rates. These data form the input to "group technology analysis (that) can also be used as a simulation tool." The results of the simulation analyses can then be used to "predict machine tool use, . . . to form work cells, . . . and to determine specifications for an entire manufacturing facility and to base the layout of the facility on the specification." (Teicholz and Orr, 1987, p. 2.113)

General Motors developed a "manufacturing automation protocol" known as MAP that is a "a set of rules that govern how, in an ideal world, machines of any make should communicate with each other." ("Factory of the Future", 1987, p.10) The first General Motors factory application of the MAP protocol consisted of the electronic interconnection of 21 different types of machines from 13 different manufacturers in a truck assembly plant in Michigan.

Deere & Company used the MAP protocol to resolve "hardware interfacing problems" in a diesel engine and tractor manufacturing and assembly plant. The firm took advantage of "the computer aided manufacturing systems group's past experience in installing networks of programmable controllers and linking networks of computers and other computer controlled equipment in Deere's manufacturing facilities." (Deere, 1988, p. 8)

Gunn describes the concept of "work cell device programming," the author's description of "what used to be called computer numerically controlled (CNC) or numerically controlled (NC) programming." He further points out that "the device in the work cell today might be a CNC machine tool or it could just as easily be a robot, a vision system, or a coordinate measuring system." (Gunn, 1987, p. 39)

The attributes of Variable 4-C include the exchange of dimensional and material characteristics of components, process characteristics and requirements, such as expert knowledge of assembly methods; optimal shop floor layouts, machine allocation and distribution, tooling requirements; activity durations and cycle times, and direct feed to CNC machines and robots.

CONCLUSION

This chapter presented an overview of the literature that formed the point of departure for this research and the basis for the framework used to describe the integrated manufacturing effort. The twelve framework variables capture important attributes of context, organization, process, and content on integrated new product development projects. The next chapter provides a description of the cogeneration projects that I studied using this framework as a guide to collect construction project data.

CHAPTER 4

OVERVIEW OF COGENERATION AND DESCRIPTION OF THE PROJECT CASE STUDIES

INTRODUCTION

Cogeneration is simply the combined production of steam and electricity from a single heat source. However, the recent resurgence in cogeneration has a number of implications for the engineering and construction industry, the utility industry, and American industry in general. Utilities are no longer the sole providers of power to American industry. The creation of independent power producers has revitalized the power industry with a sense of competition, providing alternatives for users of electrical and steam power, and opportunities for entrepreneurial developers in this new market.

The previous chapter presented the framework of integrated manufacturing. I developed the framework not only as a mechanism for describing the attributes of the integrated manufacturing environment, but also as a guide to collecting data on a group of eight different cogeneration projects. This chapter first provides a brief overview of cogeneration, and then describes the sample of eight projects that I studied.

COGENERATION

In simplest practical terms, cogeneration is the production of steam as well as electricity from the same heat source. Various authors and agencies offer other technical and legal definitions. The Electric Power Research Institute (EPRI) defines cogeneration as "the simultaneous production of electric and thermal energy in a facility from a single primary energy source." (EPRI, 1988, p. S-1)

Cogeneration is not a new concept. "In the early years of this century, most U.S. industrial firms generated their own electricity; 50 to 60% of total electric energy was generated on-site. Much of this on-site generation was cogeneration." (EPRI, 1988, p. 1-3) But since the 1930's, most electrical power has been generated and distributed in the United States by a number of large, regulated public utilities.

During the last 15 years, however, the concept of cogeneration has received renewed attention, and a new trend in power generation has emerged. This trend is characterized by the increasing role of independent, private firms in the power generation business.

This shift in electric generation strategy was the result of an increasing public awareness of the need to develop alternative or more efficient energy sources. This public concern was reflected in legislation that provided incentives for the private sector to invest in alternative energy technologies.

In 1978 the federal government enacted the Public Utility Regulatory Policies Act, known as PURPA. This legislation "provided significant benefits to cogenerators, . . . by establishing a special class of power producers known as Qualifying Facilities." (EPRI, 1990, p. 1-5)

Four of the most significant benefits to Qualifying Facilities include exemption from federal and state utility regulations, supplemental utility power at nondiscriminatory rates, a guarantee of interconnection and backup service, and reasonable buy-back rates (EPRI, 1990, p. 1-6). Reasonable buy-back rates are defined as the utilities' avoided cost, or marginal cost of generating additional power. Coupled with attractive investment tax credits, the PURPA legislation provided a powerful incentive for the private sector to finance and develop independent power generation facilities.

(The interested reader is referred to Butler (1984), EPRI (1988), EPRI (1990), and Limaye (1985) for a more detailed description of cogeneration.)

COGENERATION PROJECT DEVELOPMENT

The principal participants in a "typical" cogeneration project are diagrammed in **Figure 4-1**. Independent cogeneration projects generally begin with a developer identifying a steam host; that is, a facility that has a need for steam. Steam uses include processing vegetables, facility heating, manufacturing processes, and a variety of other applications. The developer will then put together the three fundamental contracts that define the project from a cash flow perspective. These are the steam sales agreement, the power sales agreement, and a long term fuel supply agreement.

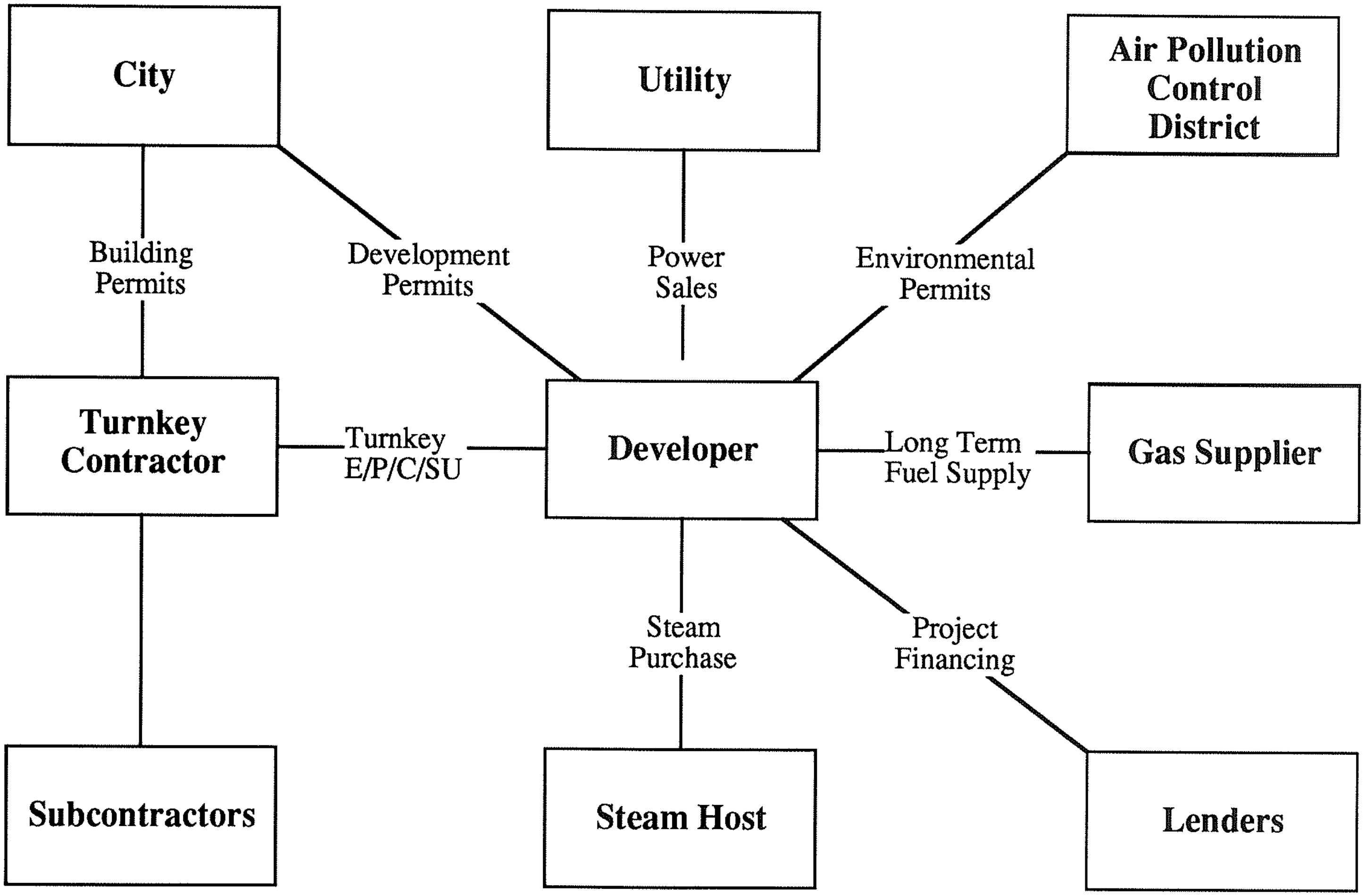


Figure 4-1

Typical cogeneration project structure

The steam sales agreement is with the steam host, and details the quantity and quality of steam to be provided, as well as the price. The power sales agreement is with the utility that will purchase and distribute the electrical power produced by the plant. The utility may be local, or the electricity may be "wheeled" through the local utility's distribution network to end users in another region. The power sales agreement also addresses issues such as how the plant will be utilized; as a base load plant that provides a steady continuous source of power, as a peaking or cycling facility that operates on diurnal cycles to match demand cycles, or as a fully dispatchable unit that produces power when requested by the utility. In the latter case, compensation includes both capacity payments that reflect plant availability, and power payments for the actual power produced.

Armed with letters of intent for these contracts, the developer typically shops for financing. During this project development phase, the developer also structures the project by contracting for engineering, construction, operations, and maintenance services. This process is closely related to the financing process. Lenders want some sort of assurance that the project will be delivered in a timely and professional manner. Therefore, developers often look towards established engineering and construction firms that can deliver the project under a turnkey contract, usually for a lump-sum or fixed price. The turnkey contract provides sole point responsibility for project execution, and the lump-sum contract fixes the cost of the project.

The developer takes the early project risk. He expends resources to obtain the power and steam sales agreements without any certainty of return. However, after he obtains project financing, project risk is transferred to the turnkey contractor in the form of schedule and technical performance guarantees.

Most cogeneration plants are financed by third parties, or "off balance sheet." This limits the liability of the project participants, but leveraging the project also shifts some of the project risk to the financial community. These risks are reflected in relatively high interest rates during design and construction.

Interim finance costs, coupled with expiration or "drop dead" dates in the power sales agreement after which the utility is no longer bound to purchase the power produced by the plant, combine to create tremendous schedule pressures for these projects. In addition, the high present value of the revenue stream produced by power and steam sales creates additional pressure for timely project completion.

MAJOR MECHANICAL COMPONENTS

The major equipment components of a gas fired cogeneration plant include the gas turbine, the heat recovery steam generator (HRSG), and the steam turbine. These and other plant equipment are linked by sophisticated control networks that assist the operator in monitoring and controlling plant operations. **Figure 4-2** shows a typical process diagram for a combined cycle cogeneration plant.

Natural gas and air are burned in the combustion turbine. The combustion process drives the turbine rotor, which is connected to an electrical generator. The hot exhaust gases are collected in the HRSG where the residual heat is used to generate steam. The HRSG may contain a combustion chamber that allows burning of additional fuel to either supplement the exhaust heat from the combustion turbine or to permit generation of steam if the combustion turbine is off-line. A portion of the steam is piped to the steam host for process use, and the remainder flows through the steam generator to produce electrical power.

The engineer typically "backs into" the plant size by calculating the largest plant capacity that provides the steam host requirements and maintains the required percent of total plant output in steam. "PURPA machines," or "Qualifying Facilities" must provide at least 5% of the total plant output in the form of steam. However, since the utility, or purchaser of electricity is required to purchase all the power the plant provides, the design philosophy is typically to maximize the electrical output of the plant.

The nominal output of the generators represents a rated capacity at a given set of ambient conditions that include temperature, pressure and fuel grade. The actual operating output fluctuates according to ambient conditions.

OVERVIEW OF THE CONSTRUCTION PROJECTS

I studied eight cogeneration projects during the course of this research. Chapter 2 presents a discussion of the sample selection criteria, and data from the eight projects are summarized and presented in Appendix L.

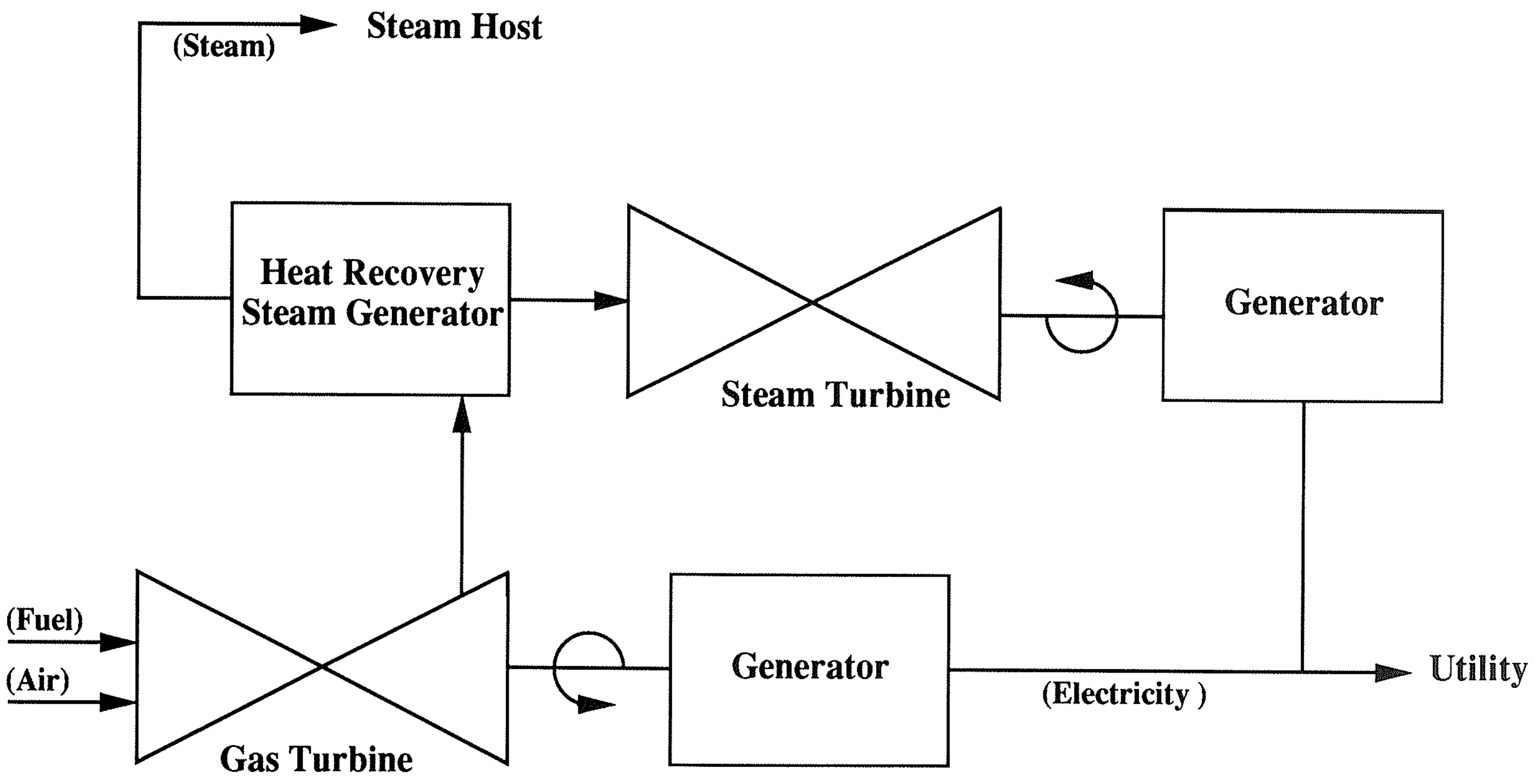


Figure 4-2

Typical combined cycle process diagram

The eight projects are referenced by the following two letter designations:

AL, BA, DE, HE, HO, MO, OX, RI.

General characteristics of the eight projects are presented in **Figure 4-3**. The plants had similar technical characteristics; each of the eight projects had a gas-fired combustion turbine, which could burn fuel oil as a backup. Seven of the eight projects were combined cycle plants, meaning that the plant used a steam turbine to extract additional energy, in the form of electricity, from the combustion process. The projects ranged from 50 MWe to 360 MWe in size, and provided steam to a variety of process facilities. Steam hosts included a manufacturing facility, two food processing facilities, two paper products plants, and three chemical plants.

The projects were in different stages of completion at the time of the site visits and interviews. As **Figure 4-4** indicates, one project had not begun construction, four projects were in the early phases of construction, and three projects were in the plant start-up and turnover phase.

The eight projects were geographically dispersed across the United States, located on both coasts. Four projects were in the western U.S., while four projects were on the Eastern seaboard.

All of the projects were delivered under some form of lump-sum, turnkey contract. Twenty one firms participated in this research. These firms included owners, developers, turnkey engineering and construction contractors, engineering firms and construction companies. The participating firms are listed in Appendix A.

I interviewed a total of 60 people on the eight different projects. Interviewees included project managers, owner's representatives, project engineers, construction managers, and field engineers. Appendix B provides a list of the persons interviewed.

Project	MO	BA	HE	AL	DE	OX	RI	HO
Nominal Capacity	60 MWe	120 MWe	90 MWe	170 MWe	50 MWe	50 MWe	230 MWe	360 MWe
Project Phase E=engineering C=construction	E = 75% C = 15%	E=100% C=98%	E=60% C=10%	E=70% C=35%	E=100% C=50%	E=100% C=98%	E=30% C=0%	E=100% C=95%
Steam Host	Chemical Plant	Food Processing Plant	Chemical Plant	Manufacturing Facility	Paper Products Plant	Food Processing Plant	Paper Products Plant	Chemical Plant
Persons Interviewed	7	9	7	7	8	7	6	8

Figure 4-3

Project summary chart

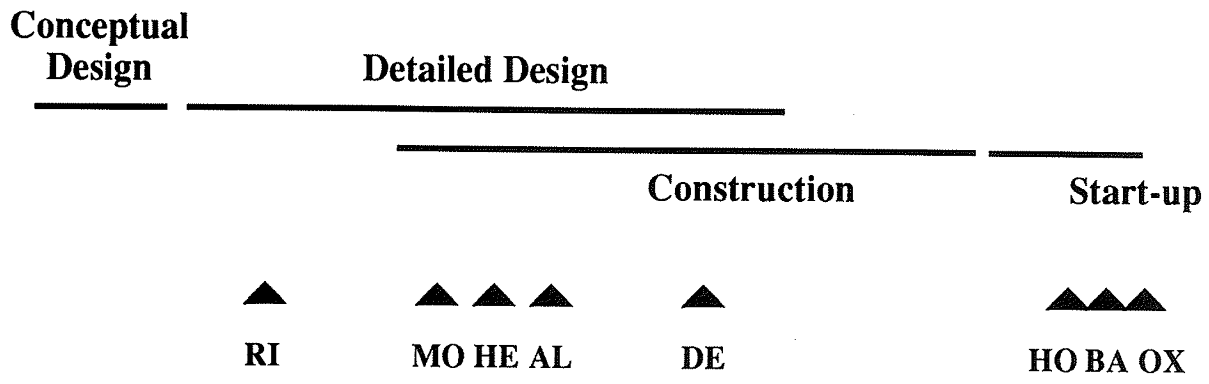


Figure 4-4

Project phase at time of interviews

CHAPTER 5

ANALYSIS

INTRODUCTION

This chapter describes the process of analyzing the data from the project case studies. The first step in analyzing the data was to assign a conformance value of low, medium or high for each variable on each case study. This resulted in the formation of an eight by twelve conformance matrix. I then computed average conformance values for each project and each variable, performed row and column transpositions of the matrix, and constructed one dimensional dot plots of the data. I used cluster analysis and factor analysis methods to group the projects and variables, and to investigate relationships within the groups. Finally, I performed a series of regression analyses of project performance data against the degree of project integration, as measured by the degree of conformance.

Three appendices to this dissertation are closely related to this chapter, and present more detailed descriptions of the analytical methods I employed. Appendix L discusses the data from the cases on a variable by variable basis. Structured by variable and element, this appendix includes a comparison of the data over the entire group of eight projects. Readers interested in a summary of the projects regarding any specific variable or element should examine the appropriate section of this appendix. As discussed in Chapter 2, this comparison across all the projects was an important step in selection of the conformance values. I separated this portion of the analysis because of its length and my desire to focus this chapter on analysis of the data following assignment of the conformance values.

Appendix M describes the details of the multivariate methods I used, cluster analysis and factor analysis. Appendix N presents the results of the regression analysis of the project performance data from the follow-up project manager questionnaires.

ASSIGNING CONFORMANCE VALUES

The framework of integrated manufacturing provided the mechanism for comparing the construction projects I studied to the process of integration in manufacturing. The framework is described in detail in Chapter 3, and **Figure 3-4** through **Figure 3-7** provide a summary of the framework structure.

The first step in the analysis of the project data was to assign a conformance value to each of the twelve variables for each construction case. I evaluated the data from each case on a variable by variable basis, and assigned a value of high, medium, or low to each case variable, depending on the degree of conformance to the integrated manufacturing framework.

In order to assure both accuracy and consistency in assigning conformances, I performed three iterations. The first assignment occurred when I transcribed my interview notes and wrote each case study. When I had finished all the case studies, I went back through all the cases on a variable by variable basis and reassigned conformance values, using the original values as a guide, but reevaluating the values with all the cases in front of me. Finally, when I began to write the analysis chapter, I reviewed the conformance values one last time.

The conformance values are consistent internally in that they reflect the degree to which the individual projects conform to the framework, relative to each other. That is, a high ranking indicates not only a high degree of conformance to the elements of the manufacturing framework, but also a higher degree of conformance than those projects with a medium or low ranking for the same variable. The process of assigning conformance values is described in greater detail in Chapter 2.

THE CONFORMANCE MATRIX

Ranking the eight projects on each of the twelve variables resulted in a matrix of 96 conformance values. The initial conformance matrix is presented in **Figure 5-1**. This 8x12 matrix is structured with the variables as rows and the project as columns. The variables are listed in the order they were originally formulated in the manufacturing framework, and the projects are listed randomly.

The next step in the analysis process was to assign numerical values to the conformance values. I assigned each conformance value of high a value of 3, medium a value of 2, and low a value of 1. I used these numerical values to compute average conformance values for each project and each variable for the sample of eight projects. This facilitated the

Integration Variable	Project							
	RI	AL	DE	HE	OX	HO	MO	BA
Variable 1-A Project development environment	L	L	H	H	M	M	H	H
Variable 1-B Timing of product and process eng	M	H	M	H	H	M	H	H
Variable 1-C Mgmt perspective of integration tech	L	H	H	L	L	L	H	H
Variable 2-A Project team attributes	H	H	M	H	M	M	H	H
Variable 2-B Engineering-production interface	L	H	L	H	L	L	H	M
Variable 2-C Vendor interactions	M	M	L	M	M	M	M	M
Variable 3-A Communication patterns	M	L	M	H	L	L	H	H
Variable 3-B Engineering generalist	M	L	L	H	H	M	M	L
Variable 3-C Computer integration	L	M	M	L	L	L	H	M
Variable 4-A Production input to design	L	H	L	H	L	L	H	H
Variable 4-B Development of process plan	M	H	L	M	M	L	H	M
Variable 4-C Electronic data exchange	L	L	M	L	L	L	M	L

Figure 5-1

Initial conformance matrix

transposition of rows and columns in an effort to reveal relationships among the variables and among the projects.

DISTRIBUTION OF CONFORMANCE RANKINGS BY VARIABLE

One way of presenting the data from the conformance matrix is through the use of histograms to plot the incidence of each conformance ranking on a per variable basis. These histograms graphically indicate the distribution of high, medium, and low conformance values for each variable. The twelve histograms, corresponding to each of the twelve variables, are presented in **Figure 5-2**.

It is clear from an inspection of the figure that there are two fundamental types of histograms, which I call distributed and bimodal. The distributed group can be further categorized as flat, skewed high, and skewed low distributions. Since there are only eight values plotted in each histogram, one for each project, the differences between the different distributed histograms are relatively minor. This indicates that, while it may be interesting to categorize the different types of distributed histograms, since they indicate how the projects performed as a group on a given variable, it may not be particularly useful due to the small sample of eight projects. Changing one or two conformance values can alter the shape of the histogram significantly. However, the difference between the distributed and the bimodal groupings is more distinctive and may be indicative of intrinsic properties of the variables themselves.

The distributed histograms indicate a range of values across the projects. This means that there was a spectrum of responses to the given variable that ranged from low to medium to high. This implies that in moving from a low conformance level to a high conformance level it is possible to occupy an interim medium state.

The bimodal distributions, however, are more indicative of a binary variable. That is, it is either on or off, represented or not represented, without an interim state. For three specific variables, the projects exhibit either a high or a low degree of conformance, with only one medium value. Inspection of these three variables, management perspective of integration technologies, the engineering-production interface, and production input to design, supports this argument. The data for the projects that I studied indicated that management was either aware and supportive of the implementation of integration technologies or not,

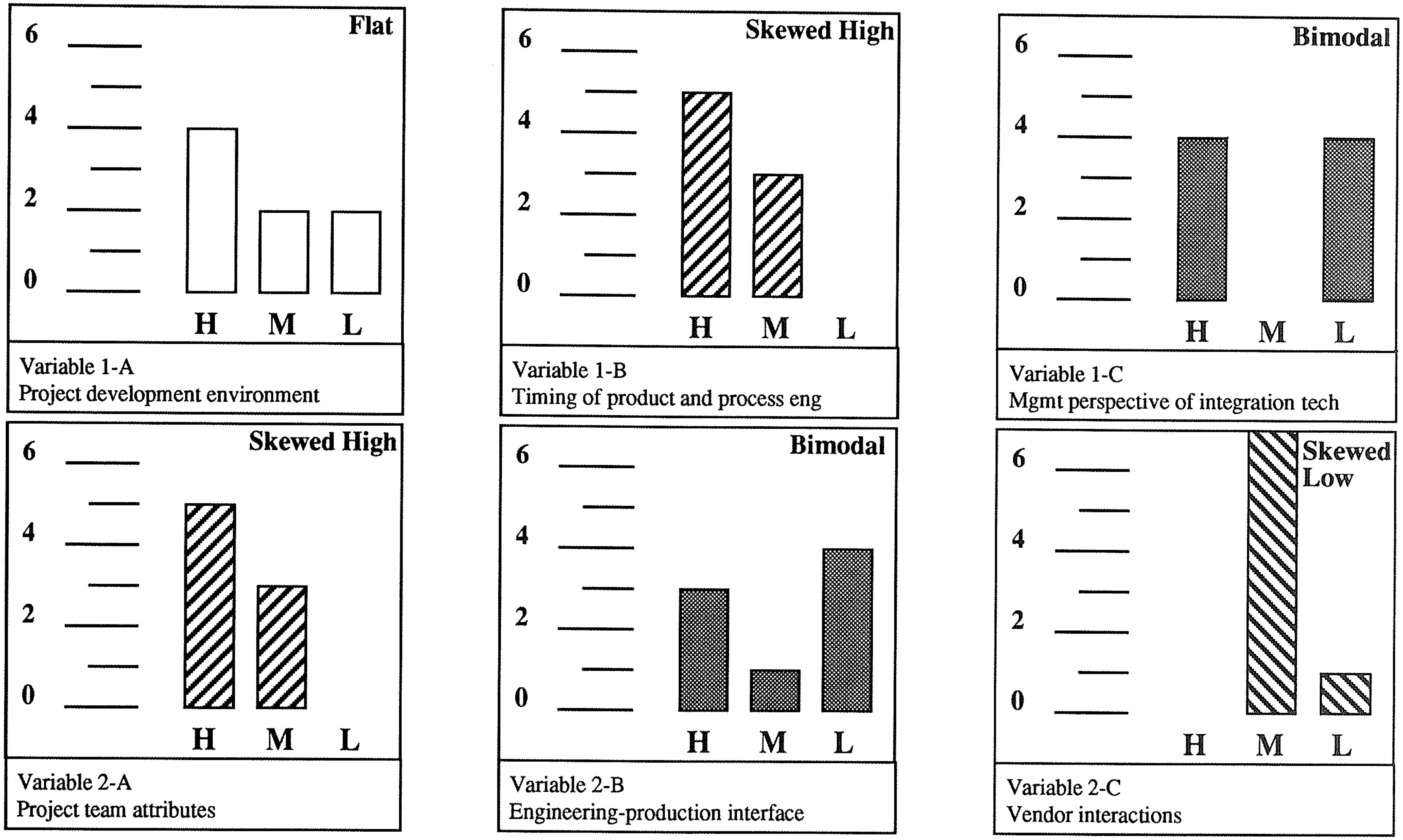


Figure 5-2a

Conformance distributions by variable

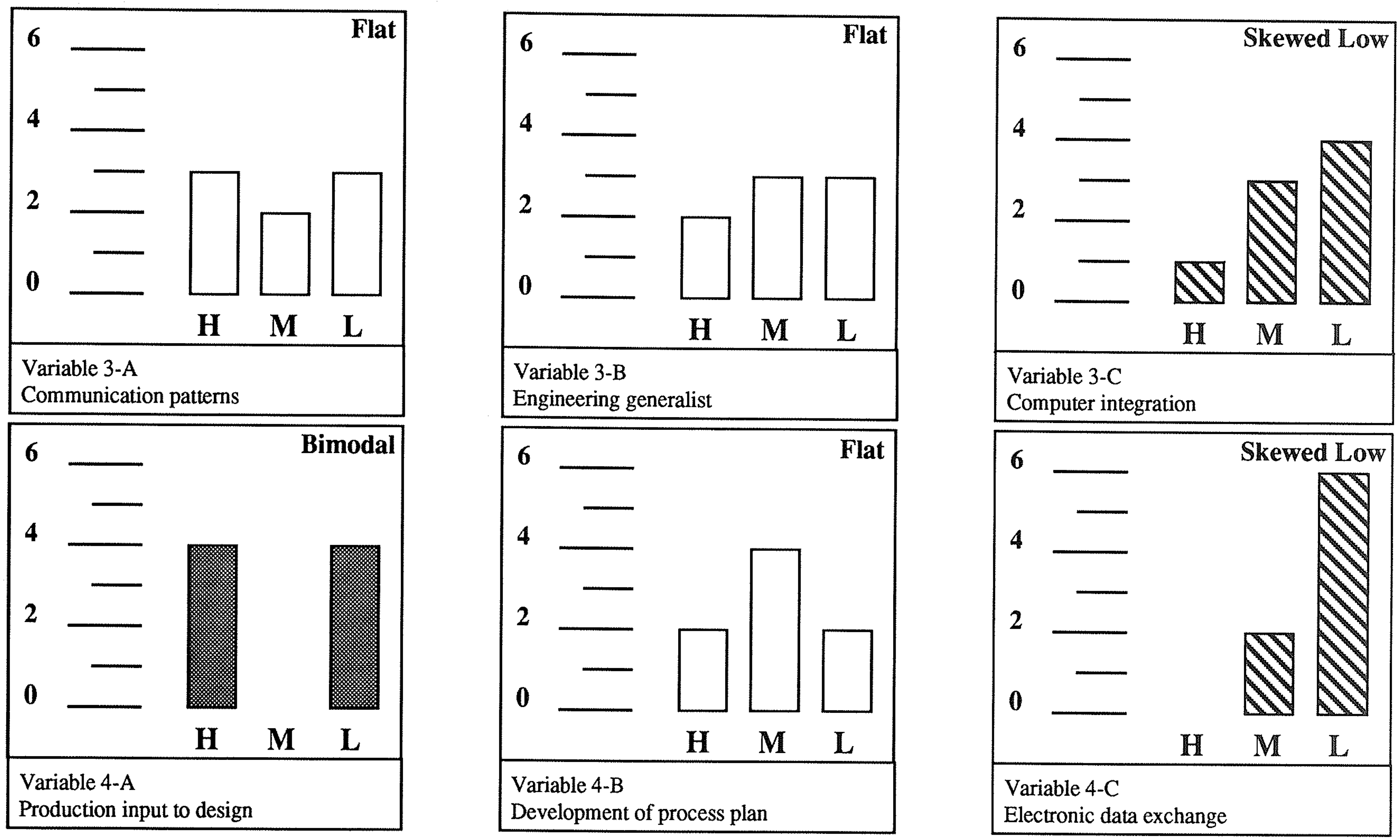


Figure 5-2b

Conformance distributions by variable

the engineering-production interface was either well established or it wasn't, and production input to design either occurred in an active fashion or was not really present.

