CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

# Impact of Integration on Industrial Facility Quality

by

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**TECHNICAL REPORT**
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# SUMMARY

## CIFE Technical Report #84

**Title:** **Impact of Integration on Industrial Facility Quality**

**Author:** Kelly Jean Fergusson (with Paul M. Teicholz)

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**Funding:** CIFE seed grant "Impact of Integration on Industrial Facility Quality"

1. **Abstract:** This report analyzes two aspects of industrial facilities: their quality; and integration in the process of developing them from inception through the first six or more months of operations. The goals of the research are to determine what constitutes a high quality facility, and how the facility development process can be better managed to achieve this result. This report was recently published as a doctoral dissertation.

2. **Subject:** Quality is defined as customer satisfaction with a comprehensive list of characteristics of the operational facility. Integration is defined as the flow of knowledge and information in three dimensions: vertically (between industry functions), horizontally (between disciplines or trades), and longitudinally (through time). Each dimension has technical and organizational modes of coordination. The study explores how integration in the facility development process affects the quality of the operating industrial facility, as viewed by the plant manager.

3. **Objectives/Benefits:** The international competitiveness of U. S. engineering-procurement-construction (EPC) firms has declined, and there is widespread owner dissatisfaction with engineering and construction services. We are in the midst of an industry crisis. The promise of advancing computer technology has not yet overcome these industry woes, so we are searching for deeper solutions. The quality movement in North American industry emphasizes the importance of process performance measurement and customer satisfaction. However, the facility development process is a very complex context in which to apply these principles. This research is a first attempt to model the impact of process performance on the quality of a facility. The measurement and modeling approaches developed can be applied by industry to drive their quality improvement programs.

4. **Methodology:** To measure quality and integration, two different questionnaires were used to gather data regarding each of 17 industrial facilities in the United States and Canada. The first was directed to diverse members of the owner organization to obtain their evaluations of plant quality. The second was directed to the prior members of the project organization including the owner representatives, as well as the engineering and construction project managers, to obtain data related to integration in the facility development process.

5. **Results:** Statistical analysis elucidated differences between distinct owner groups (strategic, project management, and operations) in their perspectives of the quality of these plants. A summary quality index was developed to encapsulate the plant manager's satisfaction with the plant. The vertical, horizontal, and longitudinal dimensions of integration were found to be independent of each other, yet each correlated positively with facility quality. Measures of both quality and integration

were validated using bivariate correlation analysis. Finally, a regression model was developed which incorporated the three measures of integration as predictors of facility quality. The model is highly significant, and the integration variables explain 82% of the variance in plant quality. Vertical and longitudinal integration are particularly promising areas in which to address integration efforts and research.

This study also uncovers facility characteristics which both owners and contractors in the EPC process could gain competitive advantage by addressing. Plant reliability and operator training are particularly critical areas to address.

6. **Research Status:** This research project, which was made possible by CIFE seed research funds contributed by our members, is complete. It was the basis for a joint proposal to the National Science Foundation (NSF) by Prof. Paul Teicholz of CIFE at Stanford and Prof. David Ashley of University of California at Berkeley. NSF recently approved the proposal to continue this course of study for two years, and funding will commence in October, 1993. One journal article based on the current study has been accepted for publication in ASCE's Journal of Performance of Constructed Facilities. During the coming months several more manuscripts will be prepared for publication.

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This report is a reprint of the author's doctoral dissertation, *Impact of Integration on Industrial Facility Quality*, by Kelly Jean Fergusson, Department of Civil Engineering, Stanford University, June, 1993. The doctoral dissertation committee consisted of Paul M. Teicholz (principal advisor), Raymond E. Levitt, C. B. Tatum, and Clifford Nass.

# ABSTRACT

This dissertation analyzes two aspects of industrial facilities: their quality; and integration in the process of developing them from inception through the first six or more months of operations. The goals of the research are to determine what constitutes a high quality facility, and how the facility development process can be better managed to achieve this result.

The international competitiveness of U. S. engineering-procurement-construction (EPC) firms has declined, and there is widespread owner dissatisfaction with engineering and construction services. We are in the midst of an industry crisis. The promise of advancing computer technology has not yet overcome these industry woes, so we must search deeper for solutions. The quality movement in North American industry emphasizes the importance of process performance measurement and customer satisfaction. However, the facility development process is a very complex context in which to apply these principles. This research is a first attempt to model the impact of process performance on the quality of a facility.

Quality is defined as customer satisfaction with a comprehensive list of characteristics of the operational facility. Integration is defined as the flow of knowledge and information in three dimensions: vertically (between industry functions), horizontally (between disciplines or trades), and longitudinally (through time). Each dimension has technical and organizational modes of coordination. To measure quality and integration, two different questionnaires were used to gather data regarding each of 17 industrial facilities in the United States and Canada. The first was directed to diverse members of the owner organization to obtain their evaluations of plant quality. The second was directed to the prior members of the project organization including the owner representatives, as well as the engineering and construction project managers, to obtain data related to integration in the facility development process.

Statistical analysis elucidated differences between distinct owner groups (strategic, project management, and operations) in their perspectives of the quality of these plants. A summary quality index was developed to encapsulate the plant manager's satisfaction with the plant. The vertical, horizontal, and longitudinal dimensions of integration were found to be independent of each other, yet each correlated positively with facility quality. Measures of both quality and integration were validated using bivariate correlation analysis. Finally, a regression model was developed which incorporated the three measures of integration as predictors of facility quality. The model is highly significant, and the integration variables explain 82% of the variance in plant quality. Vertical and longitudinal integration are particularly promising areas in which to address integration efforts and research.

## ACKNOWLEDGEMENTS

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I am indebted to the members of my doctoral committee, Professors Raymond E. Levitt, C. B. Tatum, Clifford Nass, and my principal advisor, Paul M. Teicholz for their unfailing support of my efforts. Professor David Ashley at University of California at Berkeley and Renate Fruchter at Stanford also contributed invaluable help.

In each person's individual way, Glenn Loo, Helena Ciprés Palacín, Leyla Unerdem and Chris Madison made essential contributions to this research effort. Some of the most insightful comments on my work came from my fellow students. Finally, and most heartily, I thank my true love and shining star, Robert Zeien, for his patience, understanding and encouragement.

This dissertation is dedicated to my parents, Barbara and Donald Fergusson.

# *Table of Contents*

# *List of Tables*

## *List of Figures*

# *Chapter 1 — Introduction*

## BACKGROUND

Construction is an ancient industry; it has been a part of human culture since we began building our own crude shelters 10,000 or more years ago (Leakey 1981). In the ages between then and now, the industry has become vastly more complex. Today, engineering and construction is a vital sector of the U. S. economy, with private construction accounting for 5% of the Gross National Product (GNP) on an annual basis (U. S. 1992). A typical industrial facility might cost $100 million, and have 30 or more organizations participating in its engineering, financing, regulation and construction. The task of coordinating such a project effectively is extremely difficult, and commonly results in unanticipated cost and schedule overruns, as well as facilities which do not meet the expectations of the owner.

Many techniques to improve the organization and execution of such complex projects with the objective of achieving better outcomes have been developed over the past generation: the Critical Path Method (CPM) for scheduling, the art of cost estimation and tracking, constructibility reviews, contract incentives, automated interference checking, and partnering are a few prominent examples.

Despite these strides, there is widespread owner dissatisfaction with engineering and construction services (BRT 1983). The international competitiveness of U. S. engineering-procurement-construction (EPC) firms has declined (Wiggins 1988) (Yates 1992). These serious and pervasive problems have motivated me to examine both the quality of industrial facilities as well as the process by which they are planned, engineered, constructed and put into use.

Owners spent $16 billion in construction costs alone for industrial process facilities in the U. S. in 1991 (Dodge 1992). If engineering and capital equipment costs are included, this figure approaches $100 billion. Even small improvements in either engineering and construction efficiency or facility quality would result in economic benefits in the context of this large amount of annual capital outlay. In addition, lessons learned in the realm of industrial facilities may be applicable to the development of other types of facilities such as transportation projects, office and laboratory buildings, and environmental cleanup.

But where shall we focus our efforts to improve this complex process? With limited resources to expend on improving the way we do business, what areas of improvement will have the greatest impact on customer satisfaction? As ancient and vital as the engineering and construction industry is, we have a limited understanding of how the different ways projects are executed impact the quality of the facilities which result. We are thus unable to recognize which aspects of the facility development process are most important to its successful outcome.

Although many firms in the engineering and construction industry state quality as one of their top priorities, not a single U. S. engineering or construction firm[1] has yet won the Malcolm Baldridge Award, America's highest symbol of achievement in product quality and customer satisfaction. Winners of the award must have painstakingly precise and detailed knowledge of their business processes, and what is needed to improve them. Unfortunately, such knowledge simply doesn't exist for our complex engineering and construction processes. By attempting to define, measure, and analyze these processes, we are venturing into a new frontier.

## STATEMENT OF THE PROBLEM

***Quality:*** There are currently many approaches to quality in the engineering and construction industry. Companies use inspection, quality assurance, quality control, quality management, schedules, budgets, contract incentives, and other controls to try to achieve desirable project outcomes. Millions of dollars are being spent annually on quality improvement programs. Why, then, is our industry plagued by so much litigation? Why is the rate of productivity growth so low compared to manufacturing? Why do owners question whether they are receiving their money's worth when they invest in the design and construction of a new industrial facility (BRT 1983)? What exactly is this elusive concept of *quality*, and how can it be measured?

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[1] Granite Rock Co., a *supplier* of construction materials, won the award in 1992 (ENR 1993). Wallace Co., a valve manufacturer, also won the award previously. Supplying construction material is a notably less complex process than facility development.

***Integration:*** The facility development industry in the U. S. is highly fragmented, both across project phases (planning, design, construction, and operations), and within project phases (i.e. between disciplines) (Howard 1989). There are both advantages and disadvantages to this fragmentation. On the one hand, specialization leads to economies of scale and resulting competitiveness. On the other hand, the burden of information transfer and coordination seems to increase with the degree of fragmentation. Emerging technical tools (database, artificial intelligence, and modeling capabilities), and advancing organizational techniques (Total Quality Management, matrix organizations, human networking, partnering) are all efforts to address these gaps in communication or inadequate understanding between project participants. However, we lack ways to describe and quantify integration, and thus to compare different integration strategies.

***Impact of Integration on Quality:*** There is a general sense that integration is a good thing, that it will have a positive impact on project outcomes. However, there are also serious risks associated with concerted integration efforts by companies, whose economic survival in some cases is determined on a project by project basis. There can be tremendous start up costs associated with implementing advanced organizational and technical integration tools. For example, matrix organizations, which typify a high degree of organizational integration, have a higher proportion of managers, thus cost more to run than organizations with traditional hierarchical structures (Davis 1977). What are the most important types of integration with respect to achieving high quality plants? How can we measure the relative benefits of different integration strategies and achieve the most benefit for our integration investment?