The implication of this observation is that for the distributed variables, projects within a firm may move incrementally from a low to a high degree of conformance on these variables as they learn or restructure projects. But in the case of the bimodal variables, the project must make a jump from one binary position to another with no (observed) intermediate point. For these bimodal variables, a phased or incremental approach to shifting from a low conformance mode to a high conformance mode may not be feasible. This observation has implications for projects that endeavor to make the transition from low conformance levels to high levels, and these implications are discussed in the conclusions chapter.

REORDERING THE CONFORMANCE MATRIX

I assigned each of the low, medium and high values in the conformance matrix a numerical value of 1, 2, or 3 respectively. Summing and averaging these values across rows and columns gives an average ranking for each project and an average ranking for each variable across the eight projects. The rows and columns can then be transposed, or reordered, on the basis of their average values.

Reordering matrix columns by project averages

Figure 5-3 presents the results of reordering the columns representing the projects based on the average overall conformance ranking for each project. They are ranked from left to right in ascending order of project conformance.

The use of only three ranking values, high, medium and low means that there is some degree of sensitivity to the assignment of the conformance values. The total number of ranking "points" that a project can receive ranges from 12, if all low values were assigned, to 36 if all high values are assigned. This means that there are only 25 possible positions that a project might occupy along the scale. A change in the ranking of any one project variable, say from low to medium, results in a change of one point, which corresponds to a difference of 0.083 on the 1.0 to 3.0 scale.

Integration Variable	Project							
	HO	RI	OX	DE	AL	HE	BA	MO
Variable 1-A Project development environment	M	L	M	H	L	H	H	H
Variable 1-B Timing of product and process eng	M	M	H	M	H	H	H	H
Variable 1-C Mgmt perspective of integration tech	L	L	L	H	H	L	H	H
Variable 2-A Project team attributes	M	H	M	M	H	H	H	H
Variable 2-B Engineering-production interface	L	L	L	L	H	H	M	H
Variable 2-C Vendor interactions	M	M	M	L	M	M	M	M
Variable 3-A Communication patterns	L	M	L	M	L	H	H	H
Variable 3-B Engineering generalist	M	M	H	L	L	H	L	M
Variable 3-C Computer integration	L	L	L	M	M	L	M	H
Variable 4-A Production input to design	L	L	L	L	H	H	H	H
Variable 4-B Development of process plan	L	M	M	L	H	M	M	H
Variable 4-C Electronic data exchange	L	L	L	M	L	L	L	M
	1.42	1.58	1.67	1.75	2.17	2.33	2.33	2.75

Figure 5-3

Conformance matrix ordered by columns (projects)

The project average conformance rankings range from a high of 2.75, indicating a relatively high overall degree of conformance to a low of 1.42, indicating a fairly low overall degree of conformance. This range of values across the projects is represented in **Figure 5-4**, which plots the overall project conformance values along a line that ranges from low average conformance to high.

Inspection of this one dimensional dot plot indicates that the projects tend to fall into one of two groups, those with generally lower conformance values and those with higher values. The observation that the projects cluster into two groups based on their average conformance values is supported by a cluster analysis of the projects, which is described later in this chapter.

Reordering matrix rows by variable averages

Figure 5-5 shows the results of further reordering the matrix first presented in **Figure 5-3**. In this case, the variables have been reordered, with those variables having the highest overall conformance ranking at the top, and those with the lowest overall ranking at the bottom. As a result, the upper right quadrant of the matrix generally represents project variable values with the highest degree of conformance (more high rankings) and the lower left quadrant represents the project variable values with the lowest degree of conformance (more low rankings).

The average values for the variables across the eight projects range from a high of 2.63 to a low of 1.25. These average values indicate the areas where the projects as a group ranked high or low when compared with the variable values from the manufacturing framework.

The average values for each variable across all the projects are plotted in **Figure 5-6**. As noted previously, the average variable values are sensitive to changes in the individual conformance values. In the case of the variable averages, there are only 16 possible values that the variable averages can assume, from a low of 1.0 to a high of 3.0. Therefore a change of one conformance value by one degree, for example from medium to high, changes the average variable value by a value of 0.125.

There are several interesting general characteristics of this plot. The dot plot indicates a central tendency for the variables to group around the average overall value of 2.00. This further supports the observation that the comparative research approach using the

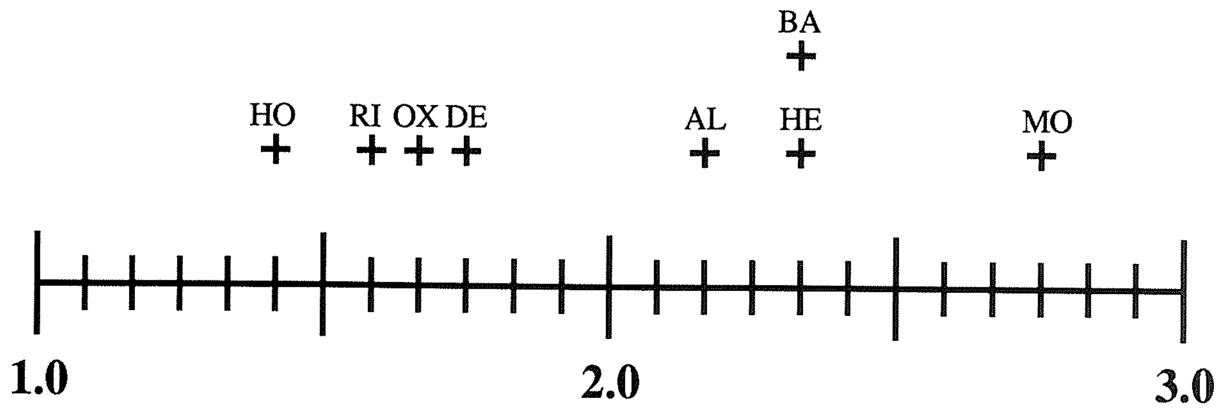


Figure 5-4

One dimensional dot plot of average project conformance values

Integration Variable	Project								
	HO	RI	OX	DE	AL	HE	BA	MO	
Variable 1-B Timing of product and process eng	M	M	H	M	H	H	H	H	2.63
Variable 2-A Project team attributes	M	H	M	M	H	H	H	H	2.63
Variable 1-A Project development environment	M	L	M	H	L	H	H	H	2.25
Variable 3-A Communication patterns	L	M	L	M	L	H	H	H	2.00
Variable 1-C Mgmt perspective of integration tech	L	L	L	H	H	L	H	H	2.00
Variable 4-A Production input to design	L	L	L	L	H	H	H	H	2.00
Variable 4-B Development of process plan	L	M	M	L	H	M	M	H	2.00
Variable 2-B Engineering-production interface	L	L	L	L	H	H	M	H	1.88
Variable 2-C Vendor interactions	M	M	M	L	M	M	M	M	1.88
Variable 3-B Engineering generalist	M	M	H	L	L	H	L	M	1.88
Variable 3-C Computer integration	L	L	L	M	M	L	M	H	1.63
Variable 4-C Electronic data exchange	L	L	L	M	L	L	L	M	1.25
	1.42	1.58	1.67	1.75	2.17	2.33	2.33	2.75	

Figure 5-5

Conformance matrix ordered by columns and rows (projects and variables)

Note: This is a one dimensional plot. The vertical position of each variable has no meaning.

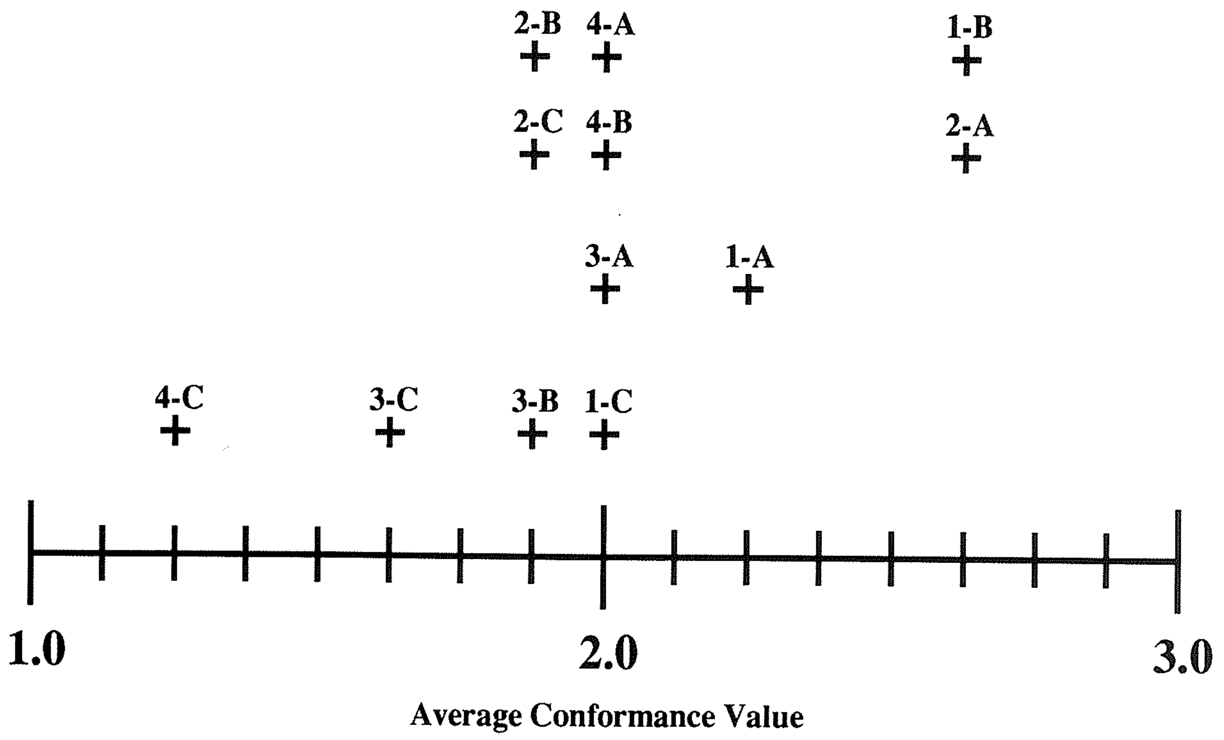


Figure 5-6

Variable average conformance value dot plot framework is a meaningful and appropriate mechanism for studying issues of integration on the sample projects.

However, there are several outlying points on both the high and low ends that merit further discussion. The outlying variables and the central group of medium conformance variables can be clustered into three distinct groups, with interesting implications for projects. These groupings and their implications are addressed in the subsequent section on project variable grouping.

GROUPING PROJECTS

After reordering and plotting the project and variable average conformance values, I aggregated the projects into two distinct groups. Differentiated by their average conformance values, the projects fall into two clusters, a high conformance group and a low conformance group. These groupings are based on an inspection of the average project conformance values and by the application of a series of cluster analysis techniques.

Grouping projects by average conformance value

The average project conformance values fall into two groups when plotted on a one dimensional dot plot, as was indicated in **Figure 5-4**. One group has generally higher overall conformance values and the other has generally lower conformance values.

The difference between the highest ranking member of the lower group and the lowest ranking member of the higher group is five conformance points, the same number by which the highest ranking project differs from the second highest. One might argue that since this difference is the same, three clusters or categories ought to be considered. However, the differences in the case data between the lower ranking group of projects and the higher ranking group of projects were much more striking than the difference between the one high ranking project and the other members of the high group. The conformance values were assigned based on the data in the cases, and a review of the case data supports this grouping scheme. The lower ranking projects were more traditional in their processes, and were less integrated both internally between design and construction, and externally with the client than were the projects that ranked higher overall. There is a distinctly different flavor to the two groups of cases.

Cluster analysis of projects

Additional support for grouping the projects is provided by cluster analysis techniques. I used the absolute value of the difference between each variable value as the measure of similarity between projects. I then used two hierarchical agglomerative clustering algorithms, single linkage and complete linkage, to cluster the projects. The details of the methods I used are fully described in Appendix M.

The use of cluster analysis techniques resulted in the same project grouping as by inspection of conformance values. This is not surprising, since the differences in conformance values is the measure of association used to cluster the projects. However, I took into account the differences between each project on a variable by variable basis rather than an average basis. I also weighted the difference between a high and a low conformance ranking more strongly than a difference between a high and a medium or a medium and low ranking. This accentuated the more distinctive differences between the projects. **Figure 5-7** lists the two project clusters.

Comparison of high group and low group

Figure 5-8 illustrates the difference in average conformance rankings between the two groups on a variable by variable basis. The high conformance projects ranked higher than the low conformance projects on all variables but one. However, two variables, 4-A and 2-B, contribute a disproportionate amount to the difference between the two groups.

The column to the far right in **Figure 5-8** indicates that the greatest differences between the high conformance group and low conformance group conformance averages are due to the contributions of these two variables. The projects in the high conformance group were almost all ranked high (one medium) for these two variables, while all members of the low group were ranked as low for these same two variables.

These variables are two of the bimodal variables that I described in the previous section of this chapter dealing with variable histograms. Variable 4-A is <u>production input to design</u>, and variable 2-B is <u>engineering production interface</u>. Project rankings on these two variables contributed substantially not only to the difference between the two project groups, but to both the overall high and overall low averages for the projects.

High Conformance Cluster

Project	Average Conformance Value
MO	2.75
BA	2.33
HE	2.33
AL	2.17

Low Conformance Cluster

Project	Average Conformance Value
DE	1.75
OX	1.67
RI	1.58
HO	1.42

Figure 5-7

Project clusters

	Low Conformance Group					High Conformance Group						
Integration Variable	**HO**	**RI**	**OX**	**DE**	**Avg**	**AL**	**HE**	**BA**	**MO**	**Avg**	**Δ**	
Variable 1-A Project development environment	M	L	M	H	2.00	L	H	H	H	2.50	+ .50	
Variable 1-B Timing of product and process eng	M	M	H	M	2.25	H	H	H	H	3.00	+ .75	
Variable 1-C Mgmt perspective of integration tech	L	L	L	H	1.50	H	L	H	H	2.50	+ 1.00	
Variable 2-A Project team attributes	M	H	M	M	2.25	H	H	H	H	3.00	+ .75	
Variable 2-B Engineering-production interface	L	L	L	L	1.00	H	H	M	H	2.75	+ 1.75	*
Variable 2-C Vendor interactions	M	M	M	L	1.75	M	M	M	M	2.00	+ .25	
Variable 3-A Communication patterns	L	M	L	M	1.50	L	H	H	H	2.50	+ 1.00	
Variable 3-B Engineering generalist	M	M	H	L	2.00	L	H	L	M	1.75	- .25	
Variable 3-C Computer integration	L	L	L	M	1.25	M	L	M	H	2.00	+ .75	
Variable 4-A Production input to design	L	L	L	L	1.00	H	H	H	H	3.00	+ 2.00	*
Variable 4-B Development of process plan	L	M	M	L	1.50	H	M	M	H	2.50	+ 1.00	
Variable 4-C Electronic data exchange	L	L	L	M	1.25	L	L	L	M	1.25	0.00	
	1.42	1.58	1.67	1.75		2.17	2.33	2.33	2.75			

Figure 5-8

Differences in average variable conformance values between high conformance project group and low conformance project group

In other words, a good part of the reason that the high projects scored high and the low projects scored low was due to these two variables. In fact, as demonstrated in **Figure 5-9**, some 40% of the difference in the rankings between the high group and the low group can be attributed to the contribution of Variables 4-A and 2-B. If each variable contributed the same proportion to the difference between the two groups, the expected contribution of any two variables would be two twelfth's or 16.7%.

Since these two variables are consistently ranked high in the high project group and low in the low project group, they would appear to be related, and they are indeed strongly positively correlated, with a computed correlation coefficient of 0.944. The nature of the variables themselves is consistent with this observation. If there is a well defined engineering construction interface, it is logical to expect that more information will flow between the two groups. Conversely, the act of getting construction input into the design process would tend to build or strengthen the interface between the two groups. Exploring the relationships between these and other variables was the objective of the variable grouping procedures described in the next section.

GROUPING VARIABLES

I used several techniques to group the twelve integration variables. The first is based on inspection of the average values of the variables across the projects. I then applied cluster analysis methods using the absolute values of differences in project rankings as an association measure. Finally, I used the variable correlation coefficients as a basis for a factor analysis of the variables.

Grouping variables by average conformance value

One method of grouping the variables is by the overall average conformance value of the variable across the projects. **Figure 5-10** presents a one dimensional dot plot of the variables along the range of possible average values.

The variable averages have a strong central tendency, and cluster fairly tightly around the overall average conformance value of 2.00. The outlying variables, both high and low, indicate areas where the construction cases as a whole exhibited very strong or very weak conformance when compared to the manufacturing framework. Based on inspection of this

	High project group	Low project group	Difference	Percent difference
Contribution of variables 2-B and 4-A	23	8	15	40%
Contribution of all other variables	92	69	23	60%
TOTALS	115	77	38	100%

Disproportionate contribution of variables 2-B and 4-A to the difference between the low conformance group and the high conformance group

Figure 5-9

Contribution of Variables 2-B and 4-A

Note: This is a one dimensional plot. The vertical position of each variable has no meaning.

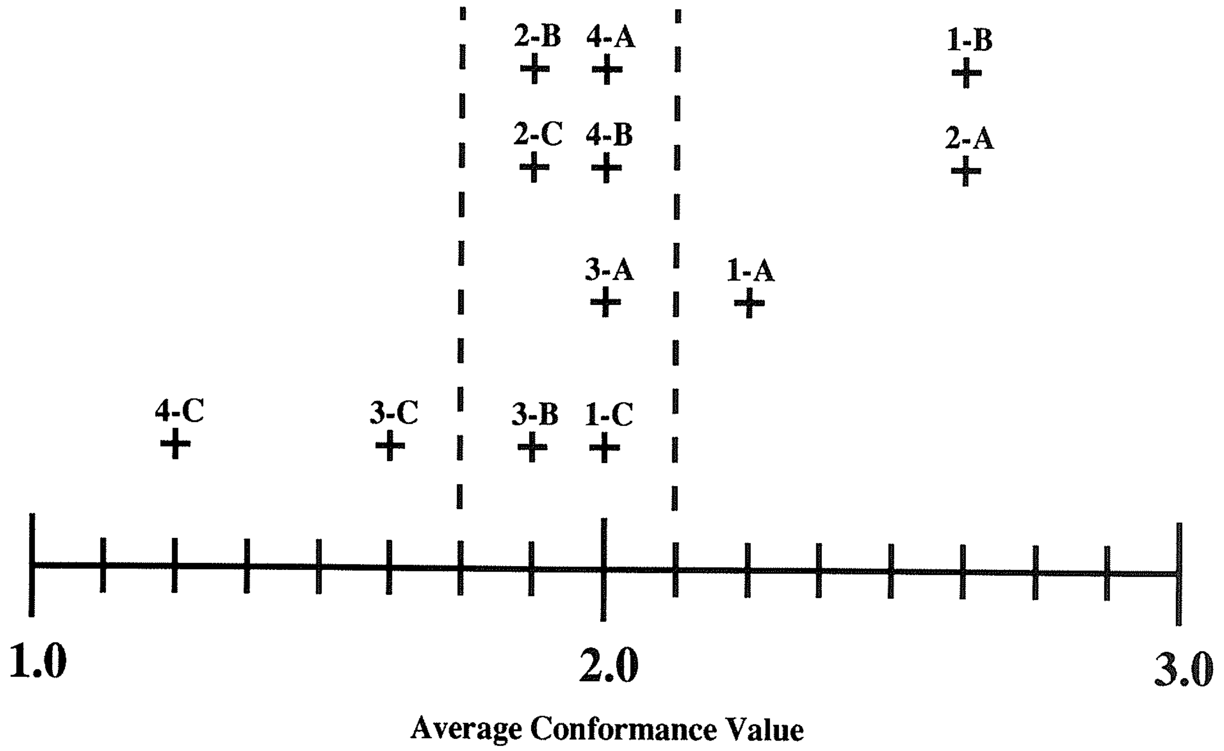


Figure 5-10

Variable grouping by average conformance value

dot plot, there appear to be three general groups of variables, as segregated by the dotted lines. In order to explore the possibility that there were distinct variable groupings, I applied cluster analysis and factor analysis methods to the variables.

Cluster analysis of variables

I again used hierarchical agglomerative techniques to cluster the variables based on the absolute value of the differences in conformance rankings across the projects, and I applied both single linkage and complete linkage algorithms. (See Appendix M for a complete discussion of cluster analysis.)

However, cluster analysis proved to be a weak methodology for grouping variables, since the approach leads to multiple solutions. There are no clear criteria for determining the number of clusters, and the population of each cluster varies depending upon how the algorithms are applied.

The use of cluster analysis did provide some peripheral support for variable grouping. I was able to arrive at the same groupings as those that I eventually determined through the use of the more powerful factor analysis methods.

Correlation coefficients

Factor analysis methods use the coefficients of correlation between the variables as a basis for grouping. The correlation coefficient matrix is presented in Appendix M as **Figure M-7**. The large number of correlation coefficients makes it difficult to use them directly as a means of grouping variables. However, the positively skewed distribution of the correlation coefficients indicates that the variables, when considered as a group, act together.

Correlation is a measure of the tendency of different variables to move in the same direction, or in a related fashion. Correlation coefficients are normalized to range from -1.0 to +1.0. In this case, a high positive correlation between two variables means that projects that tended to score high on one would tend to score high on the other. High negative values mean that the two variables tend to move in opposite directions, while values near zero indicate that there is little relationship between the variables one way or the other.

Figure 5-11 is a histogram of the incidence of correlation values. The distribution is skewed towards the positive end of the spectrum, with a preponderance of the values falling between +0.2 and +0.8. This indicates that the variables tend to act cohesively in capturing aspects of project integration.

There are two sets of strongly correlated variable with values of +0.9 or greater. One pair is Variable 2-B, engineering-production interface and Variable 4-A production input to design, and the other pair is Variable 1-C, management perspective of integration technology and Variable 3-C, computer integration.

Both of these pairs of variables might be expected to be highly correlated. A strong engineering-production interface would facilitate the flow of production input to design and conversely, the flow of construction knowledge to engineering would not be possible without a strong interface. Similarly, high conformance values in the area of management perspective of integration technologies would indicate a receptive environment for computer integration, while the development of integrated computer technologies would depend upon a certain degree of management support.

An important consideration here is the difference between correlation and causality. Two sets of variable values may be highly correlated (either positively or negatively) and yet have no causal relationship. For example, a young persons height and number of hours spent playing video games might both be expected to increase from age one to age ten, but there is probably no causal relationship linking the two.

In this case, however, highly positively correlated variables may actually capture attributes of the same underlying forces, and may be better grouped into one global dimension that reflects the influence of some underlying influence. The purpose of factor analysis is to explore the possibility of the existence of these underlying factors.

Factor analysis of variables

Factor analysis uses the correlation coefficient matrix as a basis for computing factor loadings for each variable. These loadings indicate the degree to which the individual variable variance can be explained by the presence of a common factor. I used a principle components approach, which assumes that all of the variance can be explained by the

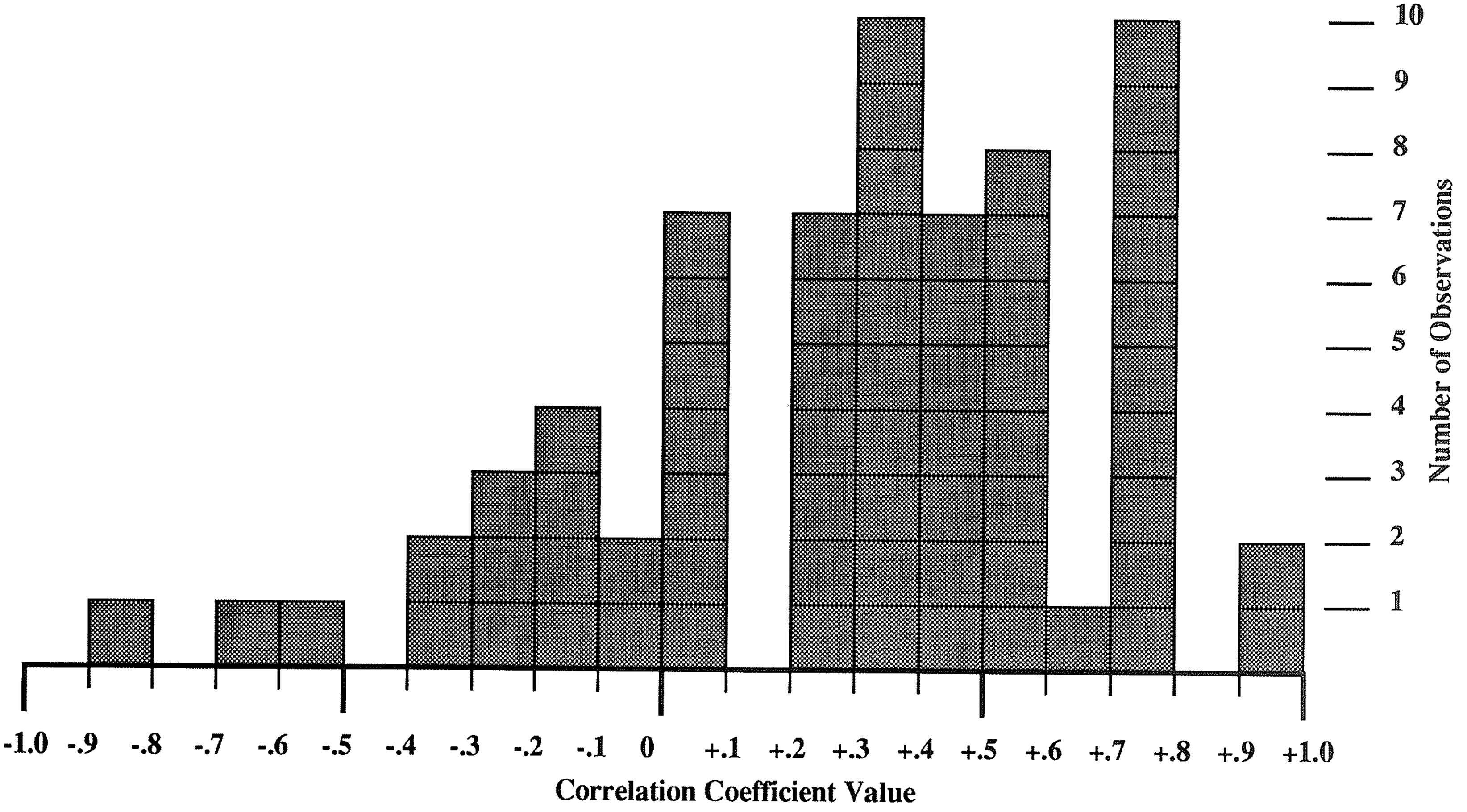


Figure 5-11

Variable correlation coefficient distribution underlying factors. A detailed description of the factor analytic methods I used is presented in Appendix M.