As accustomed as we have been in the past to thinking of projects in terms of their fragmented parts, we currently do not know enough about the fundamental process of facility development as a whole to be able to make fully rational management decisions regarding the degree or type of integration to pursue.

## RESEARCH DESCRIPTION AND SCOPE

This dissertation describes an exploratory study. It attempts to measure both the quality of the completed and operational facility as well as the levels of integration in the process that culminates in the completed facility. But to measure quality and integration, I first had to define these concepts, then develop simple yet complete measurement systems for them.

Using these systems, I collected data from some 80 individuals involved in 17 projects. These interviews took place starting in June 1991 and ending in January 1992. I analyzed the set of data generated in these interviews to show that integration can be used to predict facility quality. Because this is the first study of its kind, I have numerous suggestions and insights on how it might be complemented by ensuing studies that explore these issues in an empirical, quantitative manner.

## PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of this research is to improve the quality of industrial facilities by increasing fundamental understanding of the facility development process. The objectives are to define quality and integration more precisely, and then to address the impact of integration on quality.

The first objective is *to establish the meaning and measurement of industrial facility quality*. To accomplish this I develop a generalizable yet detailed definition of industrial facility quality. Next, I develop criteria for, implement, and evaluate a quality measurement method that focuses on industrial facilities as the product of the facility development process. Once the definition and measurements are established, the data analysis determines which aspects of quality are the most important to achieve.

The second objective is *to establish the meaning and measurement of integration in the industrial facility development process*. Based on themes in organizational theory and economics literature, I present a theoretical framework that may be used to elicit, understand, and explain patterns in the integration data. I develop and implement measures of integration applicable throughout the facility development cycle to show how knowledge and information flows can be measured.

The third and final objective is *to increase understanding of how integration in the facility development process impacts the quality of the operational facility*. The conceptual integration framework is embodied in a statistical regression model that predicts the quality of a plant as a result of the project's integration parameters. I determine the relative impact of different types of integration on industrial facility quality. I discuss why integration affects quality in the context of the theoretical framework, and thus provide a rational basis for the improved management of the facility development process.

## OVERVIEW

This dissertation analyzes two aspects of industrial facilities: their quality; and integration in the process of developing them from inception through the first six or more months of operations. The goals of the research are to determine what constitutes a high quality facility, and how the facility development process can be better managed to achieve this result.

I collected data from 17 industrial facilities in the United States and Canada, and analyzed owner perspectives on the quality of these plants. I defined and modeled integration in the facility development process as the flow of knowledge and information between project participants. Using data collected from the 17 projects, I determined the impact of varying degrees of integration on the quality of the facilities produced. An overview of the main theme of the research is shown in Figure 1.1.

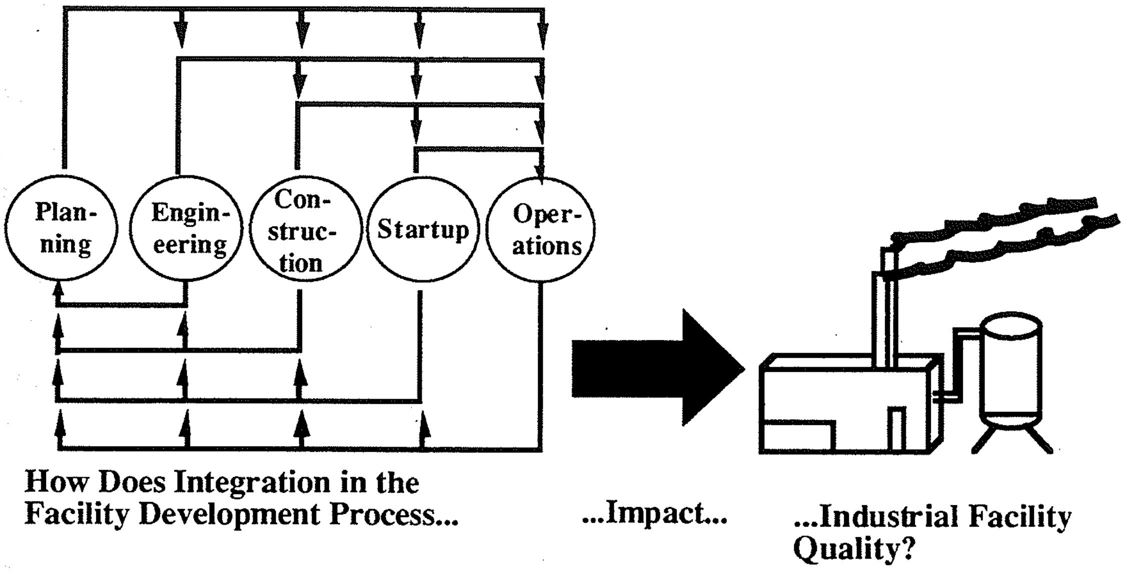

*Figure 1.1. Overview of the research.*

The left-hand part of the figure displays the facility development process composed of five subprocesses. The feed-back and feed-forward arrows symbolize the flow of knowledge and information between the subprocesses. The right-hand part of the figure depicts the facility itself as the output or product of the facility development process. My intent in taking this overall process-product viewpoint is to analyze and optimize the facility development process as a whole, whereas a focus on a subset of subprocesses may have led to suboptimizing particular stages of the process to the detriment of the overall outcome. For example, the engineering process can be optimized, say on the basis of cost of engineering labor, but construction costs suffer because not enough was spent on constructibility efforts. Or construction is optimized, say on the basis of minimizing change orders, but to the ultimate detriment of an owner who may have benefited from such a change over the life cycle of a facility.

This dissertation draws general conclusions regarding integration that will help guide the industry in its quest to provide better service to owners, and to improve the quality of its products. As our nation begins plans for an ambitious program of investment in infrastructure, it is a worthy challenge to make the most of every tax dollar by maximizing the quality of our constructed projects through improving the process of planning, engineering, construction, and use.

## LOOKING AHEAD

This chapter gave the reader a general overview of the research problem addressed by this dissertation, and a sense of my motivation for studying it. The next two chapters relate my work to the present state of knowledge of quality and integration, respectively, and outline where this study contributes to knowledge of these concepts. These two chapters present a definition of quality and a framework of analysis for integration that each are built from prior work of researchers both within and outside the domain of facility engineering and construction. Chapter 4 discusses the methodology used in the study, with references to Appendix A where the data collection instruments, hypotheses, and detailed definitions are shown. Chapter 5 analyzes and interprets the quality data, and Chapter 6 analyzes the integration data, and addresses its impact on facility quality. I discuss conclusions, contributions, and future work in Chapter 7, with references to Appendix B where I make recommendations on how to improve and build upon the current study.

# *Chapter 2 — Quality Background and Definition*

## BACKGROUND

"Quality" is a popular term in the engineering and construction industry today. Each company, and indeed, each person, has a favorite definition. There are hundreds of quality consultants and philosophers, and hundreds of books and articles. How does one make sense of this vast array of information?

Two simple models shown in Figure 2.1 may be used to help us categorize and analyze quality definitions and programs: Dumas' progressive four-step hierarchy (Dumas 1989); and Garvin's five category classification system (Garvin 1984).

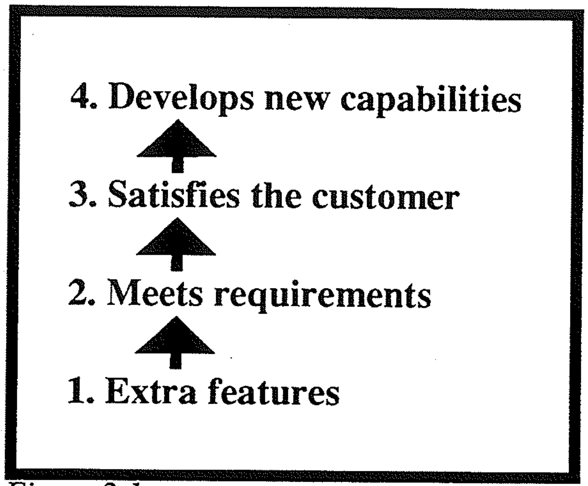

*Figure 2.1a.*
*Dumas' Hierarchy of Quality Definitions (Dumas 1989).*

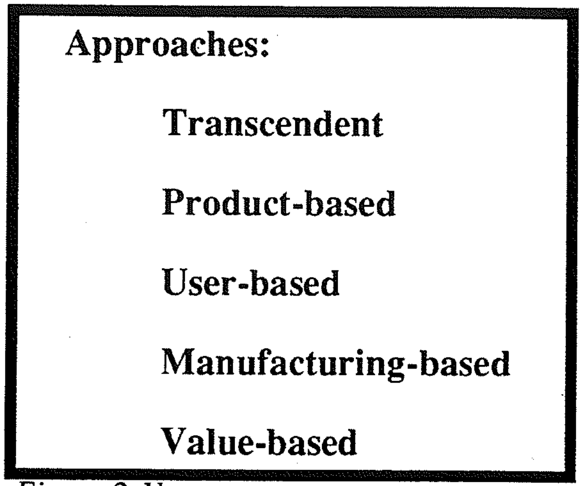

*Figure 2.1b.*
*Garvin's Five Approaches to Defining Quality (Garvin 1984).*

*These two models are useful frameworks for categorizing the wide variety of quality literature in industry and academia today. Dumas' "Satisfies the customer" definition and Garvin's "User-based approach" are similar and are adopted as the definition of quality in this study.*

Dumas' framework (Figure 2.1a) relates successive definitions of product quality to an industry's or company's competitiveness. Periodically, an upheaval occurs within a company or industry which causes advancement to the next level. Progressing to a higher level expands the definition of quality without supplanting lower levels. At the most primitive level, "quality" means the inclusion of *Extra features*. An example of this from the American automobile industry is Sloan's strategy of sustaining customer interest by annually changing features such as styling, layout, dashboard components, etc. (Womack 1990). At the second level, *Meets requirements*, quality is defined as conformance to specifications. This is the operational definition for most A/E/C firms in business today (Burati 1987; Davis 1987), and remains a vital area to improve. At the third level, the definition expands to include a focus on the customer: *Satisfies the customer.* Meeting customer and user expectations in terms of durability, reliability, or life cycle value for the initial investment are objectives for companies or industries operating at this level. Finally, the very best companies offer products which anticipate or exceed customer expectations and thereby help *Develop* customers by enhancing customer competitiveness and profitability.