The results of the factor analysis provide evidence for the presence of three underlying factors influencing the integration variables. The factor loadings on each of the variables form a basis for grouping them into a series of three dimensions corresponding to the three factors. **Figure 5-12** is the same dot plot of the variable conformance values presented in **Figure 5-10**, but with the factored variable dimensions superimposed. There are some similarities to the original groupings based on inspection of the conformance values. The two low conformance outliers, 4-C and 3-C, form a part of the group related to Factor 2. Variables 1-B and 2-A, the high conformance outliers, remain together and form part of the group resulting from Factor 1. The third group, related to Factor 3, is composed of only two variables, 1-A and 3-A.

A closer look at the nature of the variables that comprise the three groups reveals relationships between the variables in each group that go beyond their numerical conformance values or factor loadings. **Figure 5-13** lists the results of the factored variable groups, which I call dimensions. I have labeled each dimension with a name that is representative of the characteristics of the variables in the group. These are interface, technical, and environment.

The Interface Dimension represents the dominant factor influencing the variables. It accounts for 43% of the total variance. The six variables that loaded strongly onto this dimension are all generally related to project interface, or communication and organizational interaction issues. These are the variables on which the high conformance projects tended to rank higher.

The variables loading strongly on the Technical Dimension are generally related to technical integration issues. These four variables captured data on the automation tools and automated processes that form the technical or hardware aspect of the integration framework. These are the variables on which the projects ranked lower overall. Only two variables load strongly on the Environment Dimension, and the only one that loads unambiguously is Variable 1-A, project development environment.

The factor analysis provided strong support for the presence of three underlying factors that influence the integration variables. These factors also provide a mechanism for grouping

Note: This is a one dimensional plot. The vertical position of each variable has no meaning.

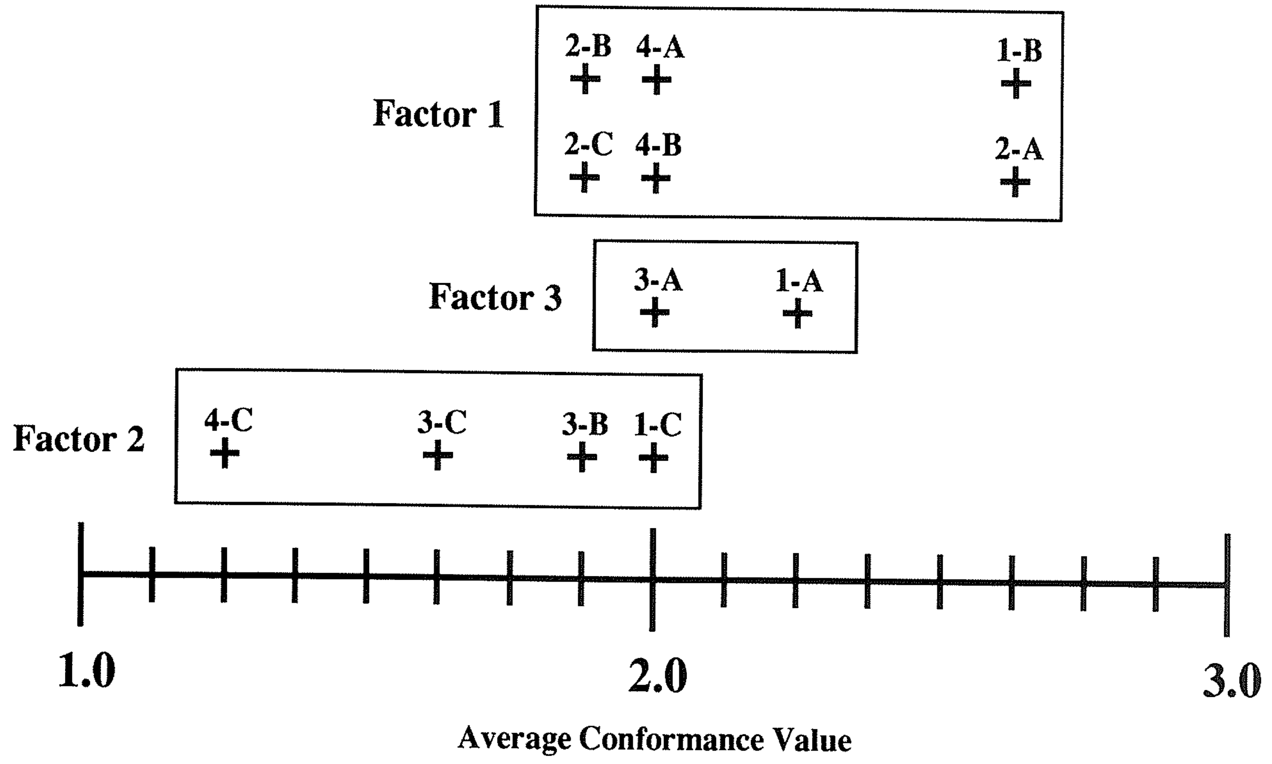


Figure 5-12

Variable groupings based on factor loadings superimposed on one dimensional dot plot of conformance values

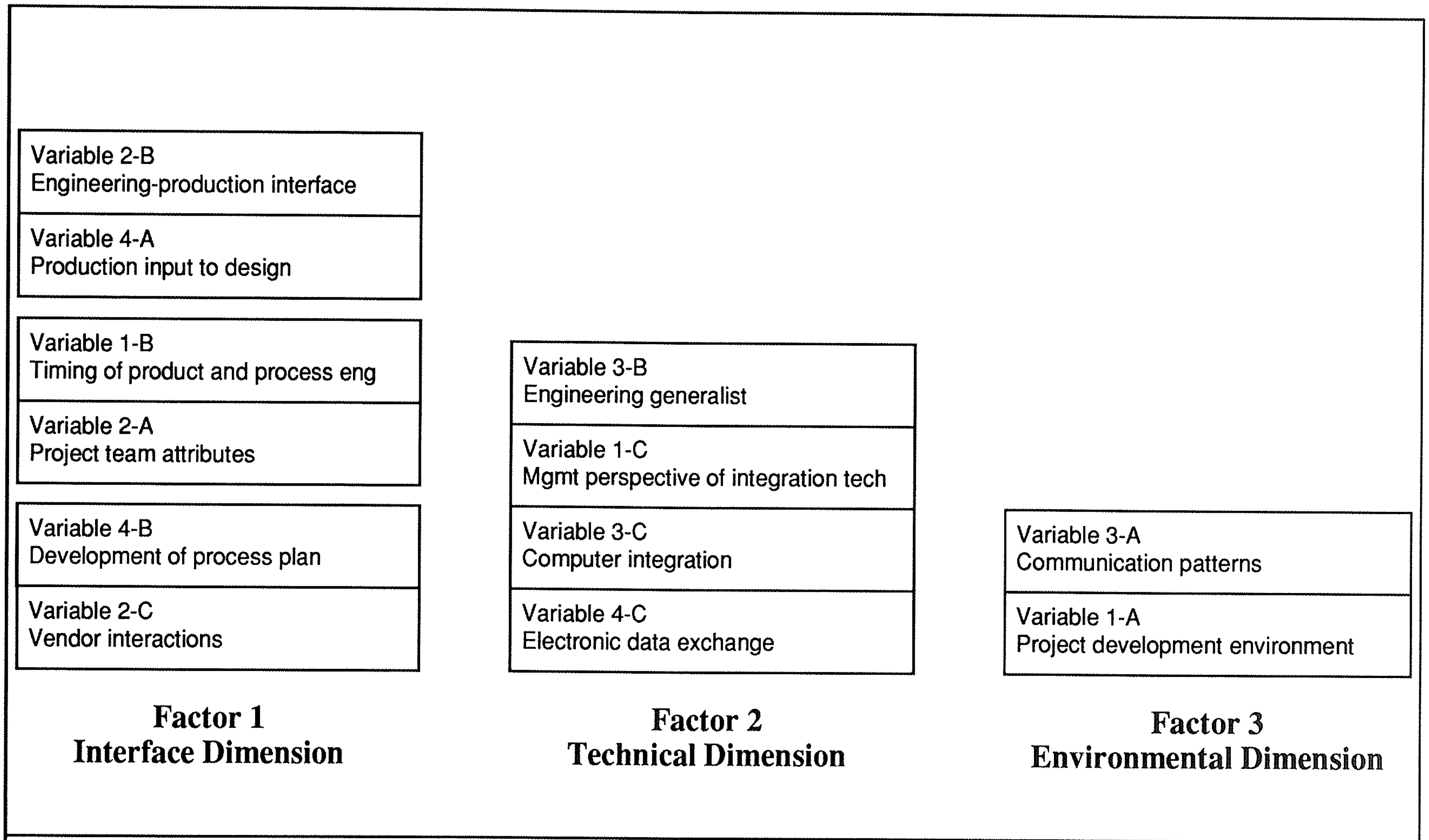


Figure 5-13

Variable dimensions based on results of factor analysis

the variables into three higher order dimensions, and I discuss the implications of these groupings in the conclusions chapter. However, it is important to note here that the identification of these factors and dimensions are the result of what is commonly termed exploratory factor analysis. This factor analysis approach provides computational support for grouping variables, but neither implies causality nor provides the logical basis for interpreting the implications of the variable grouping. Dimensional interpretation is left to the devices of the researcher, based on his common sense and the empirical variable data. Understanding the underlying forces that are reflected in the factors is a fertile area of future research.

PROJECT PERFORMANCE PARAMETERS

The final phase of analysis consisted of identifying measures of project performance and searching for a relationship between the degree of integration and subsequent project performance. In order to identify project performance parameters, I sent a follow-up questionnaire to each project manager on the projects I had visited. I asked each project manager to describe three project performance parameters he used to measure the degree of success of his project. I also asked him to rate his project's overall performance, and its performance on each of the three parameters, on a scale from one to ten. Appendix N presents a detailed discussion of the regression procedure.

Figure 5-14 presents a summary of the project performance data. The responses were fairly consistent in defining budget and schedule parameters. Other parameters included client satisfaction, product quality, and safety. Since there were incomplete data on these last three parameters, I took their average as an "aggregate quality" parameter.

The performance parameters were the dependent variables for the regression analysis. I used the average conformance values for each project, the average conformance values for each of the three factored dimensions, and the average conformance values for each variable as the independent variables. Comparing each independent variable to each dependent variable resulted in a series of 80 linear regressions. I used a t-test of the slope of the regression line as a test of significance. Of the 80 computed t-values, only four were significant at the 95% level, and only two were significant at the 97.5% level, one for Variable 3-A <u>communication patterns</u> on overall performance, and the other for Dimension 3 on overall performance. Since the Dimension 3 contains only two variables,

	Project							
	MO	BA	HE	AL	DE	OX	RI	HO
Overall Conformance	2.75	2.33	2.33	2.17	1.75	1.67	1.58	1.42
Budget Performance	6	10	7	4	9	4	9	7
Schedule Performance	10	ND	9	9	8	ND	9	9
Client Performance	9	10	6	ND	ND	10	6	7
Quality Performance	ND	10	ND	9	10	ND	8	ND
Safety Performance	10	ND	ND	ND	ND	ND	8	ND
Overall Performance	8	10	8	5	9	5	8	8
Aggregate Quality	9.5	10	6	9	10	10	7.3	7

ND = No Data
Aggregate Quality = Average of Client, Quality, and Safety Performance
Performance values ranked on a scale of 1-10

Figure 5-14

Project performance data for linear regression analysis

one of which is Variable 3-A, these two t-values both appear to be strongly influenced by Variable 3-A.

The results of the regression analysis lead me to conclude that there is no apparent relationship between the degree of integration as measured by the conformance values, and the degree of project success, as measured by the performance parameters. This does not mean that project integration does not influence project performance. It does, however, imply that there is a need for further work in developing better measures of both integration and performance, and collecting data on a much larger population in order to investigate the presence of a relationship between project integration and performance.

CHAPTER CLOSURE

In this chapter, I first described the process of assigning the conformance values for each variable for each project. I then discussed how I constructed the conformance matrix and analyzed the data. The analysis consisted of reordering the matrix, plotting conformance distribution histograms, using cluster and factor analysis to group the projects and the variables, and finally running a series of linear regressions between the conformance data and project performance data gathered from the project manager's questionnaire.

These analyses led me to formulate a series of conclusions based upon both the computational manipulations of the conformance data and a thoughtful review of the case data. These conclusions are presented in the following chapter.

CHAPTER 6

CONCLUSIONS

INTRODUCTION

The preceding chapter discussed the analysis of the data from the project case studies. It focused on the similarities between the manufacturing framework and the data from the construction cases as expressed by the conformance values. This chapter builds upon the analysis of the conformance matrix and takes the analysis a step further by describing the conclusions that emerge from the data and the analysis.

This chapter begins with a discussion of the conclusions derived from the analysis of the data. It then discusses the contribution of this research as a whole. The chapter concludes with suggestions for future research.

CONCLUSIONS

The analysis approach I used, including ordering and grouping both projects and variables, provides mechanisms for simplifying and understanding the case study data. These analytical approaches also assist in illuminating relationships among the variables and projects that may not be obvious by inspection. The data analysis methods I employed form a logical foundation for further synthesis, and thoughtful inspection of the data combined with a systematic approach to analysis led to a number of interesting conclusions.

These conclusions are derived directly from the observed data from the cases and the interpretation of the data using the approach described in the analysis section. Although each conclusion stands alone based on the data, the insights provided are interelated in their description of integration on the cogeneration projects I studied. The conclusions describe the framework validity, integration curves and dimensional shifts, the engineering-construction interface, evolutionary versus revolutionary changes, and the role of the project manager as an integration leverage point. Each conclusion is described in a separate section below, beginning with a statement of the conclusion, and including a description and explanation of the basis for the conclusion. The implications of each conclusion for research and practice are given in the contribution section of the chapter.

FRAMEWORK VALIDITY

> The attributes of project integration in the manufacturing environment are similar to those from the sample of cogeneration projects. The observed attributes of integration from the construction cases differ from the manufacturing model primarily in the degree of conformance to the framework. The conformance matrix is a valid and useful tool with which to measure the degree of integration of the sample of cogeneration projects.

There are two underlying assumptions upon which this research is founded. The first is that, in general, the framework of integrated manufacturing describes a higher degree of integration on development projects in the manufacturing industry than was present on the cogeneration projects I studied. The second is that there are sufficient similarities between the two processes that a meaningful comparison can be made. Both of these assumptions are borne out by the results of using the conformance matrix as a comparison mechanism.

None of the projects ranked high on all the integration variables, indicating that as a group, the projects that I studied were less integrated than the composite model of integration presented by the framework. However, there are similarities between the composite image of integrated manufacturing that is reported in the literature and the observed project development environment on the cogeneration cases I studied. The differences are primarily differences of degree, as reflected by the conformance values presented in the conformance matrix.

This is based on two observations. First, the project conformance values were evenly distributed among low, medium and high values, as is indicated in **Figure 6-1.** The overall average of all 96 conformance values is 2.0. The overall average of 2.0 (indicating a medium level of conformance) and the symmetrical distribution of values support the argument that a comparison of the two industries as performed in this study is a useful approach.

If there were a large number of low conformance values, one might conclude that there were too many fundamental differences between the two industries to permit a meaningful

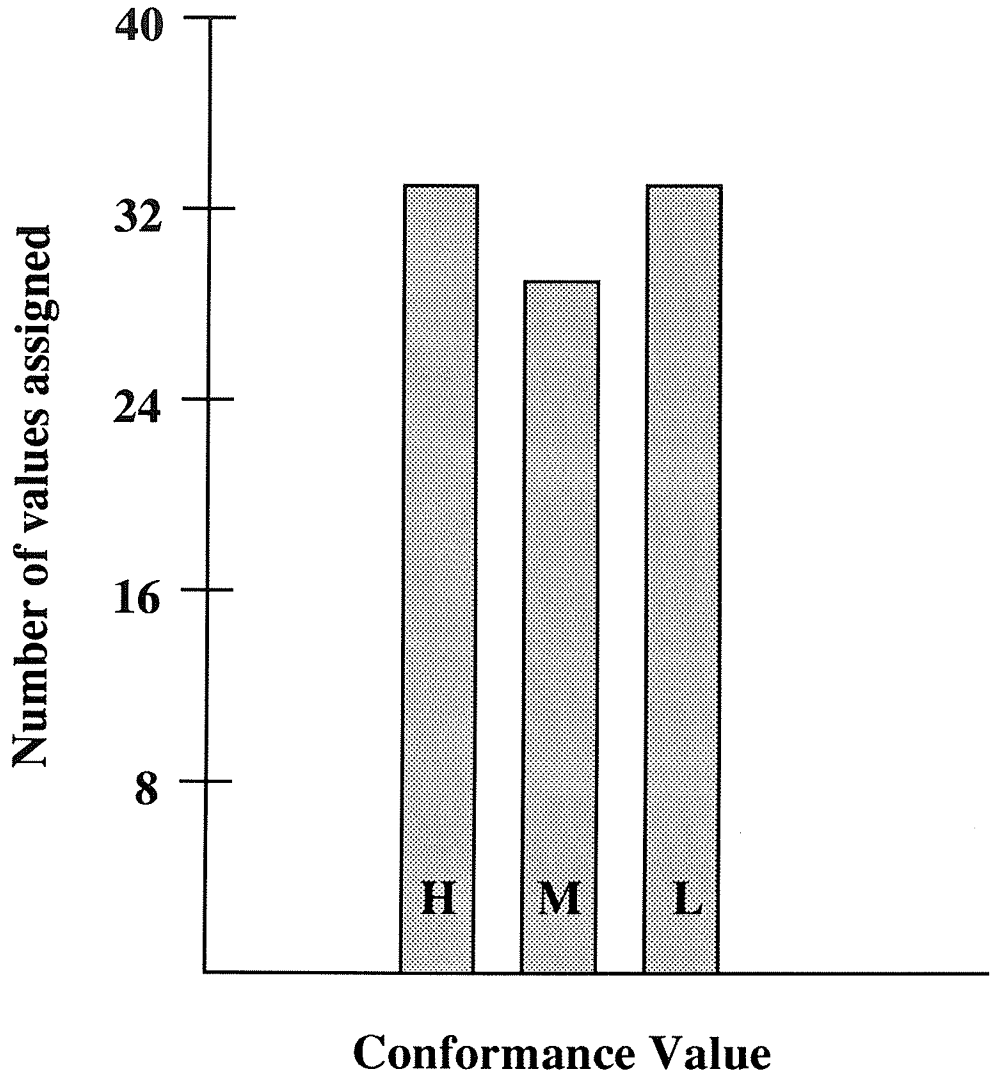


Figure 6-1

Overall distribution of the 96 conformance values

comparison. On the other hand, if the distribution were dominated by high values, one might suspect that the degree of integration on projects in the two industries was actually quite similar, an observation not supported by examination of the case data. The even distribution of conformance values supports the argument that the framework was correctly calibrated and that it captured data at an appropriate level of detail.

This line of reasoning is also supported by the skewed distribution of correlation coefficients among variable pairs, as was indicated in **Figure 5-11.** The fact that there is a tendency towards positive correlations means that the framework variables work together to describe the environment on the projects I studied. Since each of the framework variables was designed to measure some attribute of the integrated environment, I would expect there to be positive correlations between the variables. That is, the framework works consistently and cohesively as a measure of the degree of integration on the projects that I studied.

The field data presented in the case studies also support this conclusion. The variables used to describe the attributes of integrated manufacturing are appropriate metrics for examining issues of integration in construction. A "reality check" was provided by the fact that the people with whom I spoke on the different cogeneration projects were highly tuned to the questions that I raised during the course of the field interviews. They were aware of and concerned about the issues that this research addressed.

Based on these observations, with strong support from the case data and the interactions with project personnel during the course of data collection, I conclude that the framework as a whole, and the individual variables themselves, did indeed capture relevant data that can be used to make meaningful comparisons between integrated manufacturing and the sample of cogeneration projects that I studied. These projects represent different degrees of overall conformance to the manufacturing framework, and each project occupies a different position along an "integration curve" described by the degree of conformance to the manufacturing framework.

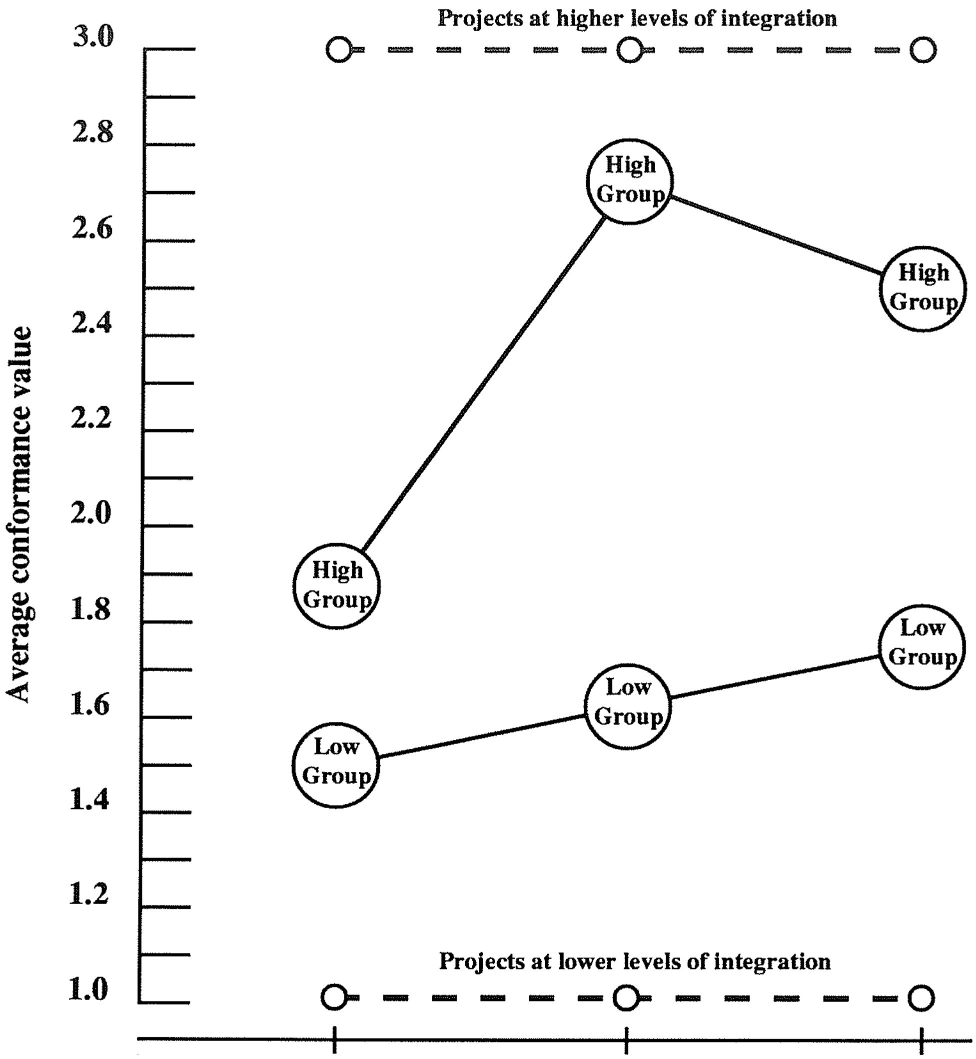
INTEGRATION CURVES AND DIMENSIONAL SHIFTS

> The move from lower to higher states of project integration is manifested by increasing degrees of conformance along the three variable dimensions, technical, interface and environment. Each project I studied has a unique integration curve represented by its conformance values as plotted by variable dimension. The integration curve is a measure of the degree of project integration, and the slope of the curve provides insight into the mechanisms that drive projects towards higher states of integration. This observation forms the basis for a hypothesis describing two fundamental mechanisms for increasing project integration, management-pull and technology-push.

The analysis presented in Chapter 5 indicated that the sample of cogeneration projects clustered into two groups, those with higher overall conformance values and those with lower values. Furthermore, the variables factored into three dimensions, which I called technical, interface and environment. Each dimension describes attributes of a fundamental factor that influences project integration. Environment captures characteristics of the project environment that affect integration. Interface reflects aspects of the interactions between project participants. Technical describes issues related to integration tools such as automation and computerization of project tasks.

The projects that I studied represent a snapshot or cross-section of cogeneration projects at various stages of integration. The degree of integration is measured by the degree of overall conformance to the framework. The results of plotting the average conformance values for the two groups of projects (representing high and low conformance) and the three variable dimensions (technical, interface, and environment) are presented in **Figure 6-2**. This diagram provides a snapshot of the two clusters of projects, each representing a different "integration curve." Projects that conform more highly to the manufacturing framework can be described as more integrated, or on a higher integration curve.

An integration curve, either for a specific project, or for clusters of projects such as the two represented here, is the map of the variable conformance values for the project or cluster, plotted by dimension. If a project were highly integrated (integration being defined here as the degree of conformance to the integrated manufacturing framework) its integration curve



	Technical Dimension Variables 3B, 1C, 3C, 4C	**Interface Dimension** Variables 2A, 4A, 1B, 2B, 4B, 2C	**Environment Dimension** Variables 1A, 3A
High Conformance Group MO, BA, HE, AL	**1.88**	**2.71**	**2.50**
Low Conformance Group DE, OX, RI, HO	**1.50**	**1.63**	**1.75**

Average conformance values

Figure 6-2

Integration curves for the two project clusters, plotted along each of the three variable dimensions

would be represented by the flat dashed line at the top of the figure, which corresponds to high conformance values across all three dimensions. Similarly, projects with low conformance values across the three dimensions would exhibit integration curves similar to the flat dashed line at the bottom of the diagram. If projects within a firm or an industry progress from lower to higher states of overall integration, their integration curves must move upwards on the conformance-dimension chart. The slope of the integration curve provides a basis for hypothesizing mechanisms of increasing integration.

The transition from a low overall level of project integration to a higher level takes place by increasing the degree of conformance for each dimension to a higher level. The fact that both the high and low clusters of projects have integration curves that rise from left to right implies that there may be an order or rationale to the increase in dimensional conformance.

One can hypothesize two possible mechanisms for increasing project integration. The first consists of a management-pull approach. This approach is a management driven, rational mechanism of increasing project integration. Managers might first build the environment that supports integration, then structure the project interfaces to expedite interaction and the exchange of information, and finally invest in the technologies that support integration.

The project data indicate that the projects I studied lie between the two extremes of overall high or overall low conformance. For both the high and low conformance groups, the integration curves slope up from left to right, illustrating the tendency towards a higher degree of conformance in both the environment and interface dimensions than the technical dimension for the two clusters.

These data lend some support to the management-pull hypothesis. Certainly, all the projects ranked lower on the technology dimension than either the interface or environment dimensions. It is clear from the case data that the projects I studied are not utilizing computer technologies such as 3–D CAD systems, project databases, simulation tools, automated planning systems to their potential. Most projects used some form of automated network scheduling package and have automated such routine functions as payroll and cost accounting, but have yet to realize the potential of computer technologies. The fact that these projects ranked higher on the environment and interface dimensions indicates that there may be a management-pull effect at work. However, whether this reflects a conscious management approach, or is merely reflective of construction's traditional strengths of project organization and management is not clear from these data.

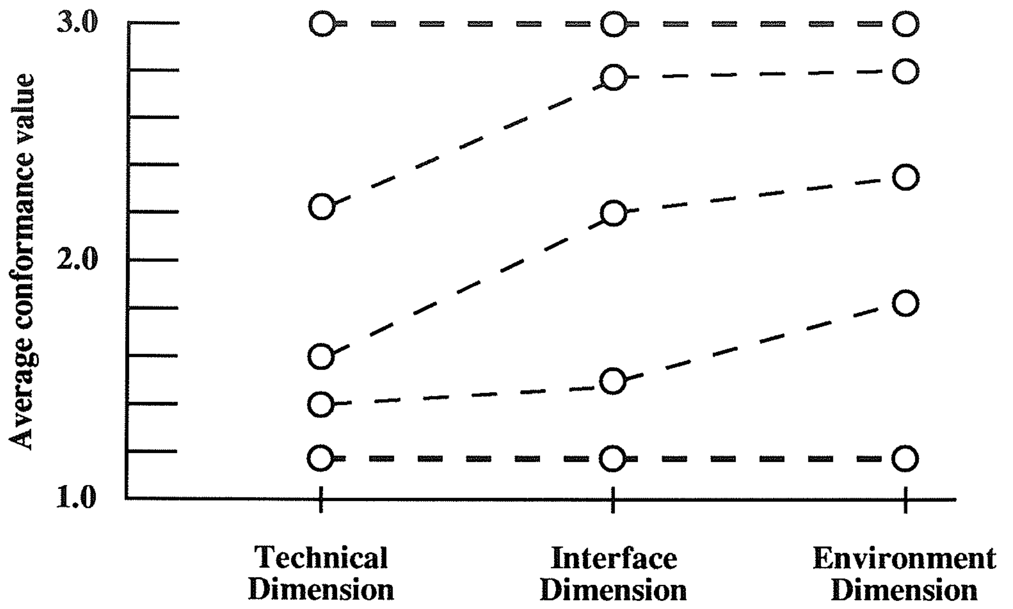
Integration curves that slope down to the right, indicating a higher degree of integration on the technical dimension than on the interface and environment dimensions, would provide evidence for the presence of a second integration mechanism, which can be described as a technology-push approach. This is a technology-driven, bottoms-up mechanism. The presence of technologies that enhance integration could act as a driver to facilitate interface interactions, which could eventually change the project development environment.

Figure 6-3 presents two families of integration curves. The first family represents the anticipated shape of a series of project integration curves that would reflect a management-pull mechanism at work. The second set represents the anticipated shape of integration curves that would support the presence of a technology-push effect at work.

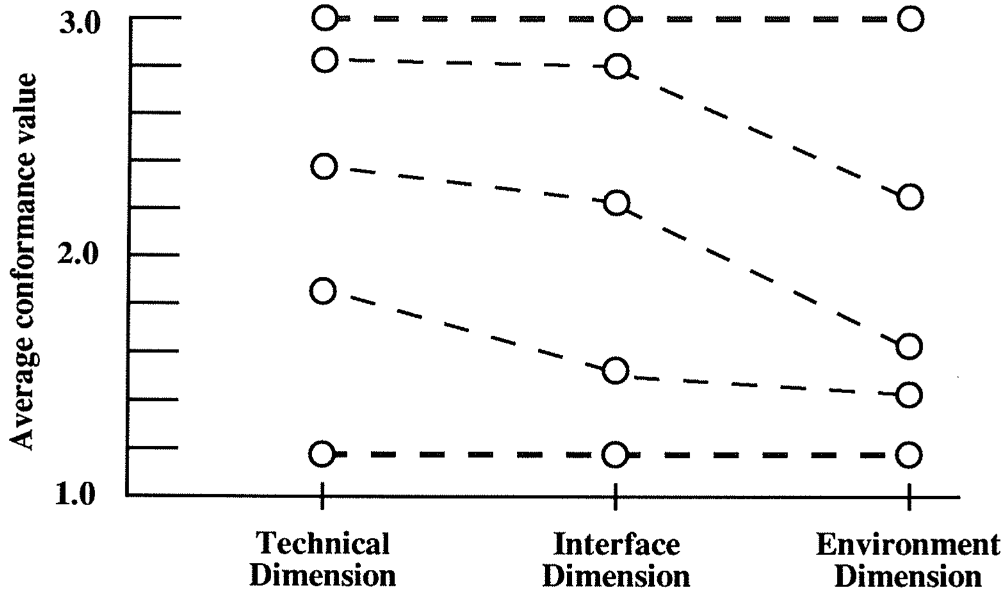
While the data do not support the presence of a technology-push mechanism on these projects, these data do not imply that a technology-push approach is not possible. The presence of automation and integration technologies within a firm or on a project may permit a different mode of increasing the level of project integration. One mechanism might be a simultaneous and synergistic increase in the conformance level of both the technical and the interface dimension in a situation where computer tools are readily available. The identification and description of a technology-push integration mechanism, as well as further investigation of the presence of a management-pull mechanism, are promising areas for further research.

THE ENGINEERING - CONSTRUCTION INTERFACE

> The dominant differentiator between the high conformance project cluster and the low conformance cluster is the structure and strength of the engineering-construction interface. This is reflected in the disproportionate contribution of two variables in the interface dimension that describe this interface. This interface contains both a formal organizational structure and a number of unstructured points, and it changes in time as the project progresses.



Anticipated integration curves for management-pull integration mechanism



Anticipated integration curves for technology-push integration mechanism

Figure 6-3

Different integration curves for technology-push versus management-pull strategies

Both the high and low conformance project clusters have integration curves that slope upward to the right, indicating the possibility of a management-pull effect on these projects. The high conformance project cluster ranked higher than the low conformance cluster on all three dimensions. However, the greatest difference between the two groups is on the interface dimension conformance rankings.

As discussed in Appendix N, the factor analysis of the 12 integration variables led to grouping the variables into three dimensions. The dimensional groupings were based on computed eigenvalues, each of which reflects a portion of the variance in the variable values captured by an underlying factor. The factor that explains the largest portion of the variance, over 42%, is the factor on which the variables that form the interface dimension load most strongly. This means that the interface dimension is the strongest descriptor of variable variance, implying that the interface dimension represents the strongest factor influencing the variables.

The influence of this dimension is also reflected in the fact that the greatest difference between the high conformance project cluster and the low conformance cluster is along this dimension. Examination of the individual variable conformance values indicates that two variables contribute a disproportionate amount to the difference between the clusters. These two variables describe the engineering-construction interface and are the dominant influence in differentiating the high and low conformance clusters.

As discussed in the Chapter 5, some 40% of the overall difference in conformance rankings between the two projects can be attributed to the effects of Variable 2-B, <u>engineering-production interface</u> and Variable 4-A, <u>production input to design</u>. If the contribution of each variable were the same, one would expect each variable to contribute 100/12 = 8.3% of the observed difference, or 16.6% for two variables.

The two variables are strongly positively correlated. In other words, projects with a high degree of conformance for one of these variables also conformed highly on the other. This implies that they are not orthogonal and that they actually capture aspects of the same phenomenon. This is not surprising since, as I argued in Chapter 5, the presence of a strong interface might be expected to facilitate the flow of information across it.

The engineering-construction interface appears to be the dominant influence in the interface dimension, as well as the significant differentiator between the high and low conformance projects, based on their relative conformance values. This demonstrates the importance that a clear recognition of the role of this interface and attention to structuring the interface play in the shift to increased levels of integration.

The engineering-construction interface is not a single point, but rather a plane slicing the project vertically through different levels in the organization and horizontally across multiple disciplines.

There are multiple interfaces between engineering and construction that represent points on this plane. It appears that there are at least two structured interface points. One is a higher level interface occupied and controlled by the project manager. This is the traditional hierarchical project structure with both the engineering and construction managers reporting to the project manager. This interface deals with issues such as staffing, planning and scheduling work, and coordinating the overall efforts of the two groups. The second level is lower in the organization, and takes the form of direct information transfer such as constructability input and the resolution of technical field problems. The position of the field engineer, an engineer with field construction experience, acting as a constructability coordinator is emerging as a focal point for the direct interaction between engineering and construction.

There are some data to support the concept of unstructured interface points, or the actual development of the project interface plane. The use of on-line manipulations of the 3D model in a "walkthru" type environment is one. The use of videotapes of the model is another. In addition, project managers who provide opportunities for engineers to visit the field and for construction personnel to work for periods of time in the design offices are actually developing unstructured interface points. These unstructured interfaces are the result of direct interaction between members of the engineering and the construction groups, both early in the project during the course of construction planning and constructability input, and later in the project during the resolution of field problems.

Due to the evolving information and coordination requirements of the two groups, the engineering-construction interface changes over the life of the project, resulting in two distinctly different temporal interfaces. The first is during the planning and design stage, where construction input is being solicited for design input and review. The second is during the field construction phase when engineering needs to supply construction with the working drawings and other information it needs to perform the work.

The relationships that form during the first phase can greatly expedite the working relationship during the second phase. Integration is enhanced not only by the immediate transfer of information, but by the establishment of longer term interpersonal relationships, which facilitate interaction later in the life of the project.

There are other key interfaces not expressly captured by the framework variables. One of these is the construction-startup interface. This represents a critical transition from a discipline or facility focus to a systems focus prior to plant commissioning and startup. In addition, the shift to preassembled and prepackaged components is changing the nature of the constructed product, just as it is changing the construction process. Detailed assembly sequences and interconnect requirements for major equipment are increasingly being developed by the equipment manufacturer. Therefore, the vendor interface takes on a process dimension in addition to the traditional product dimension.

This research demonstrates that a strong engineering-construction interface with active flow of information across it is the single most significant factor that differentiates the cluster of high conformance projects from the low conformance cluster. Further description of the engineering-construction interface, such as identification and description of the structured and unstructured interface points that form the interface plane and understanding how the interface changes as the project progresses are interesting areas for future research. Additional interfaces such as construction-startup present another opportunity for future research to describe the attributes of the interfaces, the appropriate timing of their formation, and the nature of their influence on project integration.

EVOLUTION VERSUS REVOLUTION

> The dimensional shifts describing increases in the degree of integration represent an increase in conformance at the variable level. These changes in variable conformance occur in either an evolutionary or revolutionary manner.

The previous sections presented the concepts of integration curves and dimensional shifts and described the influence of the interface dimension. The process of changing the degree of conformance along the three different dimensions, environment, interface and technical, is a process of increasing the degree of conformance of individual variables. The dimensional shifts provide a macro-view of the transition to higher degrees of integration.

This process is further understood by a taking a micro-view of the variables that make up the three dimensions. There are two distinct modes by which projects move from a less integrated state to a more integrated state on a variable basis. These can be classified as **evolutionary** or **revolutionary**.

The degree of conformance of evolutionary variables can change gradually or incrementally, as indicated by the range of conformance values for these variables. Revolutionary variables represent a set of binary attributes that exhibit either a low or a high degree of conformance, with no observed interim value. These are more indicative of a paradigm shift than a gradual shift in the degree of implementation of an integration variable.

The variable histograms presented in Chapter 5 provide insight into this process. I identified two types of variables, which I have labeled as incremental and bimodal. The incremental variables are distributed among all three levels of conformance, low, medium and high. The bimodal variables are represented by either low or high degrees of conformance. These bimodal distributions imply that while some variables can change incrementally, other project attributes "jump shift" from low to high degrees of conformance. This may be indicative of the presence of either a paradigm shift, or a "critical interface mass" that support higher degrees of conformance or integration.

Three variables exhibit characteristics of bimodality, indicative of a "revolutionary" shift to higher levels of conformance. The three binary variables that I identified are Variable 4-A, production input to design, Variable 2-B, engineering-production interface, and Variable 1-C, management perspective of integration technology. These three bimodal distributions are presented in **Figure 6-4**.

The bimodal distribution of Variable 1-C, management perspective of integration technologies, implies that a paradigm shift may be required on the part of management in order to initiate higher levels of conformance in the technical dimension.

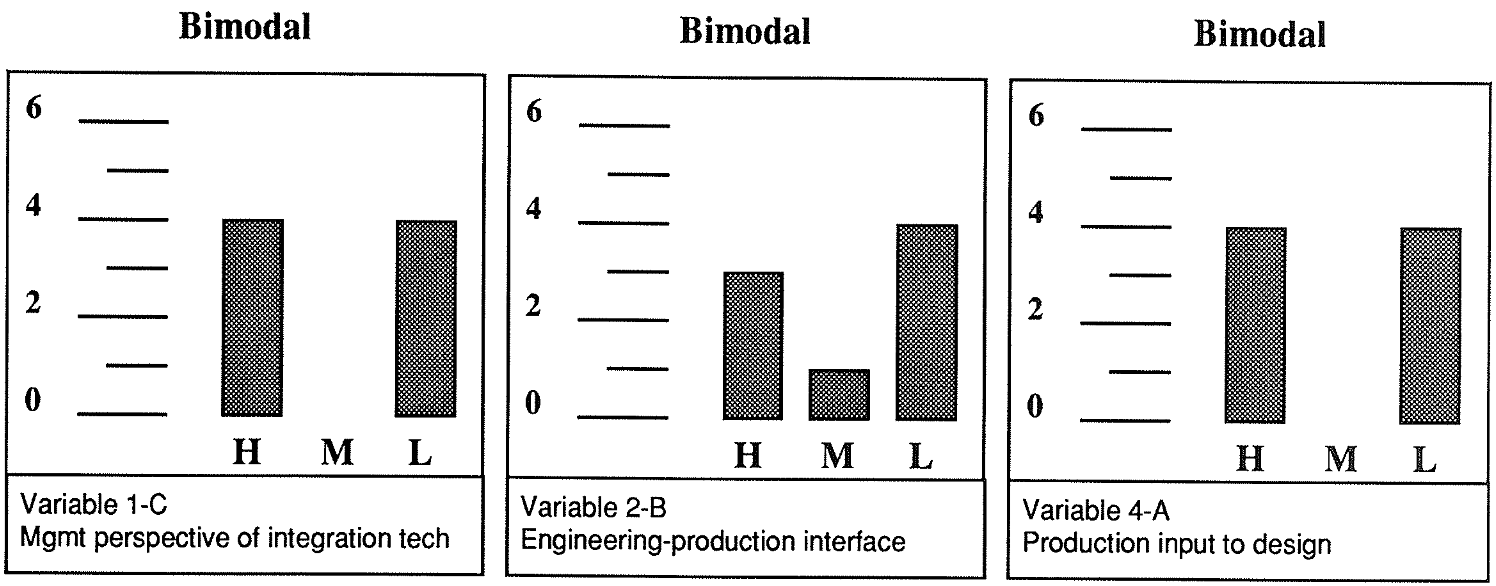


Figure 6-4

The three bimodal variables indicating areas of revolutionary change

Two of the bimodal variables, 4-A and 2-B, are included in the interface dimension. These two variables describe the engineering-production interface and are the two that contributed the most to the difference between the high conformance and the low conformance project clusters. The distributions for these two variables break cleanly along the high and low clusters of projects. That is, the high conformance projects ranked high on these variables and the low conformance projects ranked low. This observation implies that the interface plane must reach a "critical mass" before it begins to function effectively.

The implication of these observations is that for the distributed variables, projects within a firm may move incrementally from a low to a high degree of conformance with regards to these variables as they learn or restructure projects. An incremental investment in resources would appear be repaid with an incremental improvement in the degree of integration. However, for the bimodaly distributed variables, an incremental approach to increasing integration may not be feasible.

While greater degrees of integration may be achieved incrementally, or in an **evolutionary** manner for some variables, others may require a **revolutionary** fundamental project restructuring or paradigm shift by management before higher degrees of integration are possible. Exploring these mechanisms of changing conformance, and documenting and describing paradigm shifts and interface structures on other projects, holds promise for future research.

PROJECT MANAGER IS THE LEVERAGE POINT

> The project manager is the key to making the shift to higher degrees of integration along all three dimensions.

The position of the project manager emerges as pivotal focus for integration on the projects that I studied. The project manager has the power, the authority, and the ultimate responsibility for the profit or loss of the project. He is also a potential barrier, since the same attributes that enable him to focus the efforts of a dedicated project team may act as impediments to integration and the implementation of new technologies.

Sanvido (1984) presented the concept of controlling resources at one level higher than that at which they are utilized. These include integration resources. This further implies that the process of integration must work its way down from the top. If the idea of a management hierarchy is that each level has information at a more summary level, a more global perspective of the project, then the force to integrate must come from the higher level perspective. This doesn't mean that a bottom's up approach won't help. People at all levels will try to find ways to coordinate their efforts more efficiently. But any structured attempt to improve the degree of integration must necessarily come from above. **Management is the key** to integrating the efforts of the resources it controls.

This is supported by the management-pull effect on the project integration curves described earlier. The evolution of the construction project from lower to higher degrees of integration along the dimensional paths illuminates a fundamental mechanism of integration. The fact that environmental shifts precede interface and technical shifts supports the concept that the process occurs in a top-down manner. As such, the process should be effected and managed in a top-down manner, and the key point in controlling this process appears to be the project manager.

The project manager is active in each of the three dimensions along which projects progress towards higher degrees of integration. At the environment level, the project manager builds the project team and imbues it with a sense of common purpose and motivation. At the interface level, the project manager structures and supervises the different project interfaces. He forms one structured interface point on the engineering-construction plane. He is also a principal interface point between the project and the owner, as well as with corporate management.

At the level of the technical dimension, the project manager makes decisions on the implementation and use of automation tools on the project. He is responsible for the project budget that includes provisions for these tools. Even the firms with extensive in-house efforts to develop technology delegate project automation responsibility and decisions to the project manager. The position of the project manager is still that of an autonomous leader with almost total responsibility for structuring and completing a project successfully.

However, the nature of the turnkey engineer-constructor is changing from that of a "generalist" firm that does everything to a "coordinating" firm that has substantial general knowledge but subcontracts specialty work. There is a shift to distributed technical design, which increasingly occurs in the vendor's office, and the constructor is becoming more of an assembler than a fabricator. With much design and fabrication work being pushed into vendors shops through the use of preassembly and vendor supplied systems, the role of the engineering design contractor is evolving from one of generator of information to one of a coordinator or integrator of information generated by others. The coordination demands on the turnkey contractor are evolving from intensely site related tasks to more global information coordination tasks. This shift increases the coordination demands on the project and on the project manager to manage the interfaces.

The early project development environment is dominated by the need to collect and integrate information from different external entities, such as the client, the steam host, the utility, regulatory agencies at federal, state and local levels, lenders, and major equipment vendors. Each has a tremendous impact on defining the project, and these external entities exert strong influences on these projects. Managing these interfaces is an important aspect of delivering cogeneration projects.

The project team is not uniquely defined by the turnkey contractor's personnel, and there are consequently both internal and external interfaces to structure and manage. The early project stages are dominated by external interface management activities as the project is defined and as permitting and financing are arranged.

During the latter stages of the project, when project activities are predominantly related to detailed design and construction, the project focus shifts from definition to execution. During these latter project stages, internal interface management dominates the turnkey project manager's efforts.

During this latter execution stage, although internal interactions within the turnkey contractor tend to predominate and the influence of external entities diminishes, there is a perception of greater project risk. This implies that a higher degree of internal integration, as demonstrated by improved interface structuring and management, may lead to reduced project risk.

The responsibility of providing an environment where the project manager's performance is not measured by the costs of project learning falls on the firm's general management. If a project manager is handed an incomplete design, a budget and a schedule, and his performance is measured to those standards, he has little incentive to innovate or try new methods or technologies. He can deliver the project by traditional methods, with which he is familiar, with less risk.

The data on project performance parameters clearly indicate that the two principal parameters for defining performance are schedule and budget. Project managers are rewarded for bringing projects in on time and under budget. Period. They are only rewarded for experimenting or innovating if the experiment or the innovation is a success. They are only rewarded for spending project dollars and allocating project resources if the project bottom line is improved. Is it unreasonable to expect that project managers should strive to integrate when they are neither evaluated nor rewarded on the basis of degree of integration.

A company wide integration strategy should support the efforts of project managers to integrate their projects. Part of the strategy must be an equitable approach to incentive, evaluation and reward systems. Integration and automation cost real dollars not only in terms of hardware and software, but by early staffing to build interfaces, and the subsequent management of those interfaces. Therefore, new parameters and metrics for quantifying project success may be necessary. These might include such factors as the degree of integration, the use of new automation technologies, and the degree of training and cross discipline learning.

The project manager is a key factor in improving project integration. He plays a major role in structuring and managing project interfaces, including the engineering-construction interface, which was shown to be the strongest differentiator between the high and the low conformance project groups. Creating new parameters for defining project success and metrics for their measurement, quantifying the benefits of integration, and describing alternative project management structures are important areas for future research.

RESEARCH CONTRIBUTION

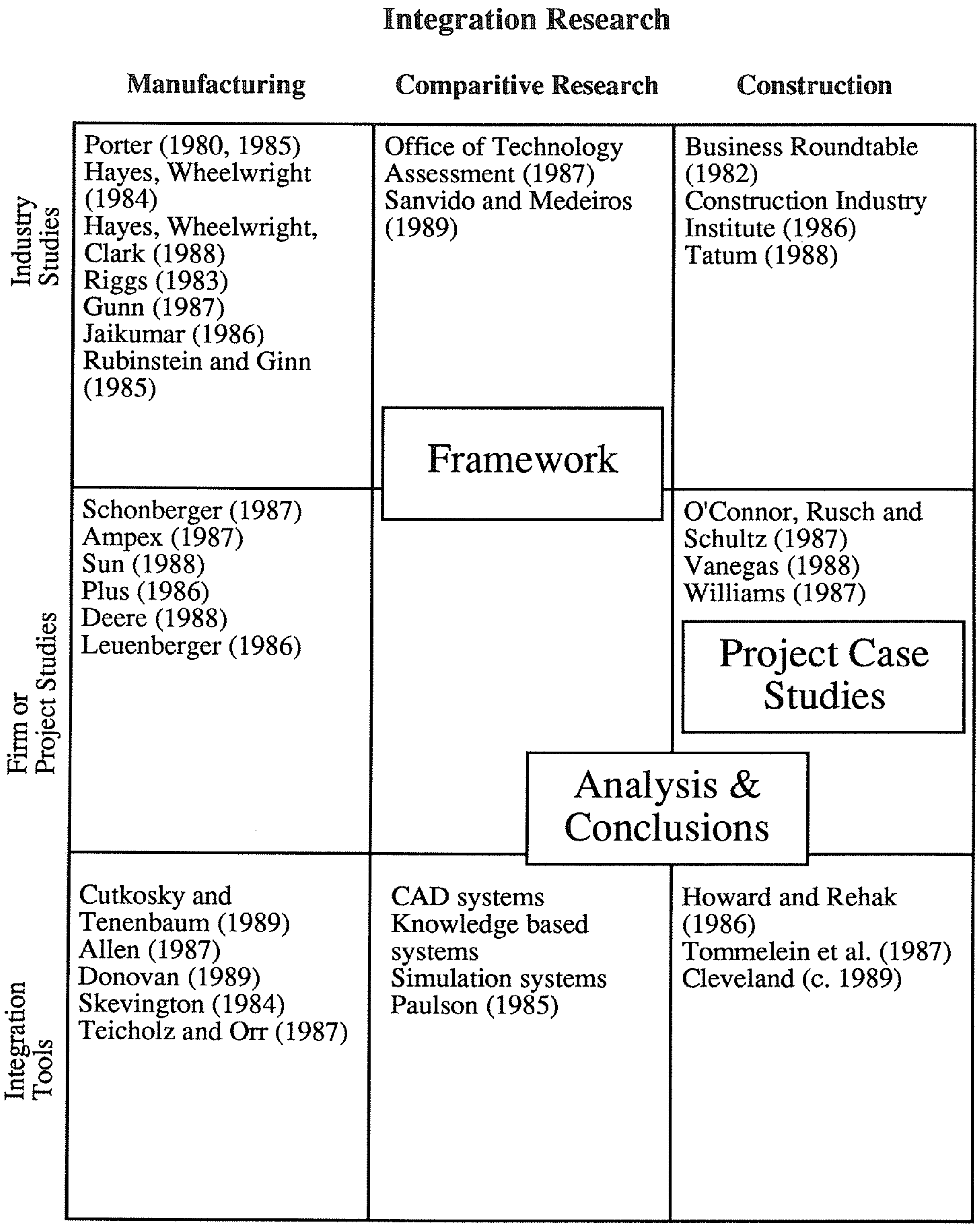
Simon and Burstein (1985, p. 51) point out that "The aim of all research . . . is to get new knowledge." This investigation increases understanding of integrating product design and process engineering in construction. The contribution of this work consists of three elements, each of which represents an incremental addition to the body of knowledge from which this research departed.

The first element is a conceptual framework that aggregates the attributes of integrated manufacturing into a cohesive, four part structure that guided this research. The second element consists of a series of project case studies that used the framework to describe and analyze issues of integration on a selected group of cogeneration projects. The third element of this contribution is the results of analysis and conclusions that describe the mechanisms of integration on these projects.

Figure 6-5 illustrates how the three areas of research contribution map onto the existing body of integration research in manufacturing and construction.

This research provides insight into the mechanisms and opportunities for the application of integrated project management techniques in manufacturing to the construction of cogeneration plants. It provides a **framework for comparison** and for the transfer of experience from one related industry to another. It provides **case based knowledge** of integration practices on a selected sample of construction projects. This research also presents **analyses and conclusions** related to the process of transition to higher levels of integration on construction projects.

This research provides an increased understanding of the nature of integration in construction and the mechanisms by which projects move from a lower state of integration to a higher state. This research has created new tools with which to measure and analyze integration, it has accumulated project data that describes the current state of integration of a selected group of construction projects, and it has developed conclusions that increase understanding of the process of moving to higher levels of integration. Finally, this research provides a platform for future work, offering new directions for research in engineering and construction management.



Integration Research

	Manufacturing	Comparitive Research	Construction
Industry Studies	Porter (1980, 1985) Hayes, Wheelwright (1984) Hayes, Wheelwright, Clark (1988) Riggs (1983) Gunn (1987) Jaikumar (1986) Rubinstein and Ginn (1985)	Office of Technology Assessment (1987) Sanvido and Medeiros (1989)	Business Roundtable (1982) Construction Industry Institute (1986) Tatum (1988)
Firm or Project Studies	Schonberger (1987) Ampex (1987) Sun (1988) Plus (1986) Deere (1988) Leuenberger (1986)		O'Connor, Rusch and Schultz (1987) Vanegas (1988) Williams (1987)
Integration Tools	Cutkosky and Tenenbaum (1989) Allen (1987) Donovan (1989) Skevington (1984) Teicholz and Orr (1987)	CAD systems Knowledge based systems Simulation systems Paulson (1985)	Howard and Rehak (1986) Tommelein et al. (1987) Cleveland (c. 1989)

Figure 6-5

Areas of Research Contribution

FUTURE RESEARCH

This research has opened doors for future work in a number of areas. These include project integration curves, project performance parameters, modeling the engineering-construction interface, and project management structures.

Future research - integration curves

The development of the concept of the integration curve leads to a number of fertile areas of future research. New data collection mechanisms, in the form of questionnaires that capture the key elements of the integration framework, would allow data collection on a much larger sample of projects. Mechanisms of integration on projects in other sectors, such as commercial construction or heavy civil work might also yield interesting results.

The small sample of eight projects restricts the strength of arguments that a management-pull mechanism is actually present on these projects. This is, however, a superb opportunity for further research on a larger sample of projects. Armed with the hypothesis that either a management-pull or technology-push effect were present, one could plot integration curves for a much larger sample of construction projects in an effort to determine the existence of these influences on a larger sample of projects. Another approach would be to return to the manufacturing environment and investigate the presence of these effects in the manufacturing environment.

The absence of evidence of a technology-push effect on these projects is interesting in itself. Why is there no evidence of a technology-push effect on these projects? Is a technology-push approach intrinsically fatal to a project, such that the population of these projects does not survive long enough to be observed?

The firms that have projects that ranked high have learned new skills, undergone paradigm shifts and realize that the nature of their "product" has changed. What are these skills? What are the new demands on project management to manage these skills?

Project performance parameters

The data I collected from the projects using the project manager questionnaire were inconclusive in determining a link or causal relationship between the degree of integration and project performance. One problem here is the fact that while the common performance parameters are cost and schedule, there is no uniform mechanism for measuring these parameters that can be applied across a sample of projects. In addition, if firms desire to increase the technical integration of their projects and increase the use of computer applications and project automation, they must devise new measures of project performance.

New project performance measures might include the degree of integration, the use of new technologies, the project safety record, the ability to generate repeat work, client satisfaction, the amount of training or learning that occurs on a project, the creation and transfer of new knowledge, such as constructability guidelines, or the degree of employee satisfaction. In other words, a project that scores high on using new technologies, that is highly integrated and that creates a sense of employee satisfaction due to the learning on the project might fall short of traditional financial success parameters, but would still be considered successful. This is equivalent to a redefinition of capital and a review of the capital investment decision for the firm and its projects.

Additional research is needed to define project performance parameters, to create new metrics to measure performance, to quantify project benefits of integration, and finally to measure the impact of integration on project performance.

Modeling the engineering-construction interface

The fact that the engineering-construction interface is the primary differentiator between the high and low conformance clusters indicates the importance of the engineering-construction interface. More work is needed to fully understand and model the interface and chronicle its changes through the life of the project. Other interfaces such as the construction-startup or engineering startup interface merit study as well.

Project management structures

The identification of the project manager as a key leverage point for integration and of the importance of his role in interface management forms a basis for future research. The development of the three dimensions of integration implies that there may be interesting alternatives to the single point responsibility of the project manager. Future work might focus on the possibility of structuring project management along the three dimensional lines as a project triumvirate. A manager of automation-integration technologies, perhaps from the corporate MIS group, might be responsible for the technology dimension, the traditional project manager for the interface dimension, and a senior corporate manager responsible for the environment dimension.

CLOSURE

This research broke new ground in comparative, case-based, inter-industry research. It made fundamental contributions in three areas: by developing a framework that allowed the comparison of the integrated manufacturing environment with a series of construction projects; by collecting data and reporting on the state of integration on those projects; and by using innovative analysis techniques to generate conclusions about the integrated environment observed on the projects. This research also paved the way for future research in a number of related areas. Finally, this research demonstrated that integration is not merely a conceptual model for projects. It can be described, quantified, and measured, and most importantly, practiced, on real projects by committed managers.