Crosby's "zero-defects" philosophy (Crosby 1979) and Juran's "conformance quality" (Juran 1974) fit at the second level, while Juran's "fitness for use" (Juran 1974) belongs at the third level. Deming's "Out of the Crisis" (1982) is a general prescriptive approach to achieving a transition from the second to the third level.

Garvin's system is composed of five approaches to quality definitions as shown in Figure 2.1b. In the *Transcendent* approach developed by philosophers, quality is an undefinable characteristic like beauty which we can only recognize by experience. The *Product-based* approach defines quality as a measurable attribute of a product, for example high quality rugs have a high number of knots or stitches per square inch. This definition is useful when all customers agree that a single attribute is the most important. The *User-based* definition recognizes that each person has different needs and expectations. Individuals attach weights to each quality characteristic of a product, and the highest quality product is one that maximally satisfies the individual user. This approach is popular among marketing people. The *Manufacturing-based* approach emphasizes conformance to requirements rather than user satisfaction and is prevalent in engineering and manufacturing departments. In the *Value-based* approach, quality is acceptable performance at an affordable price. Garvin recommends that organizations cultivate each of these five approaches to quality to enable the development and production of high quality products.

To demonstrate the pitfall of not cultivating differing perspectives by overemphasizing *Manufacturing-based* quality at the expense of *User-based* quality, Garvin cites Ishikawa's example of a Japanese paper manufacturer who:

> "discovered that [the strength and tear characteristics of] its newsprint rolls failed to satisfy customers even though they met the Japanese Industrial Standard. Conformance was excellent, reflecting a manufacturing-based approach to quality, but acceptance was poor. Other rolls of newsprint, however, generated no customer complaints even though they failed to meet the standard." (Ishikawa 1984) as cited by (Garvin 1984).

By focusing just on the Manufacturing-based approach the company created unhappy customers. A more robust view of quality that included the User-based approach soon put an end to the complaints.

Certainly the reader can envision parallels in the engineering and construction industry today, in which facility characteristics meet a specification, but fail to meet an owner's needs or expectations. This is not to say that extra features and conformance to requirements are not essential components of the definition of facility quality, but that customer satisfaction must be added to the industry's conception of quality if it is to remain competitive through the 1990s and beyond. A model of quality that incorporates customer satisfaction and is specific to the complex domain of industrial facilities is clearly necessary.

## POINT OF DEPARTURE

Traditionally, the industrial facility engineering and construction industry has operated in line with Dumas' *Meets requirements* and Garvin's *Manufacturing-based* definitions of quality. However, owner dissatisfaction with cost-effectiveness of engineering and construction services (BRT 1983) and the losses of Engineering, Procurement and Construction (EPC) firms in international competitiveness (Wiggins 1988) (Yates 1992) have prompted many EPC companies to attempt to add Dumas' *Satisfies the customer* and Garvin's *User-based* approach to their operative definition of quality.

The above definitions suggest the use of customer satisfaction with a completed facility to measure its relative merit. Such measurement could provide valuable feedback to consumers as well as providers of industrial facilities regarding the strengths and weaknesses of both facility and project performance.

Figure 2.2, below, demonstrates a gap with respect to research of quality of industrial facilities, and delineates the areas in which this study builds upon and adds to prior work. Each of the two axes in the figure is divided into two categories. The vertical axis, Quality Definition, has categories of Conformance and Customer Satisfaction. The horizontal axis, Focus of Inquiry, has categories of Process Characteristics and Product Characteristics.

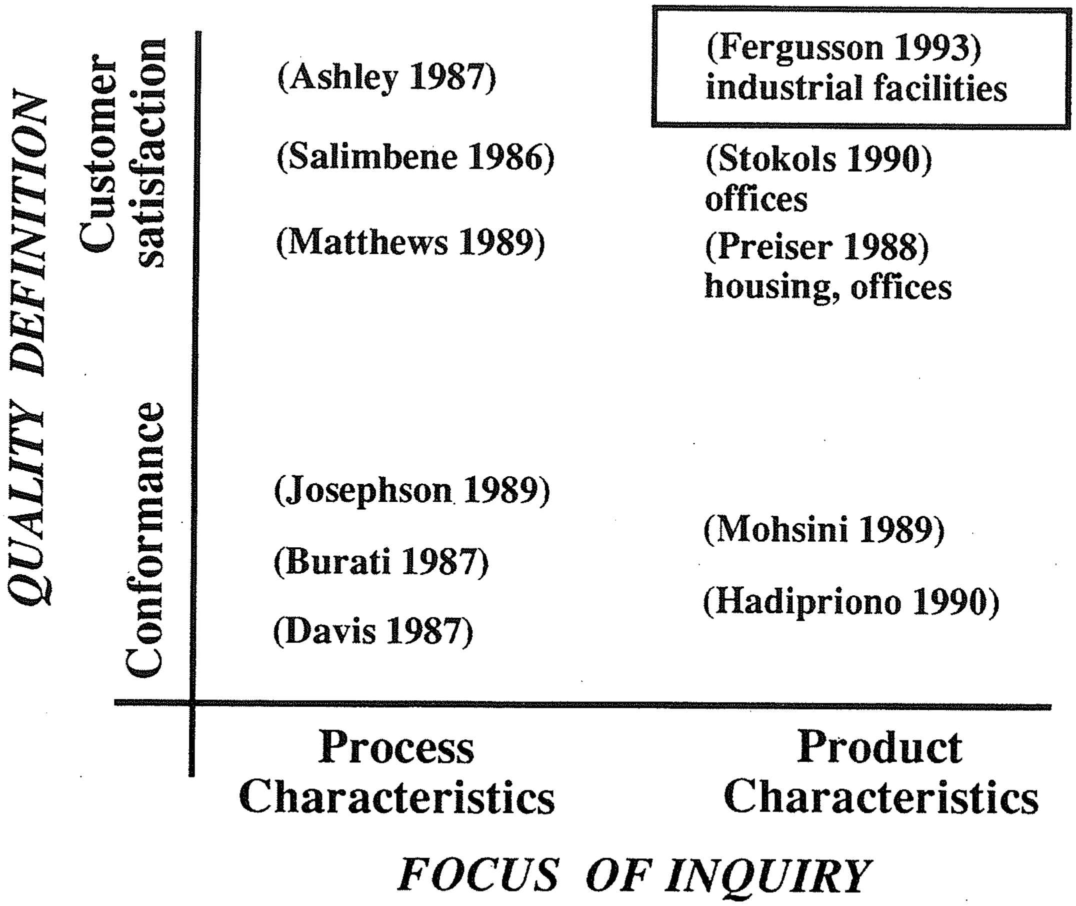

*Figure 2.2. Quality research in the domain of facility engineering and construction.*

Much prior work on measuring quality in the engineering and construction industry has focused on the quality of the facility development *process:* planning, engineering, constructing, and start-up. The Construction Industry Institute's (CII) work has primarily focused on quality of the process using the *conformance* quality definition in measuring the costs and causes of rework and prevention of errors (Davis 1987) (Burati 1987) (see also Josephson 1989). Other work adopts a *customer satisfaction* quality definition, and emphasizes project success (Ashley 1987) (Salimbene 1986), or total quality management of the process (Matthews 1989). The drawback to a process-oriented approach to analysis is that it risks suboptimization of the product to maximize process-oriented goals such as project schedule, budget, and satisfaction of the owner's project manager. The research discussed in this dissertation differs from these studies because it focuses on the facility as the ultimate, and thus more important *product,* or output, of the facility development process.

Work which views the facility *as a product* includes Hadipriono (1990), who uses fuzzy set concepts to quantify qualitative assessments of facility component performance. Mohsini (1989) proposes that performance of a building can be maximized by adjusting the relative bargaining powers of participants in the process. My research differs from these studies in that it is based on a *customer satisfaction* rather than *conformance* definition of quality.

Following the example of Preiser (1988), I adopted a customer satisfaction definition of quality as well as a focus on the product. Preiser's work concerns the impact of office and housing facility characteristics on the productivity of the occupants. Maintaining a similar focus in terms of quality definition and focus of inquiry were numerous papers presented at the symposium on Overall Facility Performance in Toronto, Canada (Davis 1990). Although the facilities addressed in these papers are limited to office and laboratory buildings, a number of guidelines for possible performance measures are discussed. Especially relevant is (Stokols 1990), a study in which a 4-point Likert scale is used to obtain workers' evaluative attitudes about attributes of their work environment such as "Comfort of your chair," "Conversational privacy," and "Availability of electrical outlets." Stokols' success with this attitude measurement technique prompted me to adopt a similar approach in my research. However, Stokol's methodology did not address the multiple users or customers of a facility, nor were the relative importance of the facility characteristics to these users explored.

Preiser and Stokols address the quality of housing and office facilities in terms of *customer satisfaction* with the *product.* This viewpoint has not been extended to the study of industrial process facilities, and this gap in the literature invites exploration by researchers. This dissertation responds to this need by contributing a model for the analysis of industrial facility quality, and a measurement methodology for the industrial facility as a product based on Dumas' *Satisfies the customer* and Garvin's *User-based* (customer satisfaction) definitions of quality. The results obtained from using the methodology can be used by both owners and providers of industrial facilities to refine and achieve their strategic business goals.

## PRODUCT CHARACTERISTICS

An industrial facility is an extremely complex product, often acres in size and hundreds of millions of dollars in cost. As such, it is easier for people in the owner organization to give a meaningful, accurate evaluation of a facility if it is decomposed into smaller components and concepts. Starting in August 1990, I began developing a list of facility characteristics represented by phrases used to analyze and discuss facility quality. These phrases were culled from literature and from discussions with industry professionals. I attempted to focus primarily on product characteristics. This list was gradually refined into a set of representative items which are presented in Table 2.A.

### FACILITY QUALITY CHARACTERISTICS

1. Timeliness of start-up
2. Meeting production output specifications
3. Capital cost (including design, construction, and start-up)
4. Profitability of plant
5. Cost of operating (excluding energy cost)
6. Energy cost for operating
7. Adaptability to changing owner/operator needs
8. Control systems providing industrial process feedback (DCS)
9. Meeting emissions requirements (all waste types)
10. Meeting emissions requirements under all operating conditions (e.g. varying loads)
11. Flexibility to meet more stringent emissions requirements
12. Flexibility to use alternative fuel types
13. Adequate warranty
14. Flexibility of major systems for expansion
15. Useful operations and maintenance manual
16. Training of operators during start-up
17. Ease of operating (e.g. operation of machinery by less experienced workers)
18. Healthfulness of worker environment
19. Comfort of worker environment
20. Safety
21. Security (proprietary processes, materials, assets, etc.)
22. Storage space
23. Reliability of major systems
24. Durability of major materials
25. Cost of maintenance
26. Ease of maintenance (accessibility of equipment, clearances around equipment)
27. Ability to predict failures of major components
28. Ability to avoid catastrophic failures of major components
29. Equipment replacement cost
30. Cost of cleaning
31. Ease of cleaning
32. Architectural image portrayed by facility

*Table 2.A. Quality Characteristics of Industrial Facilities. Facility characteristics used to analyze and discuss facility quality were culled from the literature and discussions with industry professionals. Together, these characteristics represent the concept of facility quality. The characteristics are evaluated and discussed in greater depth in Appendix A.*

These items, which were validated in the study of 17 facilities, comprise the product definition of the process-product model used in this study. Each item is evaluated and defined in greater depth in Appendix A.

In this chapter I presented two taxonomies, by Dumas and Garvin, for classifying general quality definitions. I adopted Dumas' "Satisfies the customer" and Garvin's similar "User-based" definitions as the general definition of quality to be used in this study. I reviewed prior research on quality in the facility development industry, and showed where the current study is expected to contribute to this body of work. By using customer satisfaction as the general definition of quality and focusing on completed industrial facilities as the product of the facility development process, I am addressing a gap in this industry's literature on quality. I concluded this chapter by presenting a list of facility characteristics drawn from the literature and industry professionals to describe the detailed aspects of an industrial plant as a product.

In the next chapter, I present some background on integration by describing the use of the term by researchers whose work is closely related to my own. I show that there is inconsistency in usage of the term, and that there is a broad spectrum of meanings with which it is associated. To resolve these issues, I look to the evolution of the usage of the term, delving into organizations and economic theory where applicable. From these roots, I develop a broad structured framework of integration to use in analyzing the flow of knowledge and information in the 17 projects included in this study.

# *Chapter 3 — Integration Background and Framework*

Many researchers in the field of construction engineering and management have addressed the issue of integration. However, none of these researchers has suggested a broad based, internally coherent framework useful for describing and comparing different integration strategies and their probable effects on facility quality. This chapter starts by discussing prior and ongoing research that addresses the issue of integration and, where available, the definitions of integration used. It establishes points of departure for the development of an integration framework and measurement tools by assessing the contributions these studies have made toward answering the research question, 'how can we better manage information flow in the facility development process to achieve higher quality facilities?' Next, I establish a point of departure for my modeling methodology. To do so, I contrast prior approaches to predicting project outcomes based on process characteristics with the advantages of using an integration framework to structure the process variables. Finally, the bulk of the chapter is devoted to creating a conceptual model of integration by synthesizing a wide spectrum of thought ranging from economics and organization theory to engineering practice.

## INTEGRATION IN FACILITY DEVELOPMENT

### Background

Integration is a term often used in our industry, but rarely defined. The industry is perceived as fragmented, disorganized, and prone to litigation (Howard 1988). "Integration," especially computer integration, has been heralded as the solution to these industry ills. But what is integration? Is it the use of computer tools to perform what we traditionally have done manually? Is it simply communication among project participants?

Funk and Wagnalls (1973) defines integration as "the bringing or fitting together of parts into a whole." Integrity is "the condition or quality of being unimpaired or sound," and "the state of being complete or undivided." Integral is defined as "being an indispensable part of a whole; essential; constituent," and "formed of parts that together constitute a unity."

When the word "integration" is used in the research laboratory of the Center for Integrated Facility Engineering (CIFE), it is generally used to describe the sharing of data by several computer applications. An objective in the development of these applications and models is internal consistency in the project data, for example, CIFECAD (Ito 1989). Khedro (1993) manages information consistency as it is passed between applications by means of a central "facilitator," whereas in Fischer's (1993a) theory this is accomplished by broadcasting a complete new design version to all design participants for each design change. Another sense of the word is the "intelligent automation" of design, construction, or operations and maintenance tasks. Examples are the generation of architectural layouts from raw program information (Chinowsky 1991), the development of alternative mechanical system models from preliminary architectural design information (Garcia 1992), or the generation of efficient construction site layouts from project scope and site information (Tommelein 1989). Teicholz (1993) gives a compelling vision of Computer Integrated Construction (CIC) as a competitive strategy and force for change in the engineering and construction industry. These examples portray integration as the use of advancing technical tools to enhance the speed, accuracy, consistency, and utility of project information in its use by successive project participants. These studies have increased our knowledge of how and what information flows between project participants, particularly, though not exclusively, during the conceptual design phase of project development. Such work still leaves unanswered the question of how important this approach is compared to other less technology-intensive approaches to information sharing.

Several researchers have explored integration between the functions of design and construction, or "design constructibility." Using a descriptive case study approach, Vanegas (1988) finds that the construction phase of a project is enhanced by increased interaction between construction and engineering participants during design development. He identifies the idea that there are different types of integration (p. 90): horizontal integration between functions (which he calls disciplines), and vertical integration over time, between project phases. Although my taxonomy will differ from his, he identifies several key integration research needs. These include integration research in the areas of organizations, technology, decision-making, information flow and coordination. Vanegas also discusses the need for "performance indicators to measure the actual degree of integration or to measure the cost, schedule, or quality improvements due to integration."

Fischer (1989) developed an expert system which is intended to help structural engineers incorporate constructibility knowledge in their designs of reinforced concrete structures.

Fischer provides a definition of design-construction integration as "the continuous interdisciplinary sharing of data and knowledge between design and construction." This definition introduces the concepts of sharing between functions, between disciplines, and through time. It also identifies that which is being shared: knowledge, and information. However, it is limited to the facility life cycle functions of design and construction, and does not address the mechanisms of sharing. The definition of integration I adopt in my research extends Fischer's definition by including all functions of the facility life cycle and describing the mechanisms of sharing.

In his study which uses the integrated manufacturing paradigm to analyze the interface between design and construction in the development of eight electrical cogeneration facilities, Williams (1990) describes integration as "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... Integration also includes the use of tools, knowledge, experience and technology that support the integrated effort." This definition addresses the breadth of ingredients of "integration." To compare the manufacturing and construction industries on the basis of the integration of product and process design, Williams developed a framework composed of four categories, each consisting of three integration variables. The categories were *context, organization, process*, and *content*. He performed case studies of eight cogeneration facilities. His analysis involved regrouping the variables into three dimensions: interface, technical, and environmental. Williams concluded that the integrated manufacturing paradigm is a useful aid to understanding the process of facility development. However, it is limited in its ability to describe this complex process in an internally consistent manner. Williams finds no relationship between degree of integration and project success as viewed by project managers.

In another study which focuses on the link between the functions of design and construction, Nam (1992) describes three types of integration: organizational integration, in which the two functions exist within the same organization under a single leadership; contractual integration, in which a construction project manager coordinates the activities of the other participants; and information integration, in which computer technology enables participants to access a common data base of project information. Four methods for enhancing the link between engineering and construction are suggested: increased owner involvement, establishment of long term business relationships, participation of an "integration champion," and participation of individuals with strong professional values. The delineation of these four methods is an incremental step toward answering the first part of the question 'how can we better manage information flow in the facility development process to achieve higher quality facilities?' The achievement of higher quality facilities by means of these methods, however, is still left as a matter for speculation.

Vanegas (1988), Fischer (1989), Williams (1990), and Nam (1992) each emphasize the importance of constructibility in achieving a desirable project outcome. By now, most progressive engineering and construction companies have some form of constructibility program to ensure the incorporation of construction knowledge into engineering design. However, there are several other interfaces in the facility development process that have the potential for a positive impact as dramatic as that of constructibility. My research seeks to identify such interfaces, and determine the characteristics and consequences of "vendability" and "operability," the incorporation of vendor and operations information and knowledge into engineering design.

Sanvido's Integrated Building Process Model (1990) is based on the interactions between the product development functions of planning, designing, constructing, operating, and managing a facility. Sanvido's model is groundbreaking because it attempts to model the entire facility development process, rather than just a piece of it as did many prior studies. The inputs to the process derive from a strategic business opportunity, and the process output is an operational facility. The model was validated using 22 case studies to assess its representativeness of the real-life process of developing office buildings. Its three limitations are that it does not model time dependencies between functions, it is too complex to be implemented as a project control tool in its present form, and it does not assign priorities to tasks or interactions. The integration framework I present later in this chapter addresses these limitations by modeling information flow across time and simplifying the analysis context so that measures of priority and importance may be implemented.

Koskela's (1992) detailed synthesis of manufacturing's new production philosophy and its application to construction is a compelling vision for the improvement of the construction industry. More important than automating existing processes is the need to identify and eliminate non-value-added activities. Criticizing our reliance on the heuristics and experience of experts to manage work processes, he laments that our current "empirical knowledge and theoretical understanding is shallow and fragmented," and that a relatively small amount of research on "the conceptual and theoretical foundations of construction" could have "major payoffs." In particular, he identifies the need for "concepts and taxonomies for defining design and construction processes." To achieve the goal of improving project performance, he indicates the need for "measures for construction processes" and identifies the research effort discussed in this dissertation as making progress towards that goal.

For at least 55 years, vertical integration between industry functions has been identified by manufacturing and agricultural industries as an important source of competitive advantage. Blair (1983), in his analysis of the evolution of the vertical integration concept, cites fifty or more studies regarding vertical integration yet not one in the domain of facility development. Although there has been some significant theoretical work (Williamson 1979) (Stinchcombe 1985) on vertical integration in facility development, there are no empirical quantitative studies in the literature. It is possible that this neglected area of inquiry could yield benefits to the engineering and construction industry as it has with several other major industries vital to the U. S. economy.

## Points of Departure

Two points of departure emerge from the above descriptions of research closely related to my topic. The first point is that the concept of integration encompasses a wide diversity of scope and definition in the field of facility development. Although Fischer (1989) and Williams (1991) propose definitions of integration, usage of the term continues to be inconsistent and ambiguous. This research project responds to this problem by proposing a comprehensive integration framework that encompass the diverse aspects of integration throughout the development cycle of industrial facilities. This framework is a new synthesis of the diverse meanings of integration used in prior research by Vanegas (1988), Tommelein (1989), Fischer (1989), Ito (1989), Nam (1992), Williams (1992), Garcia (1992), Koskela (1992), Khedro (1993), and Fruchter (1993). After completing the review of background literature and points of departure, the remainder of this chapter is devoted to the development of this framework.

Secondly, there is a paucity of tools for measuring integration in the facility development process. These tools are critically needed if we are to improve our understanding of this process, and thus enable monitoring and improvement of the process in a rational fashion to achieve desirable outcomes. Vanegas (1988), Williams (1991), and Koskela (1992) are emphatic and explicit regarding this need, but provide no measurement tools themselves. My research responds to this lack of measurement tools by proposing several ways to measure integration.