APPENDIX A

FIRMS PARTICIPATING IN THIS RESEARCH

1.	ABB Construction Management Services	1460 Livingston Avenue North Brunswick, New Jersey 08902
2.	ABB Energy Services Inc.	1460 Livingston Avenue North Brunswick, New Jersey 08902
3.	Altresco, Inc.	235 Merrill Road Pittsfield, Massachusetts 01202
4.	Bechtel Corporation	12440 East Imperial Highway Norwalk, California 90650-3134
5.	Bechtel Power Corporation	50 Beale Street San Francisco, California 94119-3965
6.	Becon Construction Company, Inc.	P. O. Box J Boron, California 93516
7.	CRS Sirrine, Inc.	216 South Pleasantburg Drive Greenville, South Carolina, 29606-5456
8.	CRSS Capital, Inc.	1177 West Loop South Houston, Texas 77227-2427
9.	Ebasco Constructors Inc.	3000 West MacArthur Boulevard Santa Ana, California 92704-6993
10.	Ebasco Services Incorporated	3000 West MacArthur Boulevard Santa Ana, California 92704-6993
11.	Fluor Constructors International, Inc.	3333 Michelson Drive Irvine, California 92730
12.	Fluor Daniel, Inc.	3333 Michelson Drive Irvine, California 92730
13.	General Electric Capital Corporation	1600 Summer Street Stamford, Connecticut 06905
14.	Hawker Siddeley Power Engineering Inc.	10497 Town and Country Way Houston, Texas 77024

15. Miller-Kerr, Inc.	Three Riverway, Suite 900 Houston, Texas 77056
16. Power Industry Consultants Inc.	P. O. Box 71057 Marietta, Georgia
17. Saguaro Power Company	3000 West MacArthur Boulevard Santa Ana, California 92704-6993
18. Southern Company Services, Inc.	Post Office Box 2625 Birmingham, Alabama 35202
19. Southern Electric International, Inc.	798 Canal Bank Road Windsor Locks, Connecticut 06096
20. Westinghouse Electric Corporation	Westinghouse Building, Gateway Center 11 Stanwix Street, Pittsburgh, PA 15222-1384

APPENDIX B

PERSONS INTERVIEWED FOR THIS RESEARCH

1. Danny Anderson
2. Robert J. Anderson
3. David J. Antenesse
4. Wally C. Arias
5. Werner Astl
6. Richard Bailey
7. Henry L. Borkowski
8. Dean Bursheim
9. Les C. Crabtree
10. J. Hunt Crisler
11. Wm. J. (Mike) Davis
12. Dennis E. Derley
13. Darrell D. Donly
14. Jim Dunston
15. Daniel G. Ferguson
16. Werner Fischer
17. Mark Geiger
18. Kathy Gorski
19. Gerald Gottlieb
20. Kirk D. Grimes
21. Bill Gubb
22. Herbert A. Hand
23. Phillip Hardwick
24. Robert Hart
25. Greg Hartnett
26. Al Heep
27. Ken Hollenbach
28. John Z. Horvath
29. Walter Q. Howard
30. Zoltan Ince
31. Rick Iuliano
32. Ken Kinkela
33. Vince Kontny
34. Douglas E. Kopp
35. A. E. "Butch" Lake
36. Gregory Lee
37. Jim Lee
38. Max Lidl
39. Jack R. Long
40. C. A. Ludwigson
41. Robert E. Malany
42. Howard McCraney
43. J. David Melvin
44. Page D. Miller
45. Jim Minoque
46. W. John Muirhead
47. Charlie Nance
48. N. Thomas Neff
49. Arthur E. Nelson
50. Reed Nielsen
51. C. A. "Buzz" Powell
52. Greg Rahman
53. Clyde A. Raney
54. Robert L. Ryser
55. Patrick J. Sharkey
56. Derek Smith
57. George Spindle
58. Gene Testolin
59. Robert B. Whorton IV
60. Robert W. Zaist

APPENDIX C

INTERVIEW GUIDE

Project Integration on Cogeneration Projects

This research will examine issues and mechanisms of project integration on a series of cogeneration projects. One definition of integration is "the simultaneous collaboration of specialized functions." Project integration can also be defined as "the sharing of common resources to achieve progress towards common goals, from positions of equal power and status within the firm." In addition, integration includes the use of tools, knowledge, experience, and technologies that support progress towards project goals. This research will explore the project environment that promotes integration.

As a guide to collecting data, I have developed a series of categories describing different aspects of project integration. This interview guide will briefly describe each of the categories and includes questions relating to each.

PROJECT DESCRIPTION

Location

Participants

Contractual relationships

Technical description of project

Overall project schedule

CONTEXT DIMENSION

The context element of the integration framework describes the environment in which the project is defined and delivered by the turn key contractor.

Project development environment

Was the project development environment open and experimentive, or highly focused?

Were mistakes anticipated and tolerated as part of a creative, learning process?

Were different design options considered as the project progressed?

What are the competitive factors that drive the project? For example: time; money; service; proprietary technology?

What are other driving influences? For example: generating repeat business; developing an award winning design or technology; prototyping new systems; demonstrating technology; minimizing environmental impact.

Are there penalties or bonuses for timely performance or overruns?

How are jobs won? Are they bid, negotiated?

Does the firm take an equity position in projects?

How is the prime contract structured? Lump sum? Turnkey?

What are the contractual responsibilities of the turnkey contractor? Of the subcontractors?

Is there an emphasis on "design for constructability?"

Is there a conscious effort to develop a sense of goal congruency among team members?

What aspects of the forces that drive the project promote or prevent project integration?

To what extent is this a "typical" project for this firm?

Is there a sense of high level management visibility and support of efforts to integrate?

Timing of product and process engineering

Was this a "fast track" project?

When did construction planning begin?

Was construction planning actively addressed during design?

At what degree of design completion was construction begun?

Was this a typical overlap? Did construction begin earlier or later than "normal" for similar projects?

How did construction planning and design interact? Were they independent activities? Sequential or concurrent?

Management perspective of integration technologies

What was used to measure interim performance on the project?

How are lessons learned on previous projects incorporated in subsequent projects?

What time frame did management take in introducing new integration technologies?

Are integration technologies viewed as strategic tools or as project expedients?

How is the performance or efficacy of integration tools measured?

How are computer tools budgeted?

Are they expensed to projects or covered by overhead?

Who pays for training?

Is there a consolidated effort to build expertise in computer technologies or is each project viewed as unique and evaluated independently?

ORGANIZATION DIMENSION

This section will capture data on the structure and organization of the project team. This includes both the formal contractual and reporting relationships between team members as well as the informal relations that exist on the project.

Project team attributes

What is the composition of project team? (e.g., engineering, procurement, vendors, construction, subcontractors, operations, owner)

Was the team multi-disciplinary?

Is the team dedicated to the project or is some form of matrix organization used?

Are design and construction performed by the same entity?

When was team assembled? Were all factions represented from the beginning?

Are project members encouraged to learn from and train others on the team?

Is the integration of team members a factor when the team is structured?

Are most problems resolved on a discipline basis or is the entire team involved?

Is there continuity in the composition of the team during the project life?

Is there a bonus structure for team members?

Is there any other system of joint accountability or reward for team members?

Was the owner actively involved in the project?

Were project goals and performance requirements clearly defined?

Was top management actively involved in monitoring progress on this project?

How was the organization chart structured?

Is it relatively flat or hierarchical?

Are lines of reporting the same as lines of communication?

What is the management style of the project manager?

What level of responsibility and authority is given the project manager?

Engineering-production interface

Who is the "customer" of design information?

Is there a formal liaison group or individual that facilitates the exchange of information between design and construction?

Are there constructability representatives on the project team?

Do the persons providing constructability input remain active during construction?

Do designers and construction personnel talk directly to each other or do they go up and down a chain of command?

Vendor interactions

Who are the critical suppliers or vendors on the project? e.g., gas or steam turbine?

When and how are vendors selected?

What criteria are used to evaluate vendors and subcontractors?

What input do they make to design? To construction? Operations?

When are critical vendors selected?

Are there bonus/penalty arrangements with vendors?

To what extent are subcontractors used on this project?

Are there more or less vendors and subs than on previous projects?

PROCESS DIMENSION

This element of the framework examines the communications structure and patterns of the project group. This element will capture data on the methods, timing, and direction of communication among the project team members. This includes both interpersonal and electronic communication.

Communication patterns

Where were team members located?

Were they physically proximate? Was there open access to each other?

Were there regular meetings or were informal low level contacts more prevalent?

How do team members communicate? Electronically, memos, over lunch, at the coffee shop, reviewing drawings, electronic models, trading computer outputs?

At what level do team members communicate? Do they follow a chain of command, or interact directly?

Do most offices operate with an open door policy, or are meetings scheduled?

How are design reviews carried out? Formally? Regularly?

How does the design evolve?

How often are design review meetings held?

Is the design communicated in a large batch mode or in smaller incremental pieces?

Were all team members involved in design review?

Was input sought from all participants?

Was a physical or electronic model developed as a prototype?

Were there engineering change orders during design?

Were these the result of information from construction or other members of the project team? (e.g., procurement, owner, regulatory bodies)

How many were design or construction related versus owner mandated?

Does construction have the authority to mandate design changes or to veto aspects of the design?

Engineering generalist

Were highly experienced team members sought out exclusively, or were people with varying degrees of experience and different backgrounds interspersed?

What was the background of the project manager?

What was the background of the construction manager? Of the engineering manager?

What are the attributes that were considered in the selection of team leaders?

Are personnel encouraged to gain experience in more than one discipline?

How is this accomplished?

How is communication among specialists facilitated?

Computer integration

What project automation tools were used?

What computer tools are used for design, scheduling, simulation, planning, communication?

What tools are related to product design, process design, construction, and information management?

To what degree are these systems linked or integrated?

Is there an MIS group within the firm? To what extent does it participate in project data management decisions?

Were the computer tools used on the project paid for by the project or from overhead?

Was a 3D CAD model developed and maintained?

To what extent was a 2D system used?

Who develops input to the CAD model?

Does construction have access to the model for review or for planning? Can construction change the model?

Are vendors linked electronically? Can they access the model or input data?

How are as-builts developed?

CONTENT DIMENSION

The content element of the framework captures the specific information that flows between members of the project team. This element will describe the nature of the information that passes between construction and engineering, both during design and during construction.

Production input to design

How are construction material, labor and equipment requirements developed?

Are these requirements estimated during design evolution or after the detailed design is complete?

Are alternate designs considered based on construction feedback?

Does the evolution of design take into account the use of specialized construction equipment? For example, the availability of a large capacity crane such as a Transilift?

Did construction provide input regarding site layout?

Were material staging and laydown requirements, access clearances, temporary facilities, personnel ingress and egress, and other requirements communicated by construction?

How did construction communicate with design?

Did construction provide input regarding vendor or subcontractor capabilities?

What special construction technologies were used or considered?

Who supplied information on the technologies?

Did construction communicate its unique capabilities or requirements to design?

Were there specialized lifting or handling requirements?

Were there unique site conditions that required specialized knowledge?

Were offsite assembly or preassembly methods used on the project?

When was the offsite plan developed? By whom?

Development of construction (process) plan

Was a construction plan developed during the planning phase?

Is it a formal plan? Is it implemented?

Is it used only as a conceptual tool for planning or was it actually used to guide and control construction operations?

Who provided input? Were all construction disciplines involved?

Does it include timing requirements for materials and equipment purchasing and delivery?

Does it include a well defined, detailed assembly sequence?

As the construction plan was developed, were construction requirements communicated to engineering? How? Was the design modified?

Was experience from previous projects incorporated into the project plan?

Electronic data exchange

What specific information was exchanged among team members through the use of electronic media?

Were design data such as dimensions and material characteristics transmitted electronically?

Were simulation tools used to develop activity durations and cycle times? How were these data communicated and used?

Were site layout configurations developed or transmitted electronically?

Were any automated assembly or fabrication devices used on the project?

How were they programmed or controlled?

What is the product of design?

How was expert knowledge of process or construction methods captured and utilized?

APPENDIX L

SUMMARY OF THE CASE DATA

INTRODUCTION

This appendix provides a summary of the case study data. It describes the data from all the cases and is organized by the framework variables and the elements of those variables. This appendix offers an intermediate level of description that falls between the cases themselves and the numerical analysis of the conformance matrix.

The framework of integrated manufacturing provides the structure for this appendix. Each heading corresponds to one of the framework variables, and includes a discussion of the data for that variable from the projects taken as a group. Each variable is in turn composed of several elements, which are discussed under each subheading. The variables that I developed for the integrated manufacturing framework in Chapter 3 are presented in **Figure 3-4** through **Figure 3-7.** The process of assigning conformance values is described in detail in Chapter 2, and the analysis of the conformance matrix is presented in Chapter 5.

VARIABLE 1-A PROJECT DEVELOPMENT ENVIRONMENT

The average conformance across the eight projects for this variable was 2.25. Four projects ranked high in this category, while two projects ranked low. The development environment for the cogeneration projects that I studied appears to be similar to that observed in manufacturing. In spite of inherently adversarial contracts, there was a sense of high level goal congruence. Most projects were delivered by a focused team working under intense schedule pressure. As indicated in **Figure 3-4**, this variable contains the four elements discussed in the following subheadings.

Overall project level goal congruence

This issue was expressed at two levels on the projects I studied. At the contractual level, the principals were bound by an inherently adversarial contract, predicated upon incomplete design, yet stipulating a fixed price. Therefore the owner and the turnkey contractor were placed in a position of refining the plant design from adversarial positions. However, at a higher level, there was tremendous incentive for all parties to work together to deliver the plant on time. Owners are driven by the loss of revenue and the possibility of the project going "belly up" should the drop dead date be missed. The turnkey contractors are driven by stringent bonus-penalty arrangements and by their reputation in the industry and desire for future work.

Although the nature of most of the turnkey contracts created an adversarial relationship between the client and the contractor, the two groups worked together to resolve their differences with the common goal of delivering an operating plant.

Open environment that supports learning and is tolerant of mistakes

On only one project was there specific data regarding an open, experimentive, questioning approach to developing the project. At the project level there was not a specific focus on learning, but rather the emphasis was on getting a plant designed and constructed. All of the turnkey contractors had some experience in power plant construction, and the project members were highly focused by discipline. The nature of their task was generally not in developing a truly new project, but efficiently putting together the pieces of existing systems.

Emphasis on teamwork and problem solving

All the projects made use of some form of task force approach to delivering the project. Within the task force group, there was a strong emphasis on a team approach. On most projects, the project team included active representation by the client throughout the project. Some projects exhibited a close owner-contractor interface with joint problem solving efforts, but others were merely exercises in contract administration by both parties. In most cases, the client's representative acted in a review capacity, and did not have approval authority over the design or construction plan. However, suggestions by the client, or "review with comments" were tantamount to instructions to the contractor.

In one sense, the entire process of developing a cogeneration plant is a process of problem solving. However, the nature of the problems are related to overcoming the impediments to achieving known goals, rather than creating a new or fundamentally different product. Internally, within the turnkey contractor's organization, there is a great deal of emphasis on directed problem solving, in the context of refining the plant design and execution plan.

Time pressure to get the product out

The nature of the PURPA Qualifying Facility is such that it is inherently a schedule driven plant. There is tremendous time pressure for the owner to generate power to qualify, and consequently for the turnkey contractor to deliver an operating plant.

All the projects studied were developed under intense time pressure. They were driven by the power and steam sales agreements, and the related drop dead dates. The importance of the schedule was reflected in the nature of the bonus-penalty arrangements observed on all the projects, and subcontracts were often evaluated on the basis of their ability to support the schedule as much as the dollar value of the contract.

VARIABLE 1-B TIMING OF PRODUCT AND PROCESS ENGINEERING

The average ranking for this variable was 2.63. This represents the highest degree of conformance of the projects to any of the variables. This level of conformance was observed on only one other variable. Five projects ranked high for this variable, and three ranked medium. All the projects I studied used a fast track approach, with construction beginning before design was complete.

This means that there was an overlap between the two activities. Process, or construction, planning took place in a top-down fashion at two levels, a conceptual level, and a detailed level. Conceptual construction planning typically began as soon as the turnkey contract was signed. This was usually reflected in the generation of a summary or milestone schedule. Detailed planning took place after sufficient design information was generated to support the activity. Indeed, most projects showed evidence of construction actually being constrained by or driving the development of design information during the concurrent detailed design and construction phases. This included information from vendors such as equipment manuals and installation or hook-up data.

There was some discrepancy in the perception of project personnel as to the meaning of fast track. All of the projects were strongly schedule driven. All of the projects began construction before design was complete. However, the degree of overlap varied widely. Several project people also expressed the opinion that their projects were fast track simply because they were doing everything as fast as they could; that is, they were under severe schedule pressure. **Figure 3-4** summarizes the two elements for this variable, which I discuss in the following subheadings.

Concurrent or simultaneous product and process engineering

The concept of concurrent or simultaneous product and process engineering does not map directly to the construction projects I observed. Manufacturing process engineering is akin to construction planning, not construction execution. The manufacturing concept of concurrency is represented by the simultaneous completion of product design and process planning. Concurrent product and process design means that process planning activities occur in parallel with product design, but that the actual <u>production activity</u> occurs subsequently.

There is a high degree of conformance here in the sense that early planning took place to the degree that information upon which those planning decisions were based was available. Detailed construction planning cannot occur until sufficient engineering information is developed to support that planning. The manufacturing approach is to have the product completely designed and the manufacturing operations completely specified before the manufacturing process begins. The construction approach is to develop the preliminary information required for construction as soon as possible, and begin construction based on the portions of that information that are available, even if the entire project has not yet been defined. This is the essence of fast track construction, and a major difference from the manufacturing concept of simultaneous product and process engineering.

In a fast track environment, some portions of the project are decoupled. For example, the installation of the equipment foundations is not related to the electrical requirements of the equipment. Other than the location and orientation of supply lines, the foundation design essentially depends on information regarding the weight, size, anchor bolt pattern and center of mass or dynamic response of the equipment. Even when some of these are not known precisely, allowances can be made for conservative design and the foundation can be designed, engineered and installed with preliminary information. It is highly unlikely that the chassis for an automobile could be manufactured based on preliminary information regarding the size of the engine, and anticipate that the information would become available prior to the time that the engine should be installed. That is, the chassis and the engine are highly coupled.

The analog of this approach in construction might be the detailed planning that occurs prior to a planned shutdown of an operating plant. Each activity during the shutdown is planned in minute detail, since the critical constraint is the outage time. For fast track projects, the overall project development time is critical.

On the projects I studied, high level, or summary planning took place concurrently with conceptual or preliminary design. However, detailed construction planning, which is highly dependent on the generation of design information, necessarily took place after detailed design, and typically, shortly before the actual field activity began.

Overlapping development phases

The construction analog of overlapping development phases is the fast track approach. All the projects exhibited an overlap of field construction work and project engineering. Although construction planning began when the turnkey contract was signed as part of overall project planning, the detailed construction schedule was typically not developed until further along in the project when more detailed design information was available.

Five of the eight projects were ranked as high in this category, due to the fact that the fast track approach that all the projects took was a strong example of overlapping development phases. The concurrent approach was observed on most projects, but at a summary not a detailed level. Three projects made extensive use of subcontractors, who did not participate in early process engineering, and were thus ranked as having medium conformance.

VARIABLE 1-C MANAGEMENT PERSPECTIVE OF INTEGRATION TECHNOLOGIES

Of the eight projects, I ranked four as high and four as low in terms of conformance. Although this resulted in an average ranking of 2.00, this does not accurately reflect the nature of the cases. My observations of the projects indicated that each project fell distinctly into one of two groups. The first group of projects were delivered by firms that indicated a high overall awareness of the importance of automation and integration technologies. The second group appeared to have a less awareness and emphasis on the development and use of these technologies. The implications of the binary nature of this variable are discussed further in the conclusions chapter.

The projects that were ranked high were delivered by two firms, both of which have extensive internal technology development programs. They are investing in new technologies for engineering and design and are actively trying to integrate these technologies into field construction work. The other firms, whose projects ranked low in conformance, appeared to take a more traditional perspective of the use of project automation tools, which are just beginning to make an appearance on their projects.

The projects that were ranked high all developed a 3D CAD model of their plants and used 2D CAD for drafting. Three of the projects that ranked low were for the most part still using the drafting table to create design drawings, with some use of 2D CAD as a drafting tool beginning to emerge. **Figure 3-4** lists the following two subheadings that describe the elements for this variable.

Management takes long term time perspective

The projects that ranked high in this category were using tools such as 3D CAD systems and microcomputers. There was also an emphasis on exploring opportunities for the development of new tools. Most project team members conveyed a knowledgeable and open attitude towards new technologies.

In contrast, the projects that were ranked low in this category appeared to be basically doing business as usual. Two projects were working on drawing boards, since as one participant put it, the designers preferred it that way. There was little initiative on the part of project management to force the technology issue on the project and little awareness of what was happening throughout the rest of the firm.

The decision to use automated or integration technologies is a project level decision, usually made by the project manager. Even though projects are essentially stand alone efforts, they are delivered in the context of the firm's "technology culture." The projects that ranked high had a well developed technology culture, both at the project level and at the level of the firm. The projects that ranked low had a conventional culture that reflected traditional methods.

Management has strategic perspective of integration technologies

Half of the projects studied, those that ranked high, viewed the development of new engineering and construction technologies as strategic issues. This was evidenced by strong corporate MIS groups, independent CAD groups, and the proliferation and use of automation technologies on their projects. The group of project that ranked low in this category were notable for the absence of these characteristics.

VARIABLE 2-A PROJECT TEAM ATTRIBUTES

Five of the eight projects were ranked high in this category, while the other three ranked as medium. The average ranking of 2.63 was the highest of any variable. The firms were typically characterized as moving towards a project task force approach and away from a matrix organization. All of the projects used some form of a task force, with core members dedicated for the duration of the project.

There is a good deal of similarity in the descriptions of the product development team in manufacturing and the task force approach I observed on the cogeneration projects I studied. Although the project managers had almost absolute authority over their projects, they primarily acted as coordinators to support the efforts of the diverse group of technical specialists that worked for them.

The task force approach is not new in construction (see "Directions in Managing Construction," 1981). It is typically regarded as more appropriate for unique or one of a kind projects. The cogeneration projects I studied were not considered unique, except for site specific items such as civil work and layout. There was even some reference to the "cookie cutter" nature of the plants by some participants. This perception was held more by the financial participants who viewed the project as a series of cash flows rather than a site specific technical problem. However, all of the projects I studied were using some sort of a task force approach, and most indicated that they were moving away from a matrix organization. **Figure 3-5** lists the four elements that make up this variable and structure the following discussion.

Dedicated cross-functional teams

All of the projects I visited used some form of a project task force to deliver their project. Most of the firms were previously structured as matrix organizations and had recently shifted or were in the process of shifting to a task force approach. Team members included the engineering disciplines, procurement, construction, and at times technical specialists or other internal or external consultants who focused on specific issues such as permitting. Most members were fully dedicated to the team while they were involved with the project, but were rotated through the project as their particular expertise was required. The key members of the team, the project manager, engineering manager, and lead engineers were usually dedicated for the duration of the project.

Heavyweight project manager or Tiger Team approach

The project managers on the projects I visited were described quite accurately by Wheelwright's heavyweight project manager and Tiger Team structures. The project managers I observed are universally senior, experienced members of the firm. They are very knowledgeable, and have almost absolute authority over their projects as well as profit and loss responsibility. They are responsible for supervising both engineering and construction activities, and while they have backgrounds that stress one or the other of these areas (typically engineering), they take a global view of their projects and keep overall project goals in mind when allocating project resources.

They may spend more on engineering, if for example, it buys them time during construction. They may spend more on the construction budget by bringing in the construction staff early in the project to work with the engineers in the home office.

The project managers I met did not appear to wield their authority overtly on their projects. They tended to act as facilitators or coordinators rather than authoritarian directors. They recognized the talents of their team members and endeavored to provide them with the resources they needed to perform their jobs and coordinate their efforts with other team members and outside participants.

Joint accountability and reward systems

All the projects I studied had some form of bonus/penalty arrangement between the owner and the turnkey contractor. These bonuses and penalties were at times passed on to major equipment vendors as incentives to support the project schedules. However, only one project had a mechanism to distribute bonus money to project team members.

Continuity of team members through the project

Most projects made an effort to maintain a sense of continuity among project participants. For example, key players such as the project manager, construction manager and engineering manager were often involved in the project proposal stage and were subsequently assigned to the project for its duration. One project in particular had a number of key positions turnover during the project with corresponding difficulties in transferring knowledge and experience to the new team members.

VARIABLE 2-B ENGINEERING-PRODUCTION INTERFACE

The average rank for this variable was 1.88, with three projects ranked high, four projects ranked low and one medium. Although there was typically no formal representation by construction, the engineering-construction interface was characterized on most of the cases by some degree of construction representation in the engineering offices during the early project stages. The interface was often staffed informally by the construction manager or represented by the project manager.

The conformance values for this variable tended to fall into one of two categories, either high or low. There was only one medium ranking. Therefore the average conformance value tends to misrepresent this category as having an overall medium conformance. The projects actually fell into two camps. The first group had high conformance ratings and was characterized by extensive early construction involvement by members of the construction group that eventually moved to the field. The second group of projects ranked lower because there was less active involvement by construction during the early project stages.

Most of the projects reported that at some point during construction, the construction effort drove the detailed engineering schedule. That is, engineering was pressed to generate timely information to support the field effort. In this sense, construction became the customer of detailed engineering.

Although there was almost universal recognition of the opportunity for project benefit by involving construction early in the project, as manifested by comments by project team members, only some of the projects acted on this perception. See **Figure 3-5** for a listing of the three elements that are included in this variable and are discussed in the following subsections.

Manufacturing is customer of product design

On most of the projects I visited, the construction group was perceived to some extent as the customer of engineering design. This was reflected in the emphasis on early construction involvement, the solicitation of constructability input, and during the latter stages of most projects by the fact that construction typically drove the engineering effort. That is, there was a great deal of pressure for engineering to provide timely information to support the construction effort.

Use of formal liaison group to expedite design production interface

Most projects did not have a formally designated interface group or person. The project manager was often described as the de facto interface point. However, on some projects there was an effort to bring some members of the construction team into the design offices early in the project to provide constructability input, to push the construction group's learning curve to an earlier point in the project, and to build solid working relationships between the two groups to facilitate interaction later in the project.

Use of producibility experts or integrators

Although there was a trend across the projects to assign construction personnel to the engineering offices early in the project, there was less evidence of a formal designation of construction experts or construction coordinators. However, regardless of the formal designation, there was on most projects a clear recognition of the benefits of early construction involvement and this function was performed by construction personnel who were eventually transferred to the site.

VARIABLE 2-C VENDOR INTERACTIONS

The project rankings for this variable were universally medium with only one low ranking, for an average of 1.88. The projects were very similar in their interactions with vendors. All major equipment suppliers were active early since their equipment constituted the long lead time items on the projects. Most major vendors were specified by the owner prior to the turnkey contractor joining the project.

The selection of major equipment is usually made by the owner or his representative very early in the project development cycle. The turnkey contractor is at times not involved in this decision, but inherits a preliminary design and specifications from the owner. In other cases, the turnkey contractor acts in a consulting capacity to the client and participates in the conceptual phase when major vendors are selected.

One project actually purchased a gas turbine on speculation. The purchase was made before the project was certain to proceed, yet the contractor was secure in the knowledge that he could use the unit on the next project that came up.

There appear to be generally good working relations between the turnkey contractors and the major vendors. The firms that I observed delivering cogeneration plants had worked with the different turbine and boiler suppliers on other projects and generally expressed a sense of professional respect for the vendors. There was no indication that any of the turnkey contractors had a preference for or vested interest in any particular turbine vendor. The turbine vendors appear to compete based on price, availability of their units and matching performance with the required capacity for a given application. **Figure 3-5** tabulates the three elements for this variable discussed under the following subheadings.

Early vendor involvement

Major equipment vendors typically interface closely with the turnkey contractors since the balance of plant is designed around major equipment. In addition, each major vendor provides some personnel to oversee installation and start-up of his equipment, since he is the most technically knowledgeable. The issuance of warranties is predicated upon this vendor involvement.

However, there is also a trend towards moving much field assembly and testing into the vendor's shops, with fully assembled units or modules shipped to the site. In these cases there is less of an active interface with the vendor, primarily through the bid process and performance and interconnection specifications. These vendors deliver a black box, or complete system, both physically and functionally.

Strong vendor relations based on partnering

Bonus penalty arrangements were at times passed on to major equipment vendors and suppliers not only for timely supply of equipment, but also for timely generation of design information. If partnering is defined as sharing of rewards as well as potential liabilities, then there are numerous examples of these projects moving in this direction.

However, if partnering is defined as building long term, mutually beneficial relationships between suppliers and users, there are no real examples. There are only a few vendors that supply major equipment such as gas turbines, boilers, and steam turbines. They act as an oligopoly and have considerable power over their customers. They have limited supply or production capacity with long lead times for delivery, they black box their technologies, they dictate transport and installation procedures using the leverage of their warranties, and they provide the core around which the balance of plant is planned, designed and constructed. One turnkey contractor is a major turbine supplier and is vertically integrating forward into project delivery.

Use of fewer suppliers

With the exception of one project that used a construction management approach and over 50 subcontractors, the projects I visited used few subcontractors, generally for distinct speciality items. However, there is no data on whether the numbers of subcontractors is more or less than on other projects, either historically or across the industry.

VARIABLE 3-A COMMUNICATION PATTERNS

The conformance values for this variable were evenly spread across the projects. Three projects ranked high, two medium and three low for an average ranking of 2.0. Most of the projects demonstrated evidence of some communication elements observed in the manufacturing framework, but to varying degrees. The five elements of this variable are listed in **Figure 3-6** and are discussed in the following subsections.

Full two-way information exchanges between design and production

Although many of the projects assigned members of the construction team to the engineering offices during preliminary design, the principal flow was from engineering to construction as design developed. On some projects, construction provided feedback through design review, but the nature of the process was one of developing engineering data first and involving construction in a feedback loop for review. On the projects where there was active construction input, there was evidence of two way exchanges in a mode of problem resolution or discussion of alternatives during the review process.

Direct horizontal (lateral) exchanges rather than vertical flows

The lead engineers on most projects were the formal focal point for communications with their discipline. However, most projects located the task force members in one area, which supported an informal approach to group communications. This informal low level approach was, in most cases intentionally supported by the lead engineers and by project management.

Continuous, low-level interaction that supports low-level decision making

This sort of interaction was present on most of the projects, but primarily among the engineering group members. Most projects engendered an open, informal atmosphere among the design disciplines. On projects where construction was a strong presence in the engineering offices, the construction representatives tended to interact at all levels and on an informal basis.

Extensive communication, both formal and informal

These projects were universally represented by intense and continuous cycles of both informal get-togethers and formal meetings to communicate design progress to team members, coordinate related efforts and generate feedback from team members, particularly construction and the client. Indeed the entire process of project development is one of generating and communicating project information in a timely fashion.

Manufacturing approval for design release or veto of engineering design

There was little reference to a construction veto power over design. In most cases, someone representing construction was in the engineering offices early in the project reviewing the implications of equipment selection, plant layout and overall design. Even in the instances where the project was delivered by subcontractors, the turnkey contractor had a construction staff that participated in design reviews. Construction authority and participation generally extended to a review and comment function and did not include the authority to veto portions of the design. There was an indication on only one project that there were design changes made as a result of the exercise of a construction veto.

VARIABLE 3-B ENGINEERING GENERALIST

The rankings for this variable were fairly evenly distributed across the projects. Two projects ranked high while three each ranked medium and low, for an overall ranking of 1.88. **Figure 3-6** presents the three elements for this variable.

Engineering generalists as team leaders

Across all the projects I visited, experience was the number one criterion for staffing the project manager position. The typical project manager had 15 to 20 years of experience. The project managers, while rising through the ranks of construction, engineering, or project management, also had training or experience in such areas as business administration, marketing and sales.

Experience in more than one discipline

Most design engineers had experience only in their discipline. That is, they were technical specialists. One exception was a project that performed design on a system basis. The engineering group was structured along system lines rather than discipline lines.

Most of the construction personnel appeared to have more of a variety of experience. There was on several projects a perception that the younger construction people should be trained in a variety of trades. This was usually at the initiative of one or more senior persons who took it upon themselves to provide opportunities for younger engineers and field hands to get cross training experience in different areas. Due to the relatively small size of most of these projects, project personnel commented that it was necessary for team members to wear more than one hat.

Translator function between functional groups

There were two examples of staffing based on translator perspective. Several projects used the field engineer position to act as a liaison and translator between the home office design team and the field construction group. The field engineers were typically younger people with an engineering education. They were often assigned to the home office engineering team before being transferred to the field.

One project established a liaison position that coordinated the interaction between the turnkey contractor's home office organization and the firm that performed detailed design of the balance of plant. He was selected specifically because of his breadth of knowledge. His role was to act as a single point of contact between the two firms. Since he was both technically knowledgeable about a wide range of issues, and familiar with the firm's organization, if he could not resolve a specific problem, he could direct the subcontractor's representative to the appropriate person within the turnkey contractor's firm.

VARIABLE 3-C COMPUTER INTEGRATION

The rankings for this variable were dominated by low scores. There were four low rankings, three medium and only one high, for an average of 1.63. This was the second lowest overall ranking. **Figure 3-6** lists the five elements that comprise this variable, and each is discussed in the following subsections.

Applied automation technology in four areas, product design, process design, production, and information management

The greatest effort at developing and applying automation technology is in the field of product design, or plant engineering. However, there was a wide range of applications in this area. Some projects were just beginning to implement 2D CAD systems to automate drafting, while others utilized sophisticated 3D systems to design and model the plants. One project made use of a detailed Project Engineering Automation Plan, which was considered by project personnel to be a very effective means of structuring the automation effort.

There was only one instance of the development of a tool for process design, and it was not used on the project I studied. Process design, or construction planning, is being performed by construction managers based on previous experience and remains an idiosyncratic and highly personal approach.

The use of automation tools in the area of production, or in the case of the projects, construction, is non-existent. There is some research being performed by the firms involved in the research, but no applications were described or observed on the projects.

Information management appears to be a more fertile area of development, especially on some of the projects that used the corporate MIS group to help structure project applications. However, this was a clear factor on only two projects.

Integration of these distributed automation efforts

The projects that are using 3D CAD systems to model their plants are fairly well integrated in the engineering realm. Design engineers use a common CAD database to model the different disciplines. The projects are still quite polarized into two camps, design and construction. On some projects, construction is using the CAD model for design review, both in a real time environment and using tools such as Walkthru and videotapes. However, this practice is not yet prevalent on most projects.

Direct linking of design tools and manufacturing systems using CIM network technologies

There were no instances of the use of automated manufacturing, or fabrication, systems on the projects I studied. Therefore there were no instances of linking design tools with manufacturing systems. Vendors such as the turbine manufacturers are undoubtedly automated to a certain degree, but there was no data on their operations.

Common CAD database and model for product and process design permits mutual and concurrent access by design and manufacturing

Five of the projects built 3D CAD models of their plants. These models were theoretically accessible by all members of the project team. However, in most cases the access by engineering was strictly controlled to maintain the integrity of the model, and access by construction was limited to either viewing the model at a terminal, or more commonly, reviewing extracted drawings. One notable exception was a project that made the model completely accessible to all disciplines under the assumption that rational and careful engineers would no more make inappropriate changes to a computer model than they would to a paper model. The project reported increased use of computer resources due to the open environment and ready availability of resources. This included the conversion of the "old hands" on the project to a position of, if not computer literacy, at least computer acceptance.

MIS group as well as engineering takes active role in computer integration

The CAD manager at one firm noted that the fact that the CAD group was organized outside the prevailing corporate MIS structure allowed them the freedom to develop CAD tools in a sort of sanctioned skunkworks environment. A different firm involved the MIS group extensively in the development of a Project Engineering Automation Plan. The difference between the two perspectives appears to be indicative of the differences between the development and the implementation environments.

VARIABLE 4-A PRODUCTION INPUT TO DESIGN

Half the projects ranked high on this variable and half ranked low. This resulted in an average value of 2.00 across the projects, but this value is misleading and not representative of the actual bimodal distribution of rankings. As reflected in the rankings, projects tended to either be quite active in this area or not active at all. The four elements that make up this variable are presented in **Figure 3-7** and are discussed under the following subheadings.

Identification of long lead time or critical components that can drive schedule

The principal long lead items on the cogeneration projects I studied are the gas turbine generators, the steam turbine generators, and the heat recovery steam generators. These are typically specified by the client, or by the engineering group at the conceptual design stage. Construction had little if any input into these major equipment decisions. However, when construction was involved in early project definition, one responsibility typically was to identify long lead time materials. Construction was also involved in the procurement of these items.

Vendor prequalification

There was less input here from construction than from the purchasing groups. Purchasing often tracks vendors and subcontractors, and maintains a list of acceptable firms for inclusion on bid lists. In two cases, individuals noted that they conveyed good or bad experiences with subcontractors to the purchasing group for future reference. Subcontractors were also selected based on reputation in the community for smaller, local subcontractors, or previous experience for larger contractors.

Process capabilities

There was little evidence of the communication of construction capabilities to the design groups on these projects. In one instance, crane capacities at the site were communicated to help a method decision.

Feedback to design on manufacturability

This category was a strong contributor to the conformance rankings. Most projects reported construction input primarily in the areas of site civil work, concrete, and structural steel. These constituted the bulk of the work by the turnkey contractors. Most piping was spooled offsite, major equipment arrived in prepackaged modules, and subcontractors were used for specialty items.

It is interesting to note that personnel on the projects that ranked low in the category all commented that "it would be nice to have early construction input," or that "early construction input is important." However, they also noted that it was expensive, or that there just wasn't an opportunity, or that it was a luxury.

The projects that ranked high in this category all assigned construction people to the engineering offices during the early project development stages. Construction reviewed the model and drawings and began to formulate the construction plan, albeit not typically in a formal manner. The interaction between construction and engineering was typically described as energetic, two way, and interactive. Some projects experienced a learning effect in that engineering had to become accustomed to working with construction early in the project and in their offices.

VARIABLE 4-B DEVELOPMENT OF PROCESS PLAN

The rankings for this variable varied across the projects. They consisted of two highs, four mediums, and two lows, for an average of 2.00. In this case, the average value is a good indicator of the project values.

The process of planning construction was composed of two pieces: the schedule of individual activities and the administrative plan, called the indirects plan on one job. These are related to the three elements of this variable that are presented in **Figure 3-7**.

Use of a formal planning procedure resulting in documented process

Only two projects generated a formal construction plan. In both cases, the plan dealt more with construction infrastructure and administration than with specific work activities. Specific activity planning remains in the domain of the project scheduler.

Detailed material, labor, and equipment requirements for production

Portions of these items were developed by construction as part of the early planning effort. However, subcontractors are often responsible for the planning and procurement activities that relate to their scope of work.

Detailed assembly sequences

The principal control mechanism on the projects I studied was the project schedule. The schedule not only tied activities into milestones for tracking progress and establishing progress payments, but eventually evolved into the detailed project plan. This evolution from summary milestone bar charts into a detailed network of specific activities generally took place over the course of the project. All projects began with a high level summary schedule with start and finish dates and only a few major activities in between. This evolved into a network schedule with typically around 100 activities with durations and linked by logical relationships. This occurred during the proposal stage of most projects. However, at this stage, the schedule, typically developed by engineering, is heavily engineering loaded. Construction activities are still at a summary level. The detailed construction schedule evolves later in the project, often only several weeks before the specific field activities begin.

One exception is the assembly of major equipment such as the gas turbines. In all cases the turbine vendor provided an erection team to oversee installation, which proceeded according to a very precise, detailed, step by step plan.

VARIABLE 4-C ELECTRONIC DATA EXCHANGE

This variable ranked lowest overall across the projects. Of the eight projects, six ranked low, while only two ranked medium, for an average of 1.25. **Figure 3-7** lists the five elements that comprise this variable, each of which is discussed in the following subsections.

Dimensional and material characteristics of components

Vendors and suppliers supplied information about the materials and components they provided through the use of hard copies of drawings and specifications. In one instance, 2D CAD files were transmitted to the turnkey contractor, but their contents were transferred manually to the 3D model.

Process characteristics and requirements, expert knowledge of assembly methods

The knowledge of detailed assembly sequences resides in the minds of the constructors. Detailed assembly operations are not addressed until shortly before the activity occurs. One exception to this is the installation of the turbines. On the projects I studied, the turbine vendor always provided technical specialists to oversee the installation of the units. The field assembly of these units was precisely choreographed by the turbine manufacture. However, the knowledge of this detailed sequencing resided with the technical specialists and in handbooks, and was communicated in the field.

Optimal shop floor layouts, machine allocation and distribution, tooling requirements

The equivalent of shop layouts and machine and tooling requirements in construction is the development of the construction plant required in the field. This was performed independently by construction personnel during the project planning phase. There was little indication that this information was fed to engineering in any fashion, much less in any electronic format.

Activity durations and cycle times

All the projects I studied used Primavera for scheduling and tracking progress. Activity durations and their logical links to other activities are the basis for a network scheduling or precedence approach such as that used by Primavera. However, subcontractors, the client and the turnkey contractor typically maintained separate systems that were not integrated and did not share data.

One firm has developed a simulation tool that uses the 3D CAD model as a basis for performing simulated erection sequences. The simulation can create activity logic links and durations that can be downloaded to a network scheduling package such as Primavera. However, the project moved so quickly that by the time the model was sufficiently developed to be loaded into the simulation environment, construction had already developed the information it needed. Future versions of the tool will reportedly be able to work at a conceptual level earlier in the project and thus create timely data for construction planning.

Direct feed to CNC machines and robots

There were no examples of the use of automated field equipment. There may have been automated fabrication equipment in the turbine or other vendors' shops, but there were no data about this.

CONCLUSION

This appendix presented a summary of the case study data. The comparison of the variable elements of the integrated manufacturing framework with the project case data resulted in the formation of a matrix of variable conformance values. The resulting conformance matrix formed the basis for the analysis presented in Chapter 5.

APPENDIX M

MULTIVARIATE METHODS

INTRODUCTION

During the course of inspecting and analyzing the data comprising the conformance matrix, it became apparent that additional approaches to grouping the projects and variables would add more rigor to the analysis and perhaps provide additional insight to the processes influencing integration on the cogeneration projects I studied.

The general problem of describing relationships among groups of objects is addressed by the field of multivariate analysis. One branch of this field, cluster analysis, deals with methodologies for grouping individuals based on some measure of similarity. Another branch, factor analysis, provides a mechanism for identifying underlying relationships among measured variables.

This appendix first provides a general description of the two methods that I used to group projects and variables, cluster analysis and factor analysis. The appendix also discusses the specifics of the techniques I employed, presents sample computational output, and describes the rationale behind my choice of methodologies.

CLUSTER ANALYSIS

Cluster analysis methods are used to group either individuals, in this case projects, or variables that capture some measured attribute of the individuals. In general, cluster analysis techniques first define some measure of association between objects (often termed similarity) as a basis for grouping them. There are then a number of different algorithms for placing objects in related groups, based on the degree of association between objects.

Association indices

Lehman describes three types of similarity measures for cluster analysis; matching coefficients, distance measures, and pattern measures (Lehman, 1985, p. 579). Matching coefficients is a method of counting how often one object has the same value for a given characteristic as another object to which it is being compared. One limitation of this method is that it does not take into account the degree of similarity or difference between two objects; only instances of exact matches are counted.

Distance measures do take into account the nature and degree of difference between two variables. Two sets (distributions) of variable values can differ in terms of their shape, level, and dispersion (Cureton and D'Agostino, 1983, p. 369). Lehman further notes that these differences can be measured in terms of either "as the crow flies" (Euclidian) or "city block" distances (Lehman, 1985, p. 581). One approach, the Minkowski metric, accounts for all three differences and can be adapted to measure either Euclidian or "city block" distance. (See Cureton and D'Agostino, 1983, p. 370; or Lehman, 1985, p. 581 for the more general solution.)

Pattern measures are a form of distance measure, but take into account only the relative difference in variable values, not the absolute value. Correlation coefficients are one form of pattern measure, and are used as the basis of association for factor analysis approaches to grouping objects.

Cureton and D'Agostino (1983, p. 366) list a number of other indices of association, including cosines, overlap coefficients, coefficients of agreement, covariances, and Mahalanobis generalized distances. Each of the preceding similarity measures can be weighted for a given variable, based on the nature of the data and the researcher's assessment of relative importance.

There are no set rules for selecting an association index, other than common sense and inspection of the data, and Cureton and D'Agostino (1983, p. 366) note that "most clustering procedures . . . apply to any index of association." Once an appropriate measure of similarity is defined and computed for each object, it is used as the basis for clustering the objects.

Agglomerative versus divisive methods

Two fundamental approaches to grouping related objects are hierarchical agglomerative and hierarchical divisive (Lehman, 1985, p. 584). Hierarchical agglomerative algorithms begin by computing the degree of similarity between all objects, and the most similar are placed in the same group. The similarities between objects, or between objects and the newly formed group, are then recomputed and the most similar are again placed in the same group. Groups of similar objects tend to grow or agglomerate until all objects have been incorporated or until the desired number of groups have been formed. When carried to the extreme, all objects will have been placed into one group.

Hierarchical divisive approaches begin by placing all objects into one group, and then removing the most dissimilar object to form the basis of a new group. This process then follows a similar approach as that for the agglomerative methods. However, since this approach is a process of breaking an initial group into smaller sub-groups, the eventual outcome, if pursued to the limit, will be a number of groups equal to the original number of objects.

Another, non-hierarchical, approach is to define a "typical" member of each desired cluster and then to place each object into a cluster based on its degree of similarity to that "typical" member. More sophisticated statistical tests can then be used to determine the maximum degree of "differentness" of some predetermined number of clusters.

Hierarchical agglomerative clustering algorithms

The most widely used clustering approach is hierarchical agglomerative clustering, and Lehman describes three agglomerative grouping algorithms; single linkage, complete linkage, and the centroid method (Lehman, 1985, p. 584). Single linkage groups are formed based on the premise that an object is as similar to a group, as it is to the object with which it is most similar within the group. Complete linkage takes the approach that an object is as similar to a group as it is to the object within the group with which it is least similar. The centroid method begins by grouping the two most similar objects, and then creates a new object based on the average characteristics of the original two objects. The new object is then treated as any other object and the process is repeated until the desired number of clusters are formed. (See Cureton and D'Agostino, 1983, Chapter 14 for a more detailed discussion.)

One attribute of clusters formed by the single linkage method is a tendency towards a serpentine structure, while clusters generated by the complete linkage method tend towards a more compact structure. The single linkage and complete linkage approaches are both less difficult computationally than the centroid method.

In neither case, however, are there well defined rules for determining the number of clusters. The agglomerative clustering algorithms can be stopped at any point, yielding any number of clusters from one to n, the number of variables. Lehman cites researcher preference as a means of determining cluster number (Lehman, 1985, p. 595). Cureton and D'Agostino (1983, p. 367) note that "some methods prespecify the number of clusters," while others "require clustering of all variables, . . . and still others employ acceptance levels. The acceptance level may be either arbitrary or probabilistic." The number of clusters chosen is a function of logical relations in the data, researcher preference, and a certain measure of common sense.

FACTOR ANALYSIS

Factor analysis is one specific subset of the more general group of clustering methodologies. "Factor analysis can be viewed as a special type of cluster analysis. . . . factor analysis attempt(s) to find groups of variables where the similarity measure (is) the correlation coefficient between pairs of variables." (Lehman, 1985, p. 595) Although the computational techniques developed for factor analysis can be used to group individuals, this is rarely practiced. The more accepted application is in searching for underlying relationships within groups of variables.

Factor analysis methods are a group of techniques for exploring relationships between variables that are not measured directly by the variables themselves. Factor analysis methods are based on the assumption that there are two components to the variance of any variable. Some variance is unique to the variable, while some portion of the variance is related to the influence of an underlying factor. Factor analysis uses correlation coefficients as a measure of association and then groups variables based on their shared, or common, variance due to the effects of the underlying factor.

Another fundamental assumption upon which factor analysis is based is that of linearity. "Factor analysis assumes that the observed (measured) variables are linear combinations of some underlying source variables (or factors). That is, it assumes the existence of a system of underlying factors and a system of observed variables. There is a certain correspondence between these two systems and factor analysis "exploits" this correspondence to arrive at conclusions about the factors." (Kim and Mueller, 1978, p. 8)

Exploratory versus confirmatory

Factor analysis is typically described as either exploratory or confirmatory. Exploratory factor analysis attempts to describe the nature of underlying relationships that may not be evident directly from an examination of the measured variables. "Factor analysis may be used as an expedient way of ascertaining the the minimum number of hypothetical factors . . . as a means of exploring underlying dimensions." (Kim and Mueller, 1978, page 9)

Confirmatory factor analysis, on the other hand, seeks to assist the researcher in testing specific hypotheses regarding some presumed underlying data structure. "For instance, the researcher may anticipate or hypothesize that there are two different underlying dimensions and that certain variables belong to one dimension while others belong to the second. If factor analysis is used to test this expectation, then it is used as a means of confirming a certain hypothesis, not as a means of exploring underlying dimensions." (Kim and Mueller, 1978, page 9)

There are a fairly well defined set of procedures for performing exploratory factor analysis. These begin with the computation of the correlation coefficient matrix for the variable set. Then an initial estimate of the communalities, the measure of common variance, is made. Based on these initial estimates, factor loadings on the different variables are computed and transformed to create a "simple structure." Finally, based on some specified criteria, a discrete number of factors are extracted and, perhaps most importantly, named and interpreted.

Correlation matrix and communality

The basic unit of comparison for factor analysis is the covariance between two variables. One (redundant) definition of covariance is given by Kim and Mueller; "Covariance measures the extent to which values of one variable tend to covary with values of another variable." (Kim and Mueller, 1978, p. 16) However, the central concept is that "the covariance between standardized variables . . . has a special name: correlation coefficient." (Kim and Mueller, 1978 p. 16) The matrix of correlation coefficients forms the basis for subsequent factor analysis computations.

An important caveat here is the distinction between covariation (or correlation) and causality. As Kim and Mueller point out, "It is important to note that the notion of covariation is independent of the underlying causal structure; two variables can covary either because one variable is a cause of the other or both variables share at least one common cause, or both." (Kim and Mueller, 1978, p. 16)

In the linear model assumed by the factor analysis approach, each variable's total variance is composed of two parts; one portion is related to some underlying factor, and the remaining variance is unique to the variable itself. Factor analysis is concerned with "analyzing the common variance of the variables," (Cureton and D'Agostino, 1983, p. 296) and the common variance is termed the communality. Dunteman (1984, p. 186) defines communality as "the proportion of variance of a particular variable that is predictable from the common factors."

When performing a factor analysis, some initial estimate of communalities must be made in order to proceed. "With the classical factor analysis model, the communalities are the basic quantities to be analyzed. Herein lies the trouble–there is no *a priori* knowledge of the communalities." (Harmon, 1976, p. 70) The usual approach is to use the squared multiple correlation (SMC) of each variable with all other variables as the initial estimate. Cureton and D'Agostino (1983, p. 140) argue that "the best practical initial communality estimates should be proportional to the SMC's."

However, the value of the SMC is a function of the inverse of the correlation matrix (Cureton and D'Agostino, 1983, p. 140). The process of matrix inversion requires that the cofactor each element of the original matrix be divided by the determinant of the matrix

(Rabenstein, 1982, p. 139). In the case of a singular matrix, whose determinant is zero, the inverse is not defined.

Cureton and D'Agostino (1983, p. 142) note two situations where SMC's are not used for initial communality estimates, including the case of the singular correlation matrix. "The main cause of a singular correlation matrix is the case when . . . the number of variables is greater than or equal to the number of individuals. Such matrices *can* be factored, though interpretation is sometimes difficult because the factorial fit to the errors is too good."

Cureton and D'Agostino (1983, p. 141) note that "if an initial communality estimate is too high, we shall do nothing about it, trusting to the refactoring to rectify the result." Refactoring is a recursive procedure whereby an initial estimate of the communalities is made, the factor analysis performed, and "actual" values of the communalities are computed. These "actual" values are then used as the initial estimates for a subsequent refactoring of the data. Cureton and D'Agostino (1983, p. 142) advise that "in the case (of singular matrices) refactoring once with revised communality estimates is almost always advisable."

Principal component analysis

When the analysis uses diagonal unity values in the correlation coefficient matrix the procedure is termed principal component analysis. Cureton and D'Agostino (1983, p. 296) note that "in common-factor analysis we are interested in analyzing the common variance of the variables. The common variance of any standardized variable . . . is its communality." They differentiate component analysis by noting that "in component analysis, . . . we are interested in analyzing the total variance," where "the total variance of any standardized variable is unity."

The practical implications of this difference are that communalities for each variable are not estimated, and that unities are used along the diagonal of the correlation matrix. "Formally, initial component analysis is simply initial factor analysis with unities on the diagonal of the correlation matrix." (Cureton and D'Agostino, 1983, p. 296) Other component analysis methods are described in the literature (Cureton and D'Agostino, 1983, p. 297). However, these are fundamentally the same as principal component analysis, differing only computationally, and principal component analysis is described as the "preferred procedure." (Cureton and D'Agostino, 1983, p. 297)

When the unity-diagonal correlation matrix is used instead of the communality loaded matrix, the subsequent procedures of computing eigenvalues, extracting factors (in this case, components), determining the appropriate number of factors, and transforming the loaded factor matrix, all proceed in a similar fashion as for common factor analysis.

However, even though principle component analysis is essentially the same procedurally as common-factor analysis, there remains the fundamental difference of addressing total rather than common variance. "The disadvantage of component analysis is that the total variance is not separated into common variance and unique variance, and in consequence components are more complex functions of the variables than are factors, and hence are harder to interpret." (Cureton and D'Agostino, 1983, p. 297)

Extracting factors

The ultimate computational goal of factor analysis is to identify the number of relevant underlying factors present and to determine the degree to which each factor influences each variable.

When the determinant of the correlation coefficient matrix containing the variable communalities on the diagonal is set equal to zero, it has the form of a characteristic equation. The roots of the equation are characteristic roots, or eigenvalues. The degree to which a factor is contributes to the non-unique variance of a variable is related to the eigenvalue associated with each factor.

The eigenvalues are important for two reasons. They can be used as one criterion for the selection of factors, and they are used to compute the factor loadings on each variable.

Number of factors

In theory, there are as many factors as there are variables. However, in practice, usually only a few factors contribute substantially to the observed variance of a variable. The principle of parsimony dictates that the number of factors should be significantly less than the number of variables. The determination of exactly how many factors are present is the somewhat subjective responsibility of the researcher.

There are a number of heuristics for selecting factors. Three common approaches are the roots greater than one criterion, the 75% variance rule, and the root curve criterion. The roots greater than one is the simplest criterion. It "specifies that as many factors will be retained as there are eigenvalues greater than or equal than one." (Feldman et al., 1986, p. 197)

Each eigenvalue is associated with a specific contribution to the total variance, and the percent contribution decreases for each successive eigenvalue. The 75% rule states that "as soon as the sum of the proportionate contributions of the eigenvalues exceeds 0.75, it is assumed that all relevant matrix variance has been accounted for." (Feldman et al., 1986, p. 197) The root curve criterion computes an inflection point in the plot of calculated eigenvalues, and accepts the number of factors as the rank of the eigenvalue associated with the point of inflection.

In general, the researcher should take into account issues of both parsimony and conservatism in invoking any of these criteria, balanced with a reasonable amount of common sense.

Factor loadings

Once the number of factors has been determined the factor loadings are computed. "Factor loadings are equivalent to correlations between factors and variables." (Kim and Mueller, 1978, p.21) Each factor loading represents the proportion of a variable's variance due to the influence of the factor. There is one loading value for each factor on each variable. Factor loadings may be either positive or negative, and range from close to zero to plus or minus one.

Factor loadings are usually transformed to provide a better sense of simple structure. Cliff (1987, p. 219) points out that ". . . virtually all matrices of principle components loadings are transformed in a way that is intended to make them more interpretable, and, we hope, closer to reality." Simple structure is obtained by applying a transformation, usually an orthogonal rotation of the factor axes, in order to accentuate the differences in the factor loadings for each variable. Factor loadings that are high for one factor and quite low for all other factors are generally considered to comprise a good simple structure. There are a number of more complex transforms that can be applied. These include varimax, orthomax, and equimax solutions, each of which can provide either an orthogonal or oblique solution. Oblique transforms endeavor to provide a better simple structure by allowing some correlation between the effects of the resulting factors. However, orthogonal rotation is the most common and preserves the linear independence of the factors.

The final numerical result of the process of factor analysis is a matrix of transformed factor loadings. This allows grouping variables based on their factor loadings. Good simple structure makes it relatively straightforward to assign variables to groups based on their factor loadings. The final task, that of naming, describing, and (one hopes!) explaining the significance of the factors and groups is left to the imagination and resources of the researcher. In the next section I describe the approaches I selected in the course of analyzing the project conformance data.

SELECTED APPROACHES FOR THIS RESEARCH

In applying grouping methodologies to the conformance data, it became evident that there are as many refinements, corrections and special cases to the basic methods as there are authors in the field. After examining the underlying assumptions, I generally chose the more accepted techniques offered by the various references. I also took the approach of applying simpler, more direct approaches with minimal use of the sophisticated, fine tuning techniques that some authors describe.

This was based on my view that any strong relations in the data should emerge in a straightforward manner, rather than having to be "cooked" out of the data. Indeed, I soon discovered that the adage "You can prove anything with statistics" is quite true, since one can often either direct an analytical method towards a desired goal, or, by applying a sufficient number of approaches, eventually arrive at one that supports the researcher's initial predilections.

With this in mind, I attempted to favor parsimony, conservatism and common sense during the process of analysis and in interpreting the results. The application of the methods I selected was supported by the fact that the cluster analysis, factor analysis, and inspection of the data, all yielded supporting results.