## PREDICTING PROJECT OUTCOMES

### Background

Jaselskis and Ashley (1990) use a statistical discrete choice regression modeling technique to predict "project success" from a variety of project execution variables such as project manager characteristics, project team stability, and project planning and control efforts. Project success was evaluated by project managers in terms of cost, schedule, and achieving "outstanding" construction performance. Data collected from 75 projects was analyzed to develop a regression model for each of the three success criteria. Jaselskis' approach is important to my research because it explores the cause-and-effect relationship between project execution variables and project outcome. However, his focus on success as evaluated by project managers does not address the success of the project as viewed by other stakeholders in the resultant facility. Thus, Jaselskis' approach may lead to suboptimization of the process as a whole by measuring outcomes too early in the facility life cycle. In addition, he does not use a cohesive theoretical framework as a background against which to interpret model results.

Independent Project Analysis, Inc. (IPA) is a consulting organization which assists organizations by analyzing their capital project development process. Merrow (1990) uses statistical regression to model both cost and schedule outcomes of 49 World Bank hydroelectric projects. Independent variables include project size characteristics, hydraulic head, green field factors, year of project appraisal, and proportion of appraised cost in power generation. These two models achieve excellent percentages of explained variance, 96% and 73% respectively. However, these and other models developed by IPA apply only to specific types of projects. As such, these models cannot be applied to a diverse spectrum of facility development projects. They do not contribute to developing a cohesive cause-and-effect theory of project execution, but rather perpetuate the use of heuristics as a cornerstone of project management. Like Jaselskis' approach, Merrow's (1990) focus on outcome measures of cost and schedule may neglect the viewpoints of key customers of the facility development process other than the project managers. My dissertation seeks to augment Jaselskis' and Merrow's approaches by developing a single unified framework of project analysis that is applicable to a wide range of project types, and by using an outcome variable based on owner satisfaction with the operational facility to assess the performance of the facility development process as a whole.

Alarcón-Cárdenas and Ashley (1992) propose the General Performance Model (GPM) to evaluate project execution strategies in terms of several project outcomes. Various execution strategies combining alternatives such as incentives, team building, and organizational structure have interrelated impacts on the project participants, which in turn influence the project outcomes of cost, schedule, start-up effectiveness and project benefit. The knowledge that drives the model is provided by industry experts. This model is highly relevant to my research undertaking because it addresses a similar general research question: "How do process characteristics in a structured framework affect project outcomes?" Conceivably, project and outcome data such as that generated in my research could be incorporated in the GPM to complement expert opinions and heuristics. This dissertation complements the GPM by using quantitative measures derived from an internally consistent and comprehensive framework to gather data from actual projects to predict the quality of the resultant facility.

## Point of Departure

Although progress is being made in increasing integration between facility development project participants as described by Vanegas (1988), Tommelein (1989), Fischer (1989), Ito (1989), Nam (1992), Williams (1992), Garcia (1992), Khedro (1993), Fruchter (1993), there have been no previous attempts to quantitatively relate this increased integration to the quality of the resultant facility. By analyzing integration data from 17 projects in light of the integration framework and facility quality data, my goal is to explore this relationship explicitly. Approaches by Jaselskis (1990) and Merrow (1990) that relate process characteristics to project outcome do not use a structured framework for the variables such as that provided by the integration framework that will be developed in the remainder of this chapter. Alarcón-Cárdenas' (1992) approach, while more structured than prior studies, relies on expert knowledge and heuristics rather than measured results. By predicting product quality with measured variables derived from a structured integration framework, I created a richer explanatory context for improving the industrial facility development process. Thus my research contributes to the theory base of the field of engineering and construction management. A better understanding of integration in this complex context may in turn lead to a better understanding of integration in other industries. In addition, the patterns in the data I uncover have practical implications for practicing professionals in both contractor and owner companies.

## THE DEFINITION AND COMPONENTS OF INTEGRATION

As apparent in the above literature review, existing definitions of "integration" (Fischer 1989) (Williams 1991) are limited in scope and explanatory power with respect to the facility development process as a whole. There are many types and interpretations of integration, but no internally cohesive framework to unify them. Therefore, a structured definition and framework are needed to serve as a starting point for developing theories and measurements of integration.

I propose a broad definition of integration for use in this study that encompasses this wide range of uses. Narrower definitions can be mapped onto a portion of this broad framework.

In this study, I define integration to be "the flow of information and knowledge between industry functions (vertically), between disciplines (horizontally), and through time (longitudinally). This flow of information and knowledge is accomplished by organizational (humanware) and technical (hardware and software) means of coordination." The vertical, horizontal, and longitudinal dimensions of integration are represented in Figure 3.1.

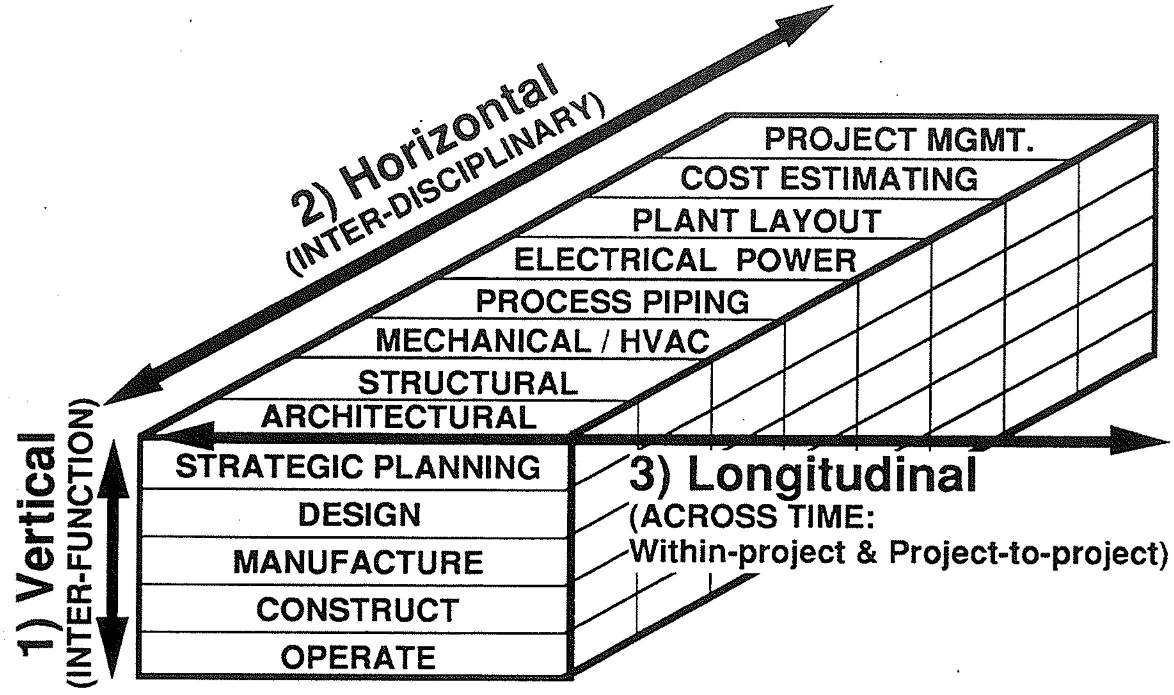

*Figure 3.1. Overview of the three dimensions of integration in facility development: vertical, horizontal, and longitudinal. Vertical and horizontal integration adapted from Thomas (1992).*

Defined in this way, integration becomes a lens or a filter through which we can examine, interpret, and better understand the facility development process. Defining integration as "flow" also allows us to think in terms of physical phenomena such as turbulence, density, viscosity, purity, velocity, and pressure.

Now, let us take a closer look at the five components of this definition of integration as the flow of information and knowledge 1) between industry functions (vertical integration), 2) between disciplines (horizontal integration), 3) through time (longitudinal integration), by 4) organizational (humanware) means of coordination, and by 5) technical (hardware and software) means of coordination. These five components will be developed in the remainder of this section, culminating in their synthesis into a cohesive and unifying framework, followed by a discussion of how this new framework relates to other selected models.

## Information and Knowledge Flow Between Industry Functions: Vertical Integration

The term "vertical integration" emerged in the economics literature. It describes an organization's ownership or control of more than one of the functions in the production of its primary product. In the context of automobile manufacturing, Womack (1989) describes vertical integration as, "Making everything connected with cars from the basic materials on up." Keidel (1975) states that vertical integration, "... starts with the discovery/ identification of a raw material and ends with a competed sale — or even service after the sale."

A parallel can be drawn between the use of the term "vertical integration" by the above authors in a manufacturing context with its application in the facility development industry. In this industry, vertical integration could start with the identification of a strategic business need (raw material) and end with a completed facility, and even operations after the facility completion. This trend is prevalent in new cogeneration facilities where the design-builder of the plant operates it under contract after completion.

As one example of vertical integration in the engineering and construction industry, Vanegas (1988) specifically analyzes the integration of construction knowledge and information into the design function.

Savage (1990) described the emergence of vertical integration as a business strategy of large American manufacturing companies in the 1880s and 90s, "Through mergers, consolidations, and other strategies, many of these companies expanded forward into distribution and back into raw materials. This 'vertical integration' helped them reduce costs, increase profits, and build barriers against other potential competitors."

The earliest formal definition of vertical integration that I have found comes from the textile industry (Davis 1938), wherein, "Vertical integration is defined as that type of organization that comes into existence when two or more successive stages of production and/or distribution of a product are combined under the same control." Despite the potential benefits of such integration to that industry, there had yet been "no comprehensive study of the advantages and disadvantages that have accompanied vertical integration in the textile industries." Just as Davis' early study addressed that gap in his industry, so too does this dissertation attempt to probe the potential of vertical integration in the engineering and construction industry. Davis found that the principal benefits of vertical integration were organizational stability, greater profits, and better planning of production. The degree of vertical integration found in organizations was partially dependent on the complexity or rate of change of the product, (Davis 1938).

Cole (1952) likewise uses Davis' definition in his study of vertical integration, however Cole's work differs from earlier studies in his attempt to determine whether vertical integration accrues benefits to the consumer. The benefits he found include "lower prices, maintenance of quality, (and) better servicing of products." In particular, Cole found that for a wide variety of products, ranging from agricultural produce to petroleum, consumers saved from 8% to 28% by purchasing from vertically integrated suppliers. Cole also introduced the idea of "quasi vertical integration," in which the benefits of vertical integration are captured equally well through contractual control or voluntary agreement as an alternative to integration through ownership.

Blair (1983), in his attempt to highlight and resolve differences between economic and legal viewpoints on vertical integration, reemphasized that ownership of functions is not a prerequisite for successful vertical integration, and that the distinction between integration through ownership versus integration through voluntary or contractual control is not important in assessing the benefits that might accrue to customers of the integrated process's products. Similarly, Williamson (1979) and Stinchcombe (1985) point out that contracts are commonly used to create temporary hierarchical organizations that reduce transaction costs and thus can create benefits of vertical integration.

Partnering is a popular emerging technique for managing the relationships of the main participants in large projects. Although it takes many forms, partnering essentially involves a pledge or contract between two organizations to perform work cooperatively on a long term basis, avoid litigation, and provide fair profits to each (CII 1991). Williamson (1979) gives a justification based on economic transaction cost theory as to why partnering ("relational contracting") is a viable, desirable form of doing business on series of large, complex, risky, long-term projects such as those in the engineering and construction industry. Such contracting sets "admissible dimensions for adjustment such that flexibility is provided under terms in which both parties have confidence." Given the uncertainty associated with the technology and duration of projects, partnering is a way of increasing vertical integration in a project organization by reducing transaction costs and enabling familiarity and trust to develop between the main participants. Partnering creates a common stake in the success of product development.

The U. S. Air Force's Integrated Computer Aided Manufacturing (ICAM) "wheel," shown in Figure 3.2, is an integration architecture featuring six manufacturing functions: Design, Fabrication, Assembly, Inspection, Material Handling, and Manufacturing Control. "Their work represents the first major step in shifting the focus of manufacturing from a series of sequential operations to parallel processing" (Savage 1990). The functions are arranged in a circle to emphasize the non-sequential input of the functions.

Similarly, conceptualizing the creation of an industrial facility in terms of functions arranged in a circle rather than sequential phases helps break traditional linear thinking modes by providing a focus on the ultimate product, the facility itself. Fischer (1993b) presents a vertically-oriented view of the facility development process as shown in Figure 3.3. The list of functions he presents (Feasibility and Program, Design Development, Construction Planning, Construction, and Operations and Maintenance), is expanded upon below.

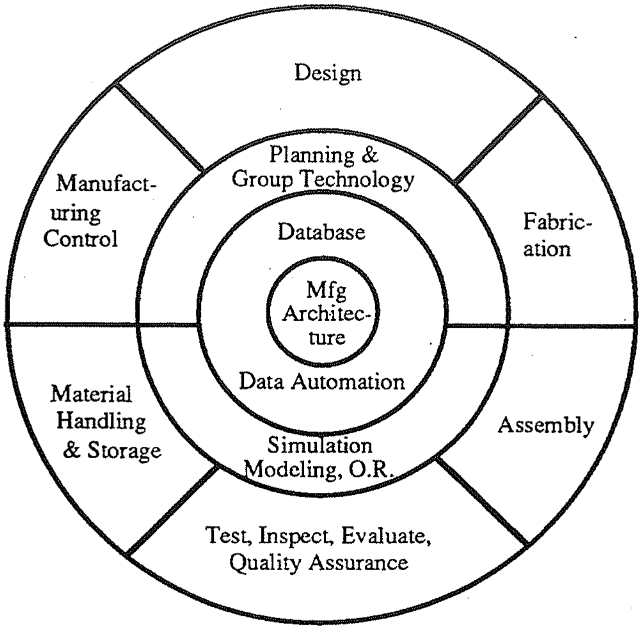

*Figure 3.2. U. S. Air Force's ICAM wheel. The functions (shown in the outer ring) are similar to those in the industrial facility development process. The functions are arranged in a circle to emphasize the non-sequential input of the functions in product development. Adapted from Savage (1990).*

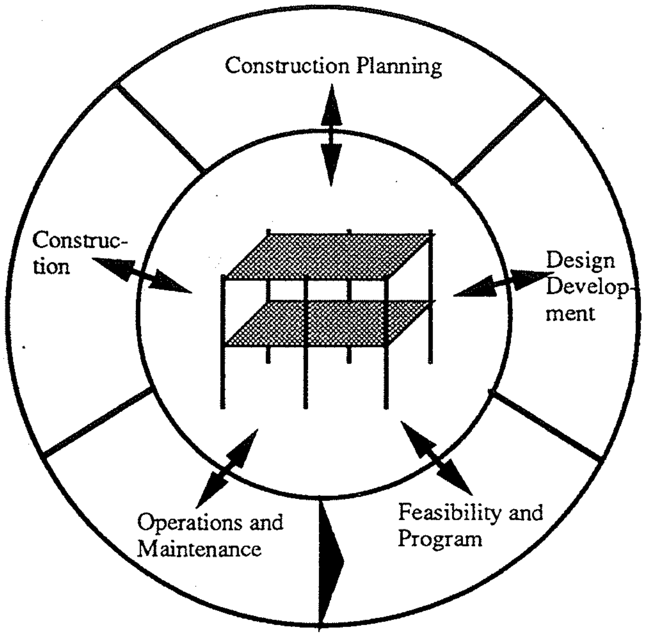

*Figure 3.3. Computer Integrated Construction (CIC), (Fischer 1993b). Some functions in the facility development process are shown in the outer ring, with a model of the product (facility) at the focus of the circle.*

Thomas (1992) discusses a technology-based approach to building systems integration. He portrays vertical integration in the context of the building industry functions of finance, design, manufacture, construct and operate. I have modified these slightly as shown in Figure 3.1.

Tatum (1989) defines integration as "sharing knowledge and data across the traditional phases in a project." Our current work extends this definition. The words "traditional phases" imply a sequential progression from function to function as the plant progresses through time from conception to operation. However, as vertical integration increases, the need for sequential distinctions between "phases" becomes obsolete. Instead, the operations function will meld with the design function, the construction function melds with the strategic planning function, etc. Truly time-related information and knowledge flow is addressed later in this chapter as longitudinal integration.

In my opinion, the primary functions in the industrial facility development industry can be listed as Strategic Business Planning (including feasibility analysis), Financing, Permitting, Conceptual Design, Detailed Engineering, Procurement, Manufacturing or Fabrication, Construction, Start-up, and Operations. These abstract functions are instantiated as participants (individuals and groups) in a particular project. In the original "control by ownership" sense of the term, a vertically integrated organization is a single legal entity which performs several or all of these functions internally.

However, Digital Equipment Corporation's study of the benefits of cross-functional integration (NNI 1989) concludes that the "redesign of processes that cross functional boundaries holds great promise. The cross-functional systems are the next frontier in the pursuit of organizational effectiveness and competitive advantage." The study emphasizes the competitive benefits of achieving this type of integration *at organizational boundaries*.

Therefore, in keeping with the observations of Cole (1952), Williamson (1979), Blair (1983), and Stinchcombe (1985), the measurement of vertical integration used in this study will not distinguish vertical integration accomplished by firm ownership from other methods of control such as binding diverse firms into hierarchical organizations through contractual means. In addition, I have chosen "information flow" rather than "control" in the project as a more useful and measurable basis of analysis for our purpose of achieving a better understanding of the process of developing an industrial facility. Therefore, a "vertically integrated" project is one with a high degree of information and knowledge flow among industry functions (regardless of ownership) during the facility's life cycle. This conception of vertical integration forms the basis of the instrument I develop for its measurement in Chapter 4.

## Flow of Knowledge and Information Between Disciplines: Horizontal Integration

Thomas (1992) portrays horizontal integration between the facility development disciplines of architectural, structural/civil, mechanical/HVAC, plumbing/piping, electrical power, lighting, cost estimating, and project management. This breakdown was shown above in Figure 3.1. He points out that:

> " 'dis-integration' appears to begin at a college or university where students are channeled into specialized fields of study such as architecture, engineering (civil, structural, mechanical, electrical or telecommunications) or construction management. The commercial world... continues this process of channeling professionals into specialized fields through separate companies, organizations, departments, institutes, societies and journals for each field."

This tradition of specialization is also reinforced by certification procedures. To become a licensed engineer in the U. S., a candidate must pass a written examination that tests knowledge in a specialized field such as civil, chemical, or mechanical engineering.

It is interesting to note that Thomas includes the professions of cost estimating and project management as horizontal disciplines. Indeed, just as mechanical and electrical engineering appear as separate departments in large engineering organizations, so too do cost estimating and project management. In this sense, a discipline is any specialized, highly trained professional area required in the successful development of a facility.

Extending the idea of horizontal dis-integration of engineering disciplines, a similar breakdown can be seen within the fabrication and construction functions. Within the fabrication function, different companies handle the manufacturing of architectural, structural, electrical, and mechanical components of facilities. And in the construction function, each discipline has its own craftspeople, unions, and firms.

Much integration research focuses on the sharing of data between disciplines during design. For example, Howard (1989) uses multimodal interfaces to provide engineers with different views of project data depending on the level of detail and type of analysis required at the time. Other work focuses on the interface between the architect and the structural engineer (Fruchter 1992). Often, this type of integration takes the form of the exchange of data between different computer applications, accessing information from common databases, or generating new information (e.g. a cost estimate) using algorithms on existing information (e.g. an intelligent model of the facility).

The word "horizontal" implies that there is no precedence in the ordering of the disciplines, and that each has equal standing. Keidel (1975) defines horizontal integration as " the non-hierarchical linking of [an organization's] parts." Davis (1952) defines the horizontal type of organization "in which two or more similar concerns are combined to perform the same functions in the same stage of distribution or production."

Thus I define a "horizontally integrated" project as one with a high degree of information and knowledge flow between the disciplines or specialties involved in the facility development process. Figure 3.4 depicts horizontal integration between several disciplines in an industrial facility development project. Horizontal integration between firms with substantial engineering work is the basis of the measurement tool for horizontal integration I develop in Chapter 4.

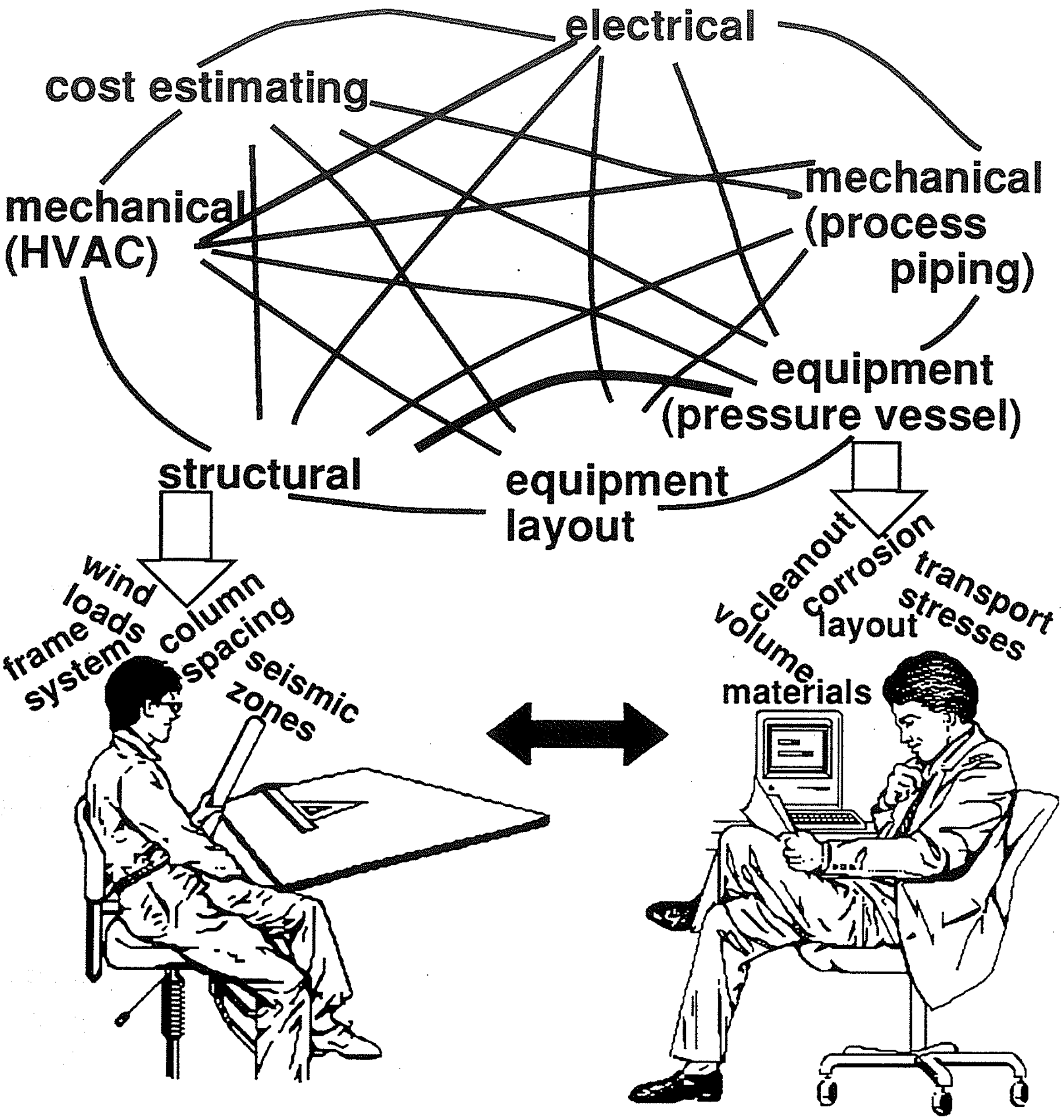

*Figure 3.4. Horizontal integration in the industrial facility development process. Of the many disciplines and specialties, just seven are shown in the network of relationship at the top of the diagram. Information and knowledge flows between them, as represented by the network of freehand curves. Integration between the structural engineer and the pressure vessel designer is highlighted. Each engineer has his or her own concerns which may affect others' designs.*

## Flow of Knowledge and Information Through Time: Longitudinal Integration

Longitudinal[1] integration is the flow of knowledge and information over time. In the development of facilities there are two major time horizons: the within-project time horizon and the project-to-project time horizon. The within-project time horizon concerns the flow of knowledge and information from conception through operation of a facility. The project-to-project time horizon concerns the flow of information and knowledge from prior to current projects, or from current to future projects. The concept of longitudinal integration draws upon three main areas in organizational and manufacturing literature: organizational learning, cycle times, and quality management.

Organizational learning is the process by which organizations retain experiential knowledge. "Organizations are seen as learning by encoding inferences from history into routines that guide behavior... despite turnover and the passage of time" (Levitt 1988). Events which lead to a success or failure for the organization are "remembered" or "encoded" by such techniques as rules, or changing work procedures. Therefore, if a particular type of project has been repeated several times, there supposedly will have been more opportunities for a participating organization to improve its performance by learning.

However, Levitt (1988) also identifies three barriers to learning: paucity of experience, redundancy of experience, and complexity of experience. As a result, organizations do not necessarily interpret experiences in a manner from which sensible rules and procedures can be derived. Therefore, the term "learning" will not be used if the "lessons" are applied inappropriately. This dissertation's definition of longitudinal integration assumes that learning results in the appropriate application of learned knowledge to new (future) situations.

Katz (1982) uses the concept of group longevity as a predictor of project performance in a large research and development organization. His study of 50 groups showed that project performance (as evaluated by managers oversee several projects) peaked between two and five years of group longevity. Lower performance before that was attributed to "an initial learning or building phase," and after that to lack of infusion of new technical knowledge into the group. To apply this concept in the industrial facility development domain, Katz's

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[1] Thanks to Julie Wald for suggesting the use of this term.

results suggest that we measure the prior association among main project participants by means of either duration of association or number of projects worked on together previously.

Longitudinal integration should not be thought of as just the flow of knowledge and information with a beginning and ending point in time, but rather the flow's progression through a repeating cycle. Drawing an analogy between longitudinal integration and the hydrologic cycle helps make this idea clearer. The hydrologic cycle is "the cycle experienced by water in its travel from the ocean, through evaporation, precipitation, percolation, runoff, and return to the ocean" (Lindeburg 1989). Within this cycle, water can be purified, used, and polluted. The cycle is repetitive and continuous over time. Like water in the hydrologic cycle, knowledge and information flows through repetitive work processes in a cyclical fashion. However, unlike water, information and knowledge are not subject to laws of mass balance. Instead, these commodities can grow indefinitely over time.

The length of time from the beginning to the end of one repetition of the work process is the cycle time. The cycle time is an important diagnostic measure in analyzing the efficiency of a work process. Stalk (1988) discusses cycle time as a crucial source of competitive advantage in a manufacturing environment. He proposes that there is a trade-off between product variety and cycle time for both the overall process (e.g. from needs identification to product shipment) as well as each step in the process (e.g. product design): the more variety, the longer the cycle times. Given the same level of product variety, "flexible factories" have shorter cycle times than "focused factories."

Drawing an analogy in the facility development industry, project organizations that repeatedly have designed similar (i.e. less variety in products) facilities can be expected to have shorter cycle times, while those that design dissimilar (i.e. more variety in products) facilities can be expected to have longer cycle times. All other things being equal, shorter cycle times are more desirable than longer cycle times because of the tremendous overhead costs associated with a facility under development. In addition, shorter cycle times might allow more repetitions of a cycle per unit of time. For example, quick generation of preliminary layout designs could lead to more alternative layout designs being generated. The more designs generated, the more likely an optimum layout design would be generated and selected by the owner for further development.

An extension of this idea is that the more complex a particular project, the longer the expected cycle time. For example, one could test the null hypothesis that the percentage of a facility's design incorporating new technology is not correlated with a longer cycle time.

In general, the faster the flow of knowledge and information, the shorter we can expect the cycle time to be because people aren't wasting as much time waiting for information they need to make decisions.

Another relevant idea from manufacturing is that of concurrent engineering: the simultaneous design of the plant and the process to construct it. Though the primary driving force is vertical integration (the functions of engineering and construction being coupled tightly together) a longitudinal integration benefit is achieved as well with a shortening of the overall project cycle time.

Total Quality Management (TQM) has been a popular topic among innumerable authors throughout the world over the past several years. The one key component of TQM is the incremental improvement of work processes using organizational, analytical, and statistical tools appropriate to the task. Processes have suppliers who supply the inputs to the process, customers who consume the outputs of the process, and activities which convert the inputs into outputs. Overall processes can be hierarchically broken down into subprocesses, each with inputs, conversions, and customers. Suppliers and customers can be either internal or external to the organization performing the conversion. Through this chain of suppliers, converters, and customers, an idea is gradually converted to a real facility.

This continuous improvement cycle of "plan, do, check, and act" is repeated every time a new facility is developed. For the overall process of facility development, the first step is to "plan" the process by which the facility will be created. The "do" is the creation of the facility. The "check" step regards evaluation of the process measurements or benchmarks that were made with respect to cycle times, waste, delays, or other process characteristics. Finally, the "act" step calls for changes in the process to increase its efficiency. This plan, do, check, and act cycle also takes place for every subprocess within the overall facility development process. A simplistic portrayal of these cycles is given in Figure 3.5.

The more times a process is the subject of the plan, do, check and act cycle, the greater the expected improvements. The more an engineering, construction, or owner company refines its work processes, the faster and smoother we can expect the flow of knowledge and information through it to be. Faster and smoother flow means better longitudinal integration because this enables the reduction of cycle times. In terms of the fluid analogy, we are smoothing the channel lining (improving the process) to reduce friction and thus reduce turbulence (make smoother) and increase the flow velocity (make faster). This idea of more refined work processes as a source of improved longitudinal integration is at the heart of the measurement tool developed for longitudinal integration in Chapter 4.