Clustering projects

My first attempt at grouping projects was based on inspection of the one dimensional dot plots of the average conformance values for each project. It was clear that several of the projects tended towards higher overall degrees of conformance, while others were ranked lower. My initial grouping was based on each project's average conformance value. This resulted in the two groups shown in **Figure M-1**.

I subsequently applied a more formal clustering method to see if these initial observations were supported. I experimented with several approaches to developing a measure of

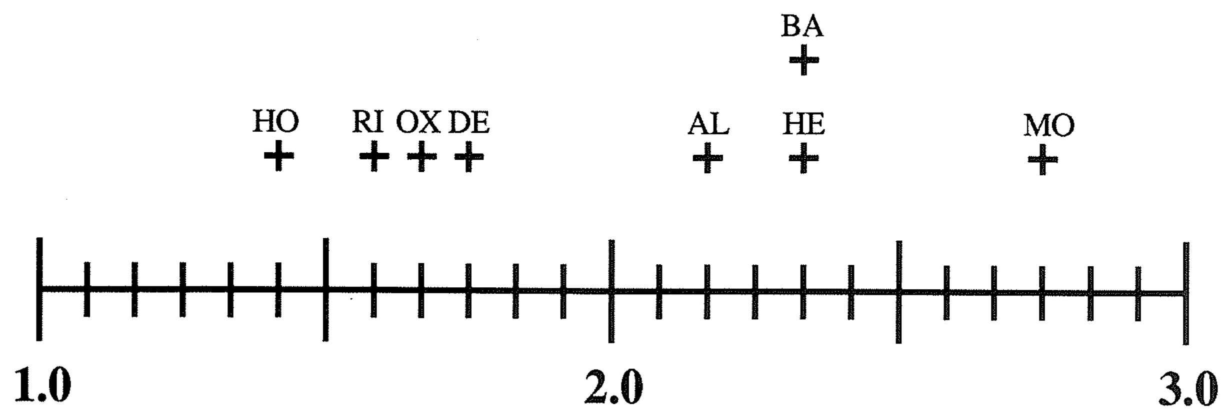


Figure M-1

One dimensional dot plot of average project conformance values

association between the projects, including average conformance values and distance measures. As might be expected, using average conformance values as a similarity measure produced the same groups that I identified by inspection.

I felt that some measure that captured the difference between each variable score for each project would give a better measure of similarity. My first approach was to simply add the absolute value of the differences between each pair of variable scores for each pair of projects.

This resulted in a symmetric distance matrix with components that were fairly close in numerical value. Using this distance matrix as a basis for clustering projects produced two different solutions, depending on how I applied the grouping algorithm. The complete linkage approach produced the same two clusters that I identified through inspection, but the last iteration of the single linkage computation branched and produced one other solution.

After further reflection, I decided that it would be appropriate to give more weight to the variables that differed by two ranking levels; that is, to accentuate the difference between variables that differed from H to L or L to H. This in effect weights these variables more than those that differed by only one ranking point. This approach reduces the effect of any errors I may have made in assigning the conformance values. For example, the subjective difference between a low value and a medium value might be borderline, but the difference between a low value and a high value is quite distinct.

I finally settled on a modified Minkowski metric as a distance measure. The Minkowski metric in its general form produces fractional values that are cumbersome to carry through the clustering algorithms, so I transformed them by taking their square root. This in no way affected the final clusters, since the crucial characteristic used in clustering is the relative value of the distance measure, not the absolute value. The process of computing Minkowski distance values is presented graphically in **Figure M-2**. For each i-j project pair, I computed the absolute difference in conformance values from c=1 to c=n (here, n=12, the number of variables). The sum of the 12 differences gave a distance measure, D, for each i-j pair of projects. The resulting distance matrix is presented in **Figure M-3**.

Having computed the distance matrix for the projects, I then applied two clustering algorithms, a single linkage method and a complete linkage method. The complete linkage algorithm is demonstrated in **Figure M-4**. (The single linkage method proceeds in a similar fashion and is not recapitulated here.) The use of calculation matrices is helpful in that it graphically illustrates the process of agglomeration as it occurs. Strong similarities between projects, indicated by low distance values, reveal associations between specific pairs or sup-groups of projects.

The procedure is simple. The two projects with the lowest distance value (represented by the circled numbers in the matrices in **Figure M-4**) are grouped together, and the distance between the group and each other project is recomputed. The distance to the new group is taken as the higher of the two alternatives, since the underlying premise is that a project is as similar to a group as it is to the least similar member of the group. After recomputing the new distance matrix (the new distance values are indicated by shaded squares in **Figure M-4**), the lowest value is again selected as the basis for grouping and the process iterates until the desired number of clusters is achieved.

	Project i	**Project j**	
Var 1-A	**L**	**M**	Δ=1
Var 1-B	**H**	**M**	Δ=1
Var 1-C	**H**	**L**	Δ=2
Var 2-A	**H**	**M**	Δ=1
Var 2-B	**H**	**L**	Δ=2
Var 2-C	**M**	**M**	Δ=0
Var 3-A	**L**	**L**	Δ=0
Var 3-B	**L**	**M**	Δ=1
Var 3-C	**M**	**L**	Δ=1
Var 4-A	**H**	**L**	Δ=2
Var 4-B	**H**	**L**	Δ=2
Var 4-C	**L**	**L**	Δ=0

$$D_{ij} = \left[\sum_{c=1}^{n} W_c \left(X_{i\,c} - X_{j\,c} \right)^k \right]^{\frac{1}{k}}$$

Minkowski Metric

$$D_{ij} = \sum_{c=1}^{n} W_c \left(X_{i\,c} - X_{j\,c} \right)^k$$

Modified Minkowski Metric

($k=2$; $n=12$; $W_c=1$;
X= variable conformance value)

For example, let Project i be AL and Project j be HO then:

$$D_{ij} = 1 + 1 + 4 + 1 + 4 + 0 + 0 + 1 + 1 + 4 + 4 + 0 = 21$$

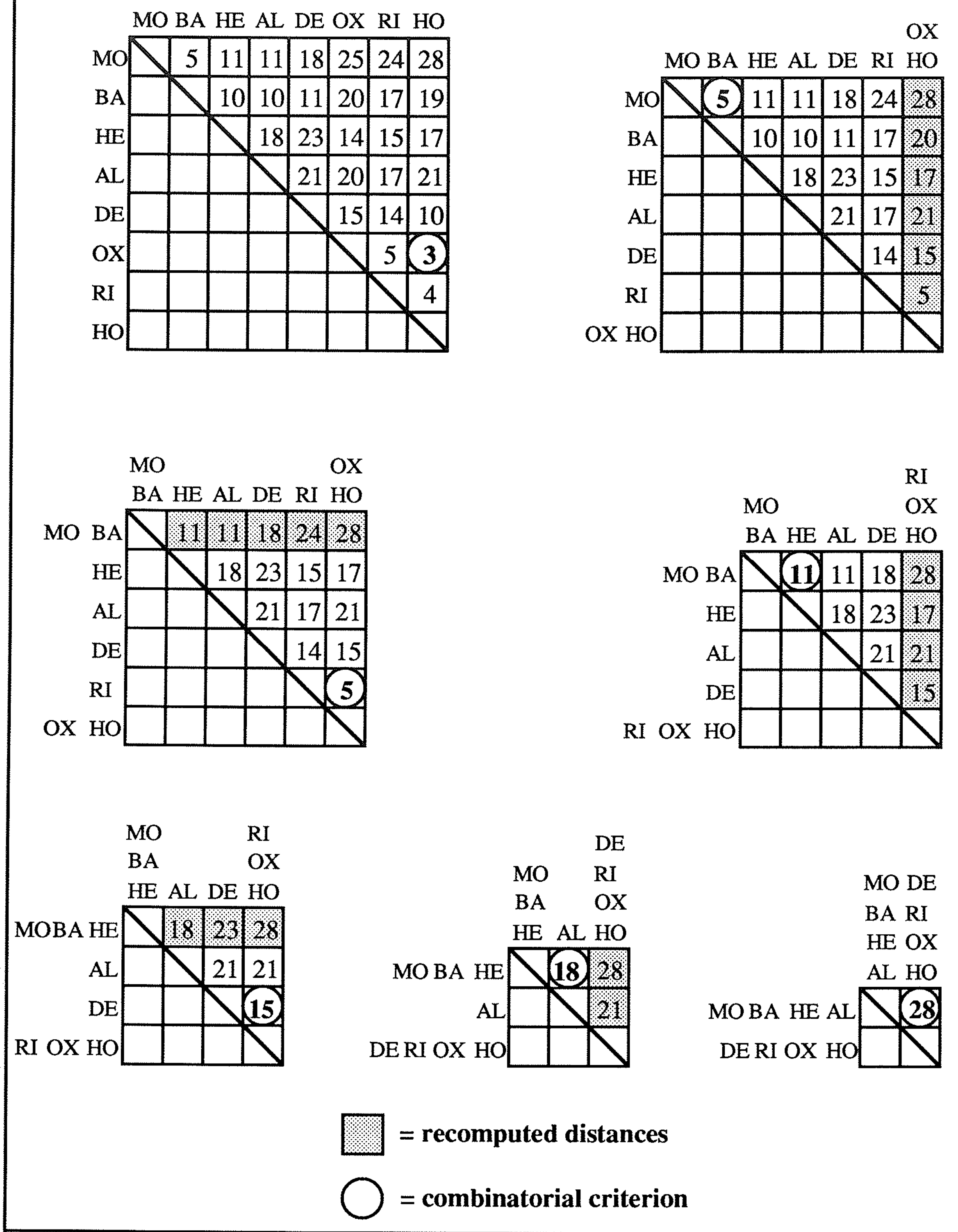
Figure M-2

The modified Minkowski association metric used to compute the measure of project similarity

	MO	BA	HE	AL	DE	OX	RI	HO
MO		5	11	11	18	25	24	28
BA			10	10	11	20	17	19
HE				18	23	14	15	17
AL					21	20	17	21
DE						15	14	10
OX							5	3
RI								4
HO								

Figure M-3

Project distance matrix using the modified Minkowski metric



	MO	BA	HE	AL	DE	OX	RI	HO
MO		5	11	11	18	25	24	28
BA			10	10	11	20	17	19
HE				18	23	14	15	17
AL					21	20	17	21
DE						15	14	10
OX							5	3
RI								4
HO								

	MO	BA	HE	AL	DE	RI	OX HO
MO		5	11	11	18	24	28
BA			10	10	11	17	20
HE				18	23	15	17
AL					21	17	21
DE						14	15
RI							5
OX HO							

	MO BA	HE	AL	DE	RI	OX HO
MO BA		11	11	18	24	28
HE			18	23	15	17
AL				21	17	21
DE					14	15
RI						5
OX HO						

	MO BA	HE	AL	DE	RI OX HO
MO BA		11	11	18	28
HE			18	23	17
AL				21	21
DE					15
RI OX HO					

	MO BA HE	AL	DE	RI OX HO
MOBA HE		18	23	28
AL			21	21
DE				15
RI OX HO				

	MO BA HE	AL	DE RI OX HO
MO BA HE		18	28
AL			21
DE RI OX HO			

	MO BA HE AL	DE RI OX HO
MO BA HE AL		28
DE RI OX HO		

▨ = recomputed distances

○ = combinatorial criterion

Figure M-4

Cluster analysis of projects using Minkowski association metric (k=2) and complete linkage clustering algorithm

It is important to note that there is often a choice of more than one value representing the lowest inter-project distance. There is no rule for choosing which value to use. Consequently, there are multiple paths along which the analysis might proceed. These paths may converge, as they do in this example, or they may diverge and produce other, non-unique solutions. This is one of the drawbacks to cluster analysis. The lack of a decision rule leads to multiple solutions, all equally correct methodologically. Furthermore, the results of the analysis may be directed by the researcher towards a desired solution.

In this case, both the complete and single linkage methods, using the modified Minkowski distance measure, converged nicely to two distinct clusters. This common solution, and the one that I utilized for further analysis, generates the same two clusters that I identified by inspection. These are referred to as the "High" group and the "Low" group, based on their average conformance values. The two groups are illustrated in **Figure M-5**.

Factoring variables

The notion that there might be some underlying relationship among the different variables occurred to me after inspection of the plot of the average variable conformance values. This one dimensional dot plot is presented in **Figure M-6**. There are three distinct groups of variables; two small groups, one at either end of the range of observed values, and a larger group clustered around the average value of 2.0. Based on inspection, I initially formulated the hypothesis that there were indeed three groups of variables, implying that there were three corresponding dimensions along which projects in general progressed as they evolved into more integrated entities.

Reflection on the nature of the variables comprising each group led me to suspect that there was indeed some relationship among the variables that might explain the tripartite grouping. This suspicion, coupled with strong suggestions from my committee, led me to pursue other, more rigorous methods of grouping variables by investigating the presence of common factors. I finally concluded that there were indeed three underlying factors present. The three resulting variable groups, or dimensions, are similar to those that I first identified by inspection, but differ slightly on the specific variables included in each group.

Cluster analysis of variables

My first approach was to use cluster analysis techniques to group variables in a similar fashion as for projects. I applied the same distance measures and clustering algorithms that I used to group projects. However, with 12 variables there was considerably more branching towards different cluster solutions. Even using the modified Minkowski distance measure, which generally tended to help the calculations converge, there were multiple, non-discrete solutions. All of the solutions are equally defensible from a methodological perspective, but interpreting the resulting clusters could lead to conflicting results.

In addition, there is no clear decision rule stipulating the appropriate number of clusters. The hierarchical agglomerative methods continue to group variables until eventually they are all grouped into one cluster. I carried my calculations down numerous branches and arrived at a number of three cluster and two cluster solutions that were at times quite different.

However, two patterns began to emerge in the variable groupings as a result of cluster analysis. Variables 2-B and 4-A fell into the same dimension when their average

High Conformance Cluster

Project		Average Conformance Value
MO	Mojave	2.75
BA	Basic American	2.33
HE	Henderson	2.33
AL	Altresco	2.17

Low Conformance Cluster

Project		Average Conformance Value
DE	Dexter	1.75
OX	Oxnard	1.67
RI	Richmond	1.58
HO	Hopewell	1.42

Figure M-5

Project clusters

Note: This is a one dimensional plot. The vertical position of each variable has no meaning.

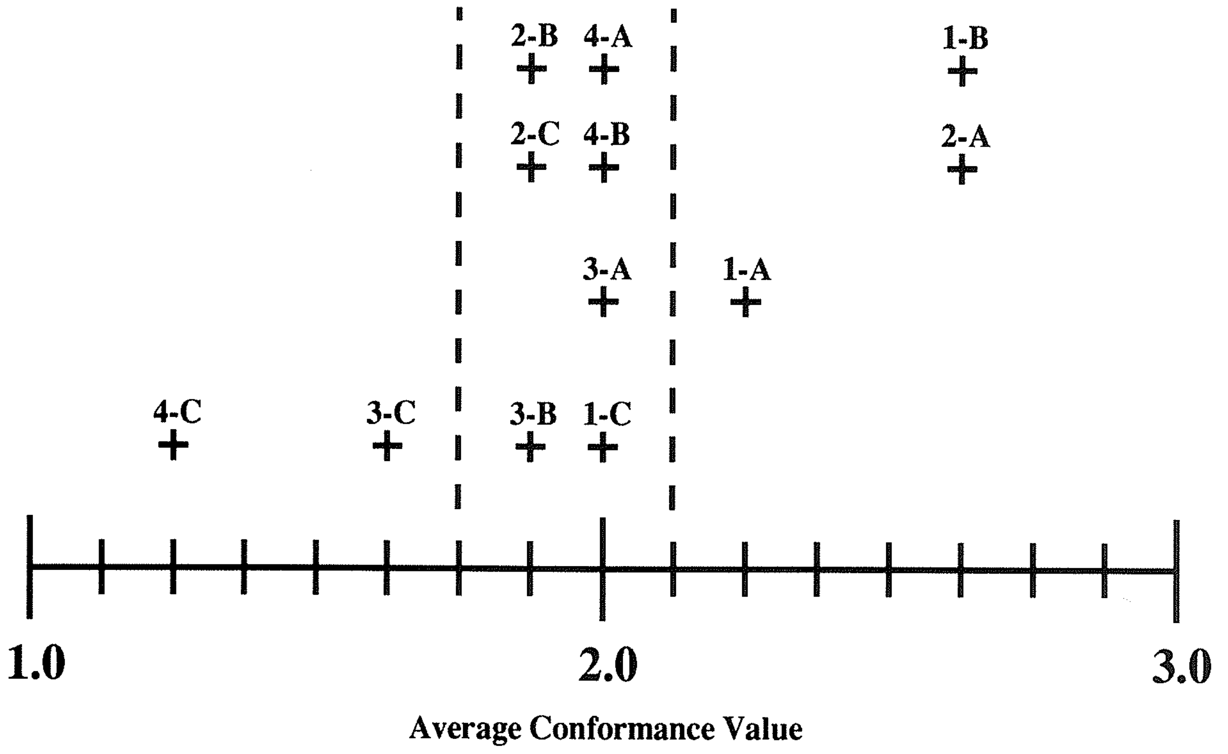


Figure M-6

One dimensional dot plot of average variable conformance values

conformance values were plotted, and variables 3-C and 4-C formed the basis for another of the original dimensions. Variables 2-B and 4-A clustered together in all of the three and two cluster solutions I computed, as did variables 1-C, 3-C, and 4-C. These are of interest since the first pair are the bimodaly distributed variables that capture attributes of the engineering construction interface and between them contribute to over 40% of the difference between the high and the low conformance groups of projects. The latter three are all strongly related to technical aspects of the projects.

Even though there are some variable relationships that repeatedly surfaced during variable clustering, due to the emergence of multiple, non-unique solutions, cluster analysis does not appear to be a strong mechanism for grouping variables. However, there is some peripheral support for the solution that I eventually accepted through factor analysis, since the predominant variable relationships in the final factored solution are obtainable through the application of cluster analysis techniques.

Factor analysis of variables

As a third mechanism for grouping the integration variables, I performed an exploratory factor analysis of the variable set. The absence of any initial communality estimates coupled with a singular correlation matrix led me to perform an initial factor analysis using unities along the diagonal, a principal component approach. I then used the computed communalities at the end of the first iteration as initial values for a second iteration, or refactoring. The results were very consistent in terms of factor loadings, which were numerically different but maintained their relative values. The resulting eigenvalues were also numerically different, but their relative values and variance contributions remained approximately the same. Since I had no basis for assigning initial communality estimates, and since there is little difference between the principal component and the common factor solutions, I accepted the results of the principal component solution for further analysis.

The matrix of correlation coefficients upon which the factor analysis was based is presented in **Figure M-7**. Eigenvalues, or characteristic values, are computed by solving the characteristic equation det $(\mu I-A) = 0$, where μ = the set of eigenvalues, I = the identity matrix, and A = the correlation coefficient matrix (see Rabenstein, 1982 for a thorough discussion of characteristic values). Solution of this characteristic equation for the correlation coefficient matrix yields a series of eigenvalues, seven of which are presented in **Figure M-8**. There are a total of 12 computed values, corresponding to the 12 variables. However, eigenvalues 8-12 are quite small, and I have included only the first seven values in the figure. It is clear that the value of each succeeding eigenvalue decreases rapidly, as does its contribution to the total variance. There are three eigenvalues greater than one, and they represent some 84% of the variance. That is, the three factors resulting from these three eigenvalues values capture or explain 84% of the original variance in the variable values.

Number of factors

Two common heuristics for factor extraction, eigenvalues greater than one and the 75% variance rule, indicate that a three factor solution is appropriate. This supports my original inclination towards three variable groups based on inspection of conformance values, and the factored variable groupings are similar to the solution at which I arrived through inspection, as indicated in **Figure M-9**.

	1-A	1-B	1-C	2-A	2-B	2-C	3-A	3-B	3-C	4-A	4-B	4-C
1-A	1											
1-B	.234	1										
1-C	.302	.258	1									
2-A	-.078	.467	.258	1								
2-B	.203	.731	.405	.731	1							
2-C	-.342	.488	-.378	.488	.357	1						
3-A	.696	.298	.289	.596	.467	0	1					
3-B	.048	.207	-.801	-.124	-.022	.424	0	1				
3-C	.379	.325	.898	.325	.509	-.204	.415	-.546	1			
4-A	.302	.775	.500	.775	.944	.378	.577	-.16	.539	1		
4-B	-.213	.73	.354	.730	.763	.535	.204	0	.508	.707	1	
4-C	.522	-.149	.577	-.149	.078	-.655	.333	-.277	.726	0	0	1

Figure M-7

Variable correlation matrix

Eigenvalues and Proportion of Original Variance

	Magnitude	Variance Proportion
Value 1	5.134	.428
Value 2	3.323	.277
Value 3	1.631	.136
Value 4	.828	.069
Value 5	.598	.050
Value 6	.296	.025
Value 7	.191	.016

$\Sigma = .841$

Note: Eigenvalues 8 through 12 are very small and are not presented here

Figure M-8

Computed eigenvalues

Note: This is a one dimensional plot. The vertical position of each variable has no meaning.

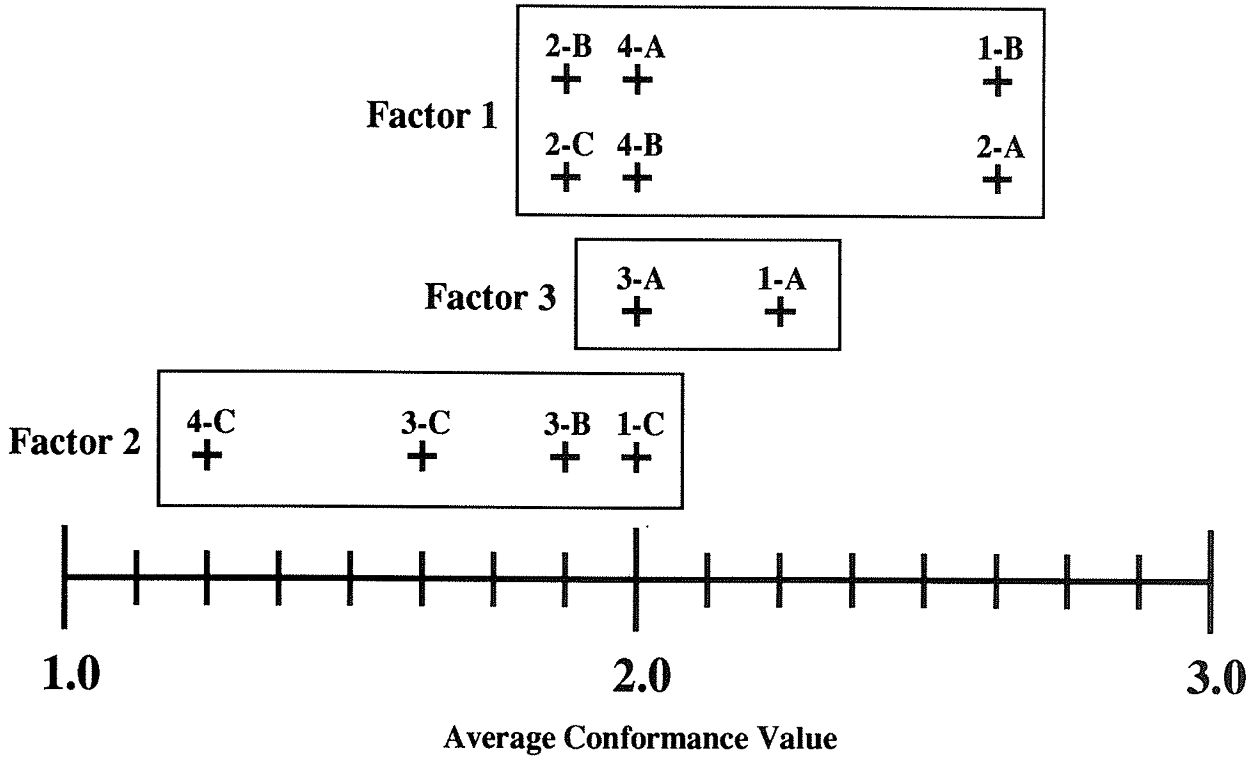


Figure M-9

Variable groupings based on factor loadings superimposed on one dimensional dot plot of conformance values

The statistics software that I used, Statview II (Feldman et al., 1986) provided several options for transforming the initial factor loadings. I performed a number of analyses using Varimax, Orthomax, and Equimax transforms and looked at both orthogonal and oblique solutions. These all provided very consistent results in terms of relative factor loadings. The factor loadings for the three factor solution using an orthogonal Varimax transform are presented in **Figure M-10**.

It is clear that there is a reasonable simple structure; the variables tend to load strongly towards one factor or another. There are strong negative loadings on only two variables. This indicates that for the most part, the variables tend to move consistently due to the influence of the factors, and in their descriptions of the integration issues I measured.

One danger of factor analysis is that of overfactoring; that is, trying to account for all of the variance in a set of variables by formulating scenarios with a large number of underlying factors. The strength of factor analysis is that it often illuminates general relationships in the variables not obvious upon inspection. Conservatism and parsimony both drive the analysis towards solutions with fewer factors rather than more.

In this case, the first two eigenvalues are 5.134 and 3.323 respectively, and account for 71% of the variance. The relatively high values and large proportion of the variance lend strong support to the presence of at least two factors. The contribution of the third eigenvalue, which has a value of 1.631, accounts for an additional 13.6% of the variance, somewhat less than the first two factors. The total variance captured by these three factors is 84%, which is considerably more than the 75% rule requires.

The variable set that I factored only has 12 members. Both the eigenvalue greater than one and the 75% variance rules are typically applied as extraction criteria when there are a relatively large number of initial variables to be factored. In addition, both factor extraction rules are somewhat arbitrary, and are intended to capture the dominant underlying influences. The fact that the first two eigenvalues are quite large relative to the third value and capture such a large proportion of the variance, indicates that they are the two dominant influences.

The variable group related to the third factor contains two variables, only one of which loads unambiguously into that group. The three variable dimensions resulting from the factor analysis are shown in **Figure M-11**. Inspection of the variables themselves reveals that three themes emerge from the variables as they are grouped in the three factor solution. These themes, which I discuss in Chapter 6 - Conclusions, are generally related to interface, technical, and project environment issues.

Project factor loadings

The factor loadings for each of the variables are an indication of how the variables move together as they are influenced by the factor dimensions. Using these factor loadings, it is possible to compute the loading of each factor, or dimension, for each of the projects.

Figure M-12 presents the basis for the project factor loading computations, and **Figure M-13** shows how the eight projects plot against the factors taken two at a time.