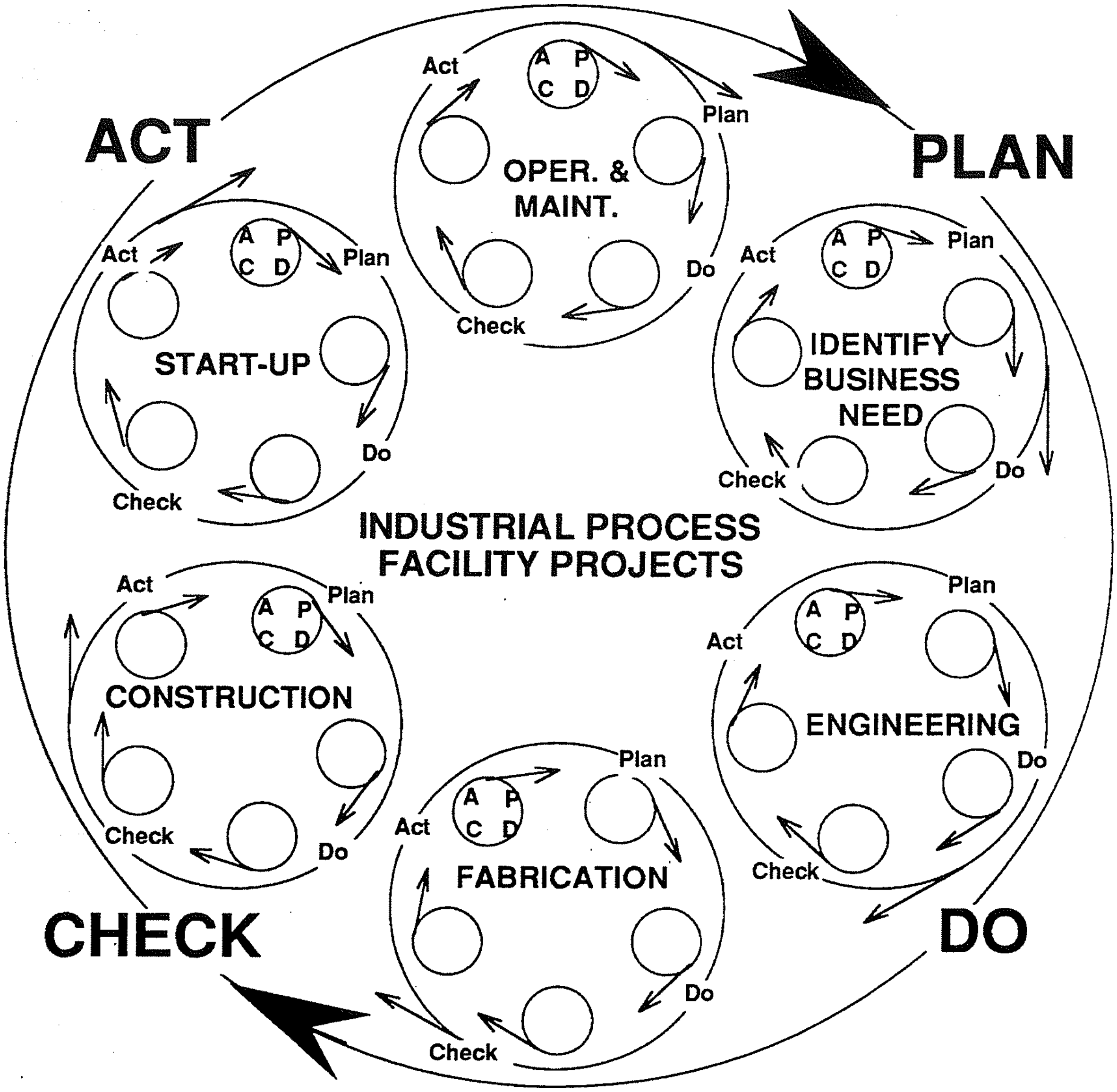

*Figure 3.5. The continuous process improvement cycle in the context of industrial facility development. Drawn by Somroj Vanichvatana.*

Incremental process improvement is similar to organizational learning, except that it adds the idea of repetition. Each conversion activity is repeated over and over again through time. Given the right tools, workers and management are empowered to fine-tune their processes to eliminate waste (such as wasted time) and improve productivity. Matthews (1989), in his CII source document, states that in order for engineering and construction companies to stay in business through the coming years, they must implement TQM.

Simpler, more traditional vehicles for enabling the flow of information through time might be the participation of experienced individuals who carry the data in their minds as they age. Whether project goals are carried forward from project inception through operations might be a function of how many people participate in the formation of the goals. Whether knowledge is perpetuated and honed from project to project might be a function of whether a database is used to store information (Reuss 1993), and whether a debriefing session occurs as each facility development cycle draws to a close.

In summary, longitudinal integration is the flow of knowledge and information through time. Reducing cycle times improves this flow by requiring the identification and reduction of time wasted waiting for information or knowledge needed to progress with the project. Organizational learning and formal process improvement techniques increase this flow by embodying experience, lessons learned, and ideas for improvement in the main facility development process or its subprocesses. This idea forms the basis for the development of a tool for measuring longitudinal integration in Chapter 4.

### Organizational (Humanware) Coordinating Mechanisms

Humanware coordinating mechanisms coordinate the flow of knowledge and information in the three dimensions of integration. Mintzberg (1983) proposes five coordinating mechanisms in organizations that form a "rough order:" mutual adjustment, direct supervision, work processes, output specifications, input skills, followed by a return to mutual adjustment and associated liaison devices. Each of these is used in the facility development process, along with characteristic tools for each type of coordination.

*Mutual adjustment* generally occurs among all project participants and organizations as each understands and internalizes the constraints and goals of the others in accomplishing the development of the facility. Meetings are the primary vehicle for mutual adjustment. An example of *direct supervision* is coordinating manual labor on the job site. *Input skills* (education and training) are very important in both engineering and construction subprocesses. *Output specifications* in the form of plan specifications are depended upon heavily throughout design and construction. *Work processes* are designed in the sense that they are planned in advance by scheduling tools and standardized procedures for tasks such as plan checking. At some level of organizational complexity, even the best work processes are no longer capable of coordinating information flow. At this point, we return to the mechanism of *mutual adjustment*. Although Mintzberg considers these mechanisms to take a rough order, we cannot assume that the order is the same for each of the three dimensions of integration[2]. Therefore, for the purposes of our framework we will simply consider these as categories of coordination, as shown in Figure 3.6. A possible criterion for ordering the coordination mechanisms might be their degree of complexity, from simple to sophisticated, based on their difficulty or cost of implementation. As future research in this area progresses, perhaps this idea can contribute to the elaboration of the three dimensions.

Another emerging concept is implicit coordination, that through a combination of common experiences and education, people can intuitively anticipate the actions or needs of other participants in accomplishing a shared goal (Kleinman 1992). An example of the use of implicit coordination is the skilled team of surgeons who have performed many operations together. Very little overt communication is required because each anticipates the others' actions and needs. However, there is a very high dollar cost to forming, training, and maintaining this team.

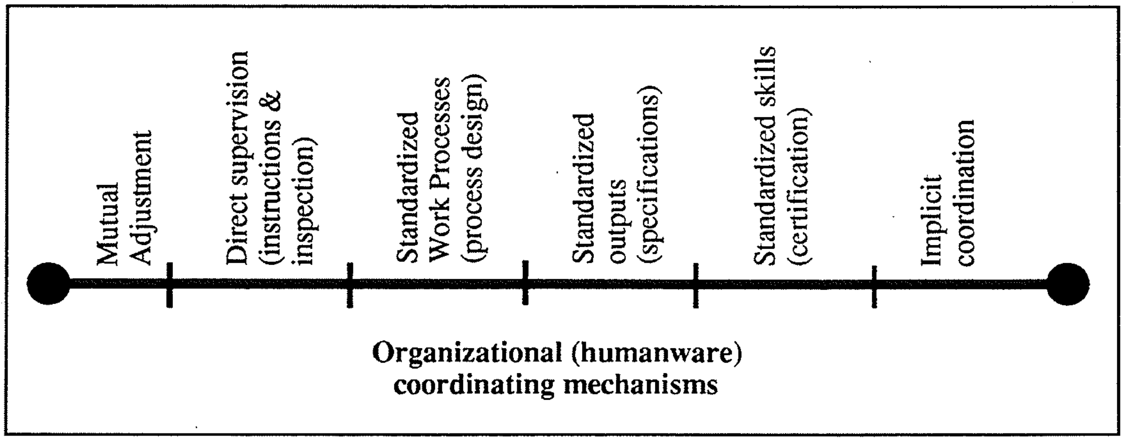

*Figure 3.6. Organizational means of coordination. Categories of humanware coordinating mechanisms. Based on Mintzberg (1983).*

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[2] Thanks to Tore Christiansen for pointing this out.

*The matrix organization:* No discussion of organizational coordinating mechanisms would be complete without mention of the matrix organization. The matrix as a form of organizational structure is discussed by Davis (1977), Mintzberg (1983), and Savage (1990), among others. The objective of the matrix is to force a balance of decision making power between conflicting organizing principles of traditional hierarchical structures by having more than one reporting chain, that is, one to each axis of the matrix. Such organizing principles include *functions* (i.e. marketing, finance, engineering, construction, operations, etc.), *products* (i.e., dams, treatment plants, power plants, etc.), *projects* (i.e. Alaska Pipeline, Chemical Plant X, Pulp Mill Y, etc.), or *geographic regions* (i.e. northwest United States, southwest United States, Europe, Asia, etc.), to name a few. Industry functions are not generally used as a basis of matrix organization because typically only one or two industry functions lie within a single firm. A form seen in facility engineering companies is the balancing of projects against technologies (disciplines). This form makes business sense because it fosters a client focus (projects) while ensuring engineering integrity (technology). Using mutual adjustment, decisions are optimized (rather than just made) by forcing resolution of conflicts between technological and client concerns.

The contribution of specific organizational coordination mechanisms to enhancing vertical, horizontal, and longitudinal integration is not analyzed in this study because the development of this concept is too immature. However, the integration framework includes this concept in its structure. Ideal measurement tools for vertical, horizontal, and longitudinal integration would tap aspects of both the organizational mechanisms of coordination discussed above as well as the technical mechanisms of coordination discussed in the next section. The measurement tools I develop in Chapter 4 aim to meet this ideal.

## Technical (Hardware and Software) Coordinating Mechanisms

Technical integration can be defined as the facilitation of knowledge and information flow by the use of hardware and software tools as coordinating mechanisms, as presented in Figure 3.7. As with organizational integration, the mechanisms are categories only, though a possible ordering criterion is difficulty, or up-front cost, of implementation. The categories range from language, letters, email, 2D models, etc. to the actual plant itself.

Future research in this area could develop a sequence of technical coordinating mechanisms for each of the three (vertical, horizontal, and longitudinal) dimensions of integration.

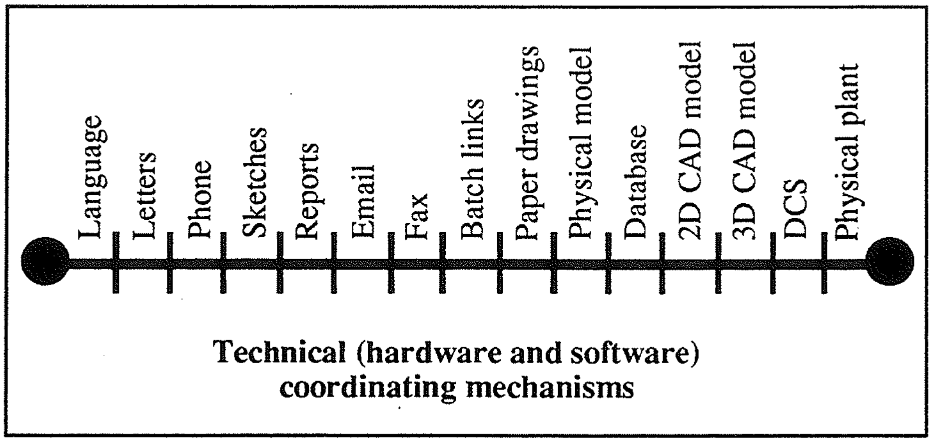


*Figure 3.7. Technical means of coordination. Unordered categories