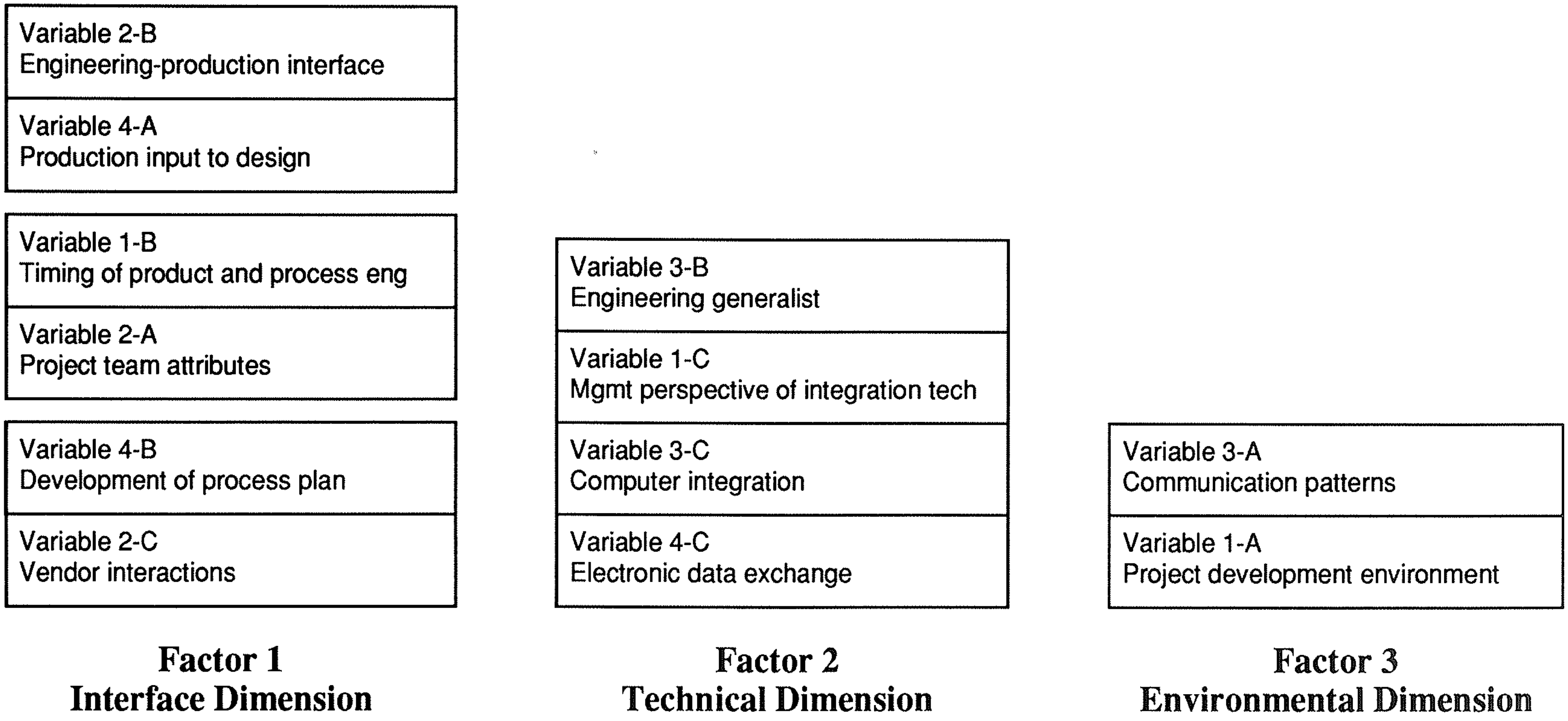
The two plots of Factor 1 are of considerable interest, since the projects break out into the same groups as developed by the cluster analysis. All four of the high conformance group

Orthogonal Transformation Solution-Varimax

Variable	Factor 1	Factor 2	Factor 3
1-A	-.009	.095	.960
1-B	.820	-.097	.183
1-C	.284	.921	.179
2-A	.853	.075	-9.78E-5
2-B	.889	.149	.218
2-C	.652	-.550	-.332
3-A	.420	.065	.769
3-B	.036	-.884	.199
3-C	.393	.801	.325
4-A	.907	.191	.259
4-B	.892	.169	-.167
4-C	-.194	.643	.568

Figure M-10

Variable factor loadings



Variable 2-B
Engineering-production interface

Variable 4-A
Production input to design

Variable 1-B
Timing of product and process eng

Variable 2-A
Project team attributes

Variable 4-B
Development of process plan

Variable 2-C
Vendor interactions

Factor 1
Interface Dimension

Variable 3-B
Engineering generalist

Variable 1-C
Mgmt perspective of integration tech

Variable 3-C
Computer integration

Variable 4-C
Electronic data exchange

Factor 2
Technical Dimension

Variable 3-A
Communication patterns

Variable 1-A
Project development environment

Factor 3
Environmental Dimension

Figure M-11

Variable dimensions based on results of factor analysis

$$Z_s = X_s F D^{-1}$$

Size of Matrix

${}_{8}\left[\ \right]^{3}$ Z = principal components on projects, standardized

${}_{8}\left[\ \right]^{12}$ X = original conformance data, standardized

${}_{12}\left[\ \right]^{3}$ F = rotated principal components variable factor loadings

${}_{3}\left[\ \right]^{3}$ D = Diagonal matrix of rotated eigenvalues,

where: $\lambda_n = \sum_{1}^{12} \left[\text{rotated factor loadings}\right]^2$ and,

$\lambda_1 = 4.684$

$\lambda_2 = 3.103$

$\lambda_3 = 2.299$

Project	F-1	F-2	F-3
MO	1.190	1.210	1.590
BA	.720	.638	.758
HE	.704	-.897	.726
AL	.974	.644	-.907
DE	-1.350	1.340	.975
OX	-.582	-1.240	-.870
RI	-.479	-.799	-1.240
HO	-1.180	-.906	-1.030

Figure M-12

Project factor loading computation

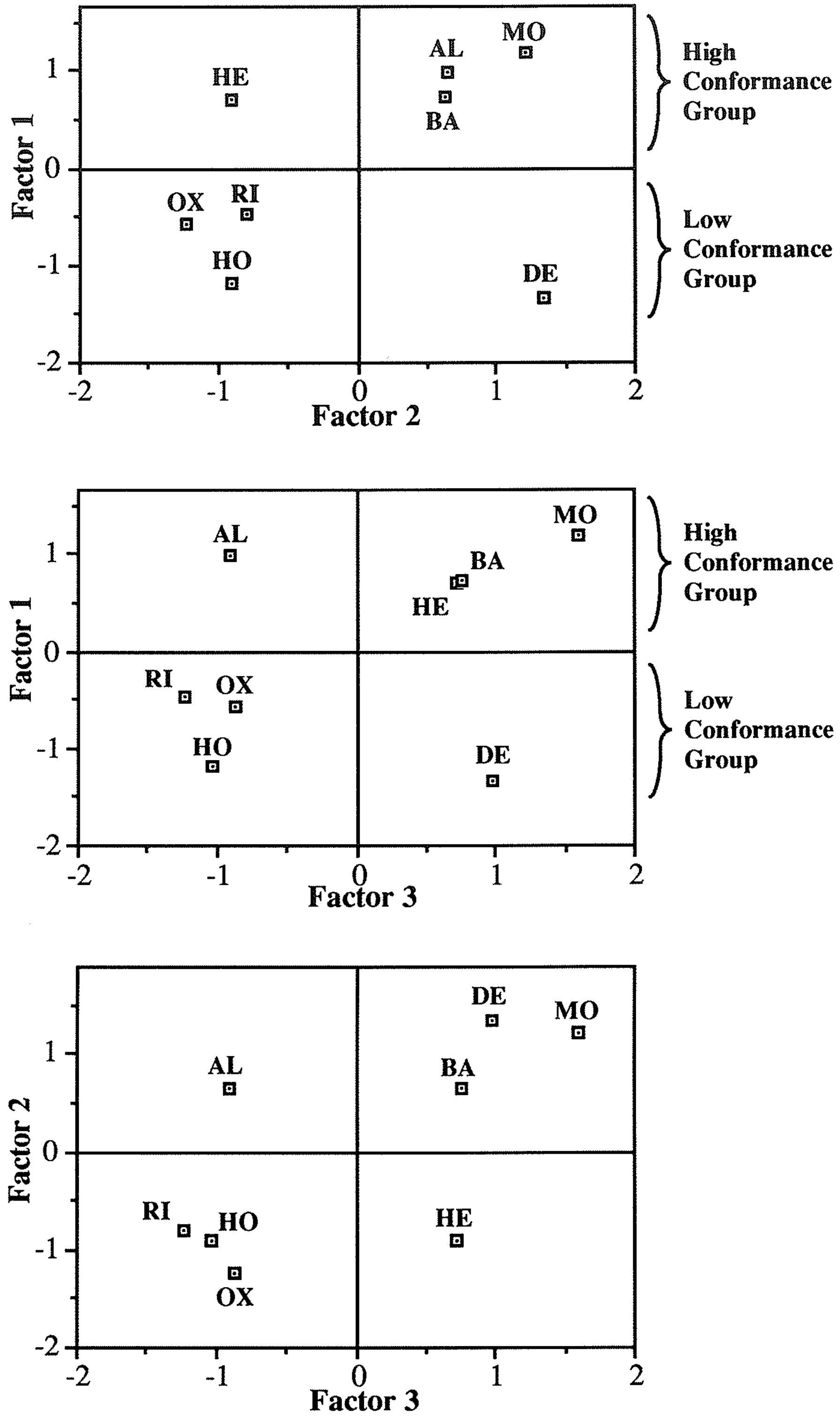


Figure M-13

Project factor loadings

projects load positively on Factor 1, while the low conformance projects all load negatively. This is further indication of the strong influence of the interface dimension as a differentiator of the two groups.

CONCLUSIONS

Dunteman (1984, p. 188) points out that ". . . in the common factor analysis model we are trying to explain the correlations among variables or, equivalently, what the variables have in common." The measure of what the variables have in common are their factor loadings, which are based on the correlations of the variables as measured across the eight projects.

With a sample of only eight projects it is difficult to make definitive statements regarding the presence of underlying factors. The fact that there are fewer projects than variables produces a singular correlation coefficient matrix, which precludes some computations during factor analysis. In addition, the distributions of the eight samples are somewhat sensitive to differences in the assignment of conformance values. This sensitivity transfers into the correlation coefficient matrix, and subsequently to the factor loadings. (Cluster analysis is based on measures of association or similarity between projects or variables and sample size is not really an issue.)

There is strong support for clustering the projects into High and a Low conformance groups. There is strong computational evidence that there are three underlying factors influencing the integration variables. However, empirical evidence in support of the third factor is somewhat weaker, since there are only two variables that load into the third dimension. Although the third factor has weaker support as an integration dimension, it still provides additional insight into mechanisms of integration.

I have labeled the dimensions that result from grouping variables on their factor loadings as interface, technical, and environment. The elements of the interface group generally capture issues related to the engineering-construction interface: when it forms, who participates, and how it is structured. The technical integration variables describe the approach to automation and the computer systems on these projects. The two variables in the environment group capture aspects of the project development environment. The implications of these groupings are discussed in Chapter 6.

Cliff (1987, p. 330) states that "in a single analysis with a single set of data, we never know." He goes on to argue that "Exploratory analysis of a single set of data should be followed by the gathering of new data, using measures that have been refined or developed on the basis of the results of the first study. . . . It is only in these latter stages that the concept of simple structure is likely to be a very close approximation to the true state of affairs. In the earlier stages, the results of a simple structure-seeking rotation should be considered advisory, rather than as a revelation of the true state of affairs." (Cliff, 1987, p. 330)

This research was an exploratory attempt to make comparisons across two different industries. The mechanism of comparison, the framework of integrated manufacturing, helped me to collect data that was amenable to analysis by both cluster and factor analysis methods. Although global conclusions are somewhat difficult to formulate, there are distinct trends in the data that not only help to reveal the mechanisms of integration present on the projects I studied, but also point the way towards areas of future research.

APPENDIX N

PROJECT PERFORMANCE PARAMETERS

INTRODUCTION

One issue that inevitably arises in any discussion of integration is the relationship between the degree of integration and subsequent project performance. This is a difficult area, not only in terms of defining project integration and performance, but in establishing rigorous methods of quantifying and measuring them.

The framework of integrated manufacturing that I developed offers one definition or standard of project integration. The conformance matrix provides a quantitative measure of the degree of integration of the projects that I studied, based on a comparison with that framework.

Project performance is a somewhat stickier issue. Most definitions of performance relate to budget, schedule and quality, although these are not defined in any standard or rigorous fashion. Even after collecting data on project performance, the relationship between these data and the degree of integration is clouded by the presence of considerable noise, or uncontrolled exogenous influences, in the data.

This appendix presents the results of my attempt to define measures of project performance, collect performance data on the projects I studied, and to ascertain the existence of any relationship with the degree of project integration.

DEFINING PROJECT PERFORMANCE

I first addressed project performance by defining a series of performance parameters and attempting to collect data for each parameter during the course of project interviews. I developed six parameters that I felt would consistently describe project performance across the eight projects that I studied, and that might also be feasible for data collection. These parameters related to project budget, schedule, and quality.

I first attempted to measure schedule performance by looking at the percent design completion at the start of construction and the ratio of the duration of construction to the duration of design. The budget parameters I initially selected were the ratio of the construction budget to the engineering budget and the total plant cost per MW of electrical output. Finally, I tried to collect data on the number of change orders and the number of field interferences as measures of quality.

These seemed like reasonable measures of project performance, and still might be good indicators of performance if consistent data could be collected across a series of projects. However, as I tried to accumulate data on these parameters during the course of field interviews and discussions with project personnel, I soon realized that there were fundamental problems with my approach. These problems were generally related to the availability of consistent data and noise in the data.

Data availability

The availability of performance data was an issue on most projects. Some data, such as project duration or nominal plant output are readily available, and some projects routinely release overall contract value in press releases or company reports. However, some project managers or their clients did not want sensitive project data, such as budget figures, made public.

Projects that made performance data available defined and tracked budget and schedule in different ways. Some projects included the cost of major equipment in the overall project budget, while other projects installed major equipment that was purchased and procured procured by the owner.

Furthermore, the total project contract value contains both margin and actual cost components. The actual cost component would be the correct portion to use in either budget ratios or a $/MW performance ratio, but data on margins is practically impossible to obtain. In addition, although there is certainly some positive correlation between plant output and cost (a bigger plant costs more than a smaller plant) or project duration and plant output, the nature of these relationships is not certain and is probably not linear.

In any case, during project execution, both schedule and budget are only estimates that do not capture the actual durations and expenditures. These performance measures can only be accurately and realistically assessed after the project is complete.

Some projects simply did not track data in a manner useful for my purposes. For example, in order to minimize the total number of change orders, owner-mandated and engineering-driven changes are often grouped together and submitted as one change order. This makes separating changes in scope from changes related to integration issues difficult. Another example is interferences, which were generally not formally tracked at all.

Since the projects were all at different stages of completion during data collection, interim performance data would have to be normalized to take into account the degree of project completion. Given the absence of data from similar finished projects, some assumption of the temporal distribution of data such as the incidence of change orders or interferences would have to be made, which further complicates the process.

Noise in the data

One difficulty in explaining project benefits or an improved competitive position due project integration is that fact that it is difficult to separate the effects of other complex factors acting on a project. This issue of ceteris paribus is generally addressed experimentally by strictly controlling for the influence of exogenous or random influences on the data.

However, there are a number of factors that affect project performance that are outside the control of project. These exogenous factors create a considerable amount of noise in the project data that may completely blanket any real effects of the degree of integration on project performance, and make attempts to establish and defend relationships between project performance and project integration extremely difficult.

For example, an integrated project may increase the duration of one portion of the project schedule, typically design and planning, for the benefit of the overall project schedule. A well planned, highly integrated project should result in an overall more efficient process phase. However, other factors may also be at work that may make it difficult to conclude that there is a direct causal relationship between degree of conformance and construction duration, even if a positive correlation were established. These include the level of construction resources applied to the project, the timing of major equipment delivery (one project received the gas turbine generators four months late due to problems in the turbine manufacturers shop), permitting issues, weather, strikes or other labor issues, or force majeure events.

Other sources of noise, or factors for which no control was established, include such diverse factors as owner imposed delays, regulatory delays, changes in project definition and scope, late delivery of major equipment, owner mandated changes, incorporation of new technologies such as NOx emission control systems, and even the discovery of desert tortoise habitats on one project site.

Therefore, any interpretation of project performance as a function of conformance, or integration, must be made cautiously and conservatively. Even if a positive correlation between conformance and performance data were established, arguments for causality in the absence of stringent controls may not be valid.

PROJECT MANAGER QUESTIONNAIRE

Due to the difficulties in obtaining meaningful project data using the performance parameters that I formulated, I tried a different approach. I decided to ask the project managers themselves how they measured project performance.

I sent follow-up questionnaires to the project managers representing each of the turnkey firms I had interviewed. A sample questionnaire is included as **Figure N-1**.

The questionnaire was designed with two purposes in mind. First, to determine how project managers defined and measured performance on their projects, and second, to collect data on how each of their projects ranked on their measures.

This approach addressed the issue of data availability since there was complete response to the survey, and the performance data were relatively consistent across the projects. However, it is important to note that the issue of noise and the caveats regarding drawing causal inferences are still applicable.

QUESTIONNAIRE DATA ANALYSIS

The purpose of collecting the questionnaire data was to explore the possibility that a relationship existed between the degree of project integration as measured by the degree of conformance, and the degree of project performance, as defined by the project managers. In order to analyze the data, I coded the responses to maintain parameter consistency across the projects. I then ran a series of linear regressions, using the conformance data as the independent variables and the performance data as the dependent variables.

Coding the data

I asked each project manager to list the three most important measures of project performance that he used to evaluate the success of his project. I then asked each to specify

Stanford Construction Integration Research Project

Project Managers Questionnaire

This questionnaire is designed as a supplement or follow up to the research interviews in which you and other project members recently participated. It is designed to capture information about how you evaluate your firm's performance on specific projects. Please take the time to consider each question and answer thoughtfully. A thoughtful, well formulated response is more valuable than is the degree of precision that you assign to each of the scaled questions. I have structured these questions so that sensitive information such as project budgets are described in terms of percentages rather than in actual dollar terms. Thank you for your help. The success of this research has been the direct result of the quality of your participation.

1. Project name:

2. Project phase: (e.g., finished, in start-up, 50% engineering - 50% construction)

3. Please list the three most important measures of project performance that you use to evaluate the success of your projects, in the order of importance from A (most important) to C (less important).

4. For each of the performance measures given in Question 3, please indicate the specific method of measuring or evaluating the performance measure. (e.g., "making budget" might be measured by the percent of funds spent or committed under the latest revised budget)

5. For each of the performance measures described above, please rank the performance of this project, on a scale of 1-10. One would indicate a low or poor degree of performance as defined by your performance measures, and ten would indicate a high level of performance, or a very successful project.

6. What was the overall duration of the project in calendar months, from the notice to proceed under the terms of the turnkey contract to project startup and turnover? How much preliminary engineering and purchasing had been performed at the time that the notice to proceed was given?

7. What was the final project cost as a percentage of the initial turnkey project budget?

8. Please evaluate the <u>overall</u> performance of this project on a scale of one to ten. Take into account your responses to previous questions, but give one aggregate value for this project.

9. Please use this space to make any other comments you feel are relevant.

(Note: The original questionnaire was three pages long, with space to answer the questions. This condensed format contains all of the original text.)

Figure N-1

Project manager project performance questionnaire

how the performance parameter was measured. There was a high degree of consistency in the responses regarding performance measures; most reflected budget, schedule or quality considerations. However, there was less consistency in the actual method of measuring performance.

I established several common categories of performance parameters, or dependent variables, based on both the description of the parameter and the method of measuring performance. Every questionnaire made some mention of budget performance, project costs, or profitability. These responses were grouped into a budget category. Six of the eight project managers listed schedule as a performance parameter, and this formed a second unambiguous category.

The remaining performance parameters were less straightforward, but fell into one of three categories; client satisfaction, quality, or safety. **Figure N-2** presents my rationale for categorizing responses into these groups. I listed the performance parameters provided by the project managers along with their descriptions of how they measure performance. By comparing the parameters and the method of measurement for each of the projects it is clear that while some parameters may differ in name, they are similar in the method by which they are measured.

I also asked each project manager to rank his project's overall performance and performance on each of the parameters he listed, using a scale of one (low) to ten (high). Since there were incomplete data for either the quality or safety categories, I established an "aggregate quality" category using the average of the client, quality and safety values for each project. I based this approach upon the rationale that both client satisfaction and safety were in a sense indicators of the overall quality of the project.

The results of coding the numerical questionnaire data into these categories are presented in **Figure N-3**. This matrix, along with the project conformance values, forms the basis for the linear regression analysis.

RUNNING REGRESSIONS

Figure N-4 lists the independent and dependent variables I used for the regression analysis. The independent variables are measures of project conformance, and consist of three groups: overall conformance, per variable conformance, and the average conformance value for each of the three dimensions derived from the factor analysis described in Appendix M. The dependent variables include budget, schedule, client, and overall performance, as well as the aggregate quality parameter. I excluded the two categories of quality and safety from the analysis since there were not sufficient responses.

I used the Statview statistical package to perform a series of linear regressions of the performance data against the degree of project integration, or conformance values. Using 15 independent variables and five dependent variables resulted in 75 sets of computations. There is similar output for each regression, and I have included sample output for the average conformance value versus overall project performance regression in **Figure N-5** and **Figure N-6**.

Figure N-5 is a plot of these data, with the best fit least squares line superposed. The Y axis of the graph represents the dependent variable, in this case the measure of overall project performance. The X axis represents the independent variable, the overall degree of

Project	Performance Parameter	Measure	Rating	Dependent Variable
BA	Client satisfaction	Client feedback and references	10	Client
BA	Quality of product	1st year availability, maintenance cost	10	Quality
DE	Quality and reliability	Plant availability %	10	Quality
HO	Customer satisfaction	Customer evaluation forms	7	Client
AL	Technical performance	Plant output and heat rate	9	Quality
OX	Industry reputation	Perception of current and future clients	10	Client
RI	Client relationship	Repeat business, client happiness	6	Client
RI	Plant quality	Unit availability, output, efficiency	8	Quality
RI	Safety	Comparison to U.S. labor statistics	8	Safety
MO	Client satisfaction	Achievement of client defined project goals	9	Client
MO	Safety	Goal of no lost time accidents or serious injuries	10	Safety
HE	Client satisfaction	Unquantifiable	6	Client

Figure N-2

Rationale for coding project performance parameters other than budget and schedule

	Project							
	MO	BA	HE	AL	DE	OX	RI	HO
Overall Conformance	2.75	2.33	2.33	2.17	1.75	1.67	1.58	1.42
Budget Performance	6	10	7	4	9	4	9	7
Schedule Performance	10	ND	9	9	8	ND	9	9
Client Performance	9	10	6	ND	ND	10	6	7
Quality Performance	ND	10	ND	9	10	ND	8	ND
Safety Performance	10	ND	ND	ND	ND	ND	8	ND
Overall Performance	8	10	8	5	9	5	8	8
Aggregate Quality	9.5	10	6	9	10	10	7.3	7

ND = No Data
Aggregate Quality = Average of Client, Quality, and Safety Performance
Performance values ranked on a scale of 1-10

Figure N-3

Project performance data for linear regression analysis

Independent Variables

Overall project conformance

Project conformance for each of the 12 integration variables

Average conformance for each of the three factored dimensions

(Conformance values are computed on a scale of 1.0 to 3.0)

Dependent Variables

Overall project performance (df=7)

Project budget performance (df=7)

Project schedule performance (df=5)

Project client performance (df=5)

Project aggregate quality performance (df=7)

(Performance values are computed on a scale of 1 to 10)

df = degrees of freedom

Figure N-4

Independent and dependent variables used in linear regression analysis of project performance against degree of integration

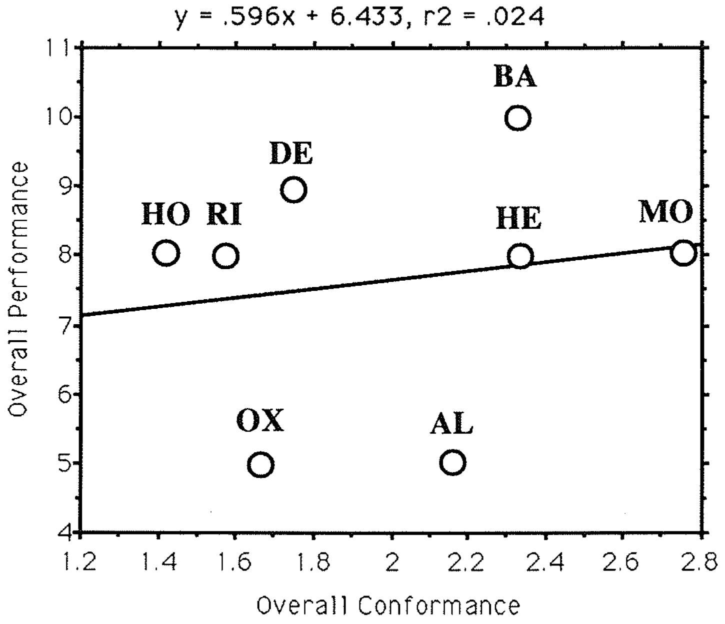


Figure N-5

Graph of regression of overall performance against overall conformance

Simple Regression X1: Overall Conformance Y1: Overall Performance

Count:	R:	R-squared:	Adj. R-squared:	RMS Residual:
8	.156	.024	-.138	1.886

Analysis of Variance Table

Source	DF:	Sum Squares:	Mean Square:	F-test:
REGRESSION	1	.53	.53	.149
RESIDUAL	6	21.345	3.557	p = .7127
TOTAL	7	21.875		

Beta Coefficient Table

Variable:	Coefficient:	Std. Err.:	Std. Coeff.:	t-Value:	Probability:
INTERCEPT	6.433				
SLOPE	.596	1.543	.156	.386	.7127

Confidence Intervals Table

Variable:	95% Lower:	95% Upper:	90% Lower:	90% Upper:
MEAN (X,Y)	5.993	9.257	6.329	8.921
SLOPE	-3.181	4.373	-2.404	3.595

Figure N-6

Regression statistics for overall performance against overall conformance

project conformance to the integrated manufacturing framework. **Figure N-6** provides the statistics for the regression in tabular format. Note that the t-value for this regression has a value of 0.386. The t-value is the primary statistic of interest here, since it provides some measure of the degree of significance of the results.

Significance of results

The most common test of significance for regression data is a t-test on the slope of the regression equation. The null hypothesis is that the slope of the regression line is zero and the t-test provides a mechanism for concluding, with a given level of confidence, that the slope of the regression line is significantly different from zero. A zero slope implies no correlation between the independent and dependent variables, and a slope significantly different from zero implies the existence of a linear relationship.

Some measure of subjectivity on the part of the researcher is reflected in the choice of a confidence level. Most texts refer to the 95% level as an appropriate level, but include t-values up to a 99.5% level. I applied the 95% criteria to my results for the regressions of the five performance parameters against the overall project conformance data and the average conformance value for each factored dimension. This means that if the computed t-value for the regression is greater than the tabular t-value for the given number of degrees of freedom, that there is a 95% chance that the relationship implied by the regression equation is not a random result.

I used the more stringent criteria of 97.5% and 99% certainty levels in evaluating the results of the 60 regressions of the five performance parameters against each of the twelve individual variable conformance values. This was due to the fact that with such a large number of regressions, one would expect that the resulting t-values would themselves have a distribution that included more spurious high values. In other words, there would be a greater probability of random occurrences of very high t-values than in a smaller population of regressions. In addition, the regressions of the individual variable data are more sensitive to conformance assignment error than the overall value for the project. With a small sample (8 projects), strong correlations between the integration variables, and substantial noise in the form of exogenous project influences, conservatism would dictate a more rigorous measure of evaluating the influence of individual variables on project performance.

CONCLUSIONS

The critical tabular t-values for the relevant degrees of freedom are presented in **Figure N-7**, and the computed t-values for the 80 regressions that I performed are presented in **Figure N-8**.

Inspection of this matrix reveals that at the 95% confidence level there are no significant t-values when the overall project conformance values, the best overall measure of project integration, are used as the independent variables.

When the three factored variable dimensions are taken as the independent variables, there is one significant t-value at the 97.5% confidence level. This t-value describes the relationship between Dimension 3, Environment, and overall project performance. Dimension 3 is composed of only two variables, one of which is Variable 3-A.

	95% Confidence Interval	97.5% Confidence Interval	99% Confidence Interval
df = 5	t = 2.015	t = 2.571	t = 3.365
df = 7	t = 1.895	t = 2.365	t = 2.998

df = degrees of freedom

Figure N-7

Critical t-values for tests of significance

Dependent Variables (Performance)

Independent Variables (Conformance)	Overall Perform.	Budget Perform.	Schedule Perform.	Client Perform.	Agg. Qual. Perform.
Overall	.386	.208	1.606	.631	.488
Int Dim	.378	.793	1.885	.392	.042
Tech Dim	.390	.185	.689	1.177	1.812
Env Dim	[b] 2.499	1.379	.374	.392	.198
Var. 1-A	[a] 1.912	.931	0	.840	.505
Var. 1-B	.862	1.365	1.414	1.549	.657
Var. 1-C	.570	.291	0	1.549	[a] 2.309
Var. 2-A	.338	.300	1.549	.417	.519
Var. 2-B	.276	.821	1.414	0	.267
Var. 2-C	.811	.934	[a] 2.449	no value	.928
Var. 3-A	[b] 2.390	1.589	.756	0	.118
Var. 3-B	.847	.998	.926	.583	1.310
Var. 3-C	.510	0	.840	1.167	1.842
Var. 4-A	.186	.291	1.414	.392	.041
Var. 4-B	1.159	1.414	2.000	.707	.442
Var. 4-C	.786	.336	0	.535	1.215
	df = 7	**df = 7**	**df = 5**	**df = 5**	**df = 7**

a = significant at 95% confidence level
b = significant at 97.5% confidence level

Figure N-8

Computed t-values for tests of significance

The 60 regressions using the individual integration variable conformance values as the independent variables resulted in no significant t-values at the 99% confidence level, and only one t-value that was significant at the 97.5% level. (Even at the more liberal 95% level, there are only a total of four significant t-values.) This t-value describes the relationship between Variable 3-A, communication patterns, and overall project performance, and this relationship appears to be the reason for the high t-value for Dimension 3 on overall project performance.

Given the nature of the variable, it is conceivable that projects with a high degree of conformance on this variable might be expected to perform better overall. However, the fact that this is the only significant t-value in a population of 80 regressions, 60 of which used strongly positively correlated variables as independent regression variables, leads me to conclude that this t-value is an outlier, not a true predictor of project performance.

The results of these analyses indicate that the degree of conformance to the integration framework is not a reliable predictor of the degree of project performance, as defined by the project managers on these projects. This does not mean that the degree of project integration is not a possible indicator of project performance. As discussed previously, the amount of noise in the project performance data may completely blanket the effect of the integration variables on project performance, and the situation is exacerbated by the extremely small sample size. In addition, there is a considerable amount of subjectivity and uncertainty in both the definition of project performance measures and in the project manager's rating of their projects.

Lave and March (1975) make the observation that "to test a model you generally want to test the truth of its derivations, rather than the truth of its assumptions."

Certainly one derivation of modeling integration using the framework I developed is in measuring the influence of integration on project performance. One opportunity for further research in this area is exploring the significance of the influence of variables that had high, although not quite significant, t-values. These may be indicative of integration forces at work, which need only more precise or sophisticated methods for measuring their influence. There is also a clear need for additional research in the areas of refining the integration framework into a more efficient mechanism for capturing data in the construction sector, and of developing more rigorous definitions and measures of project performance.

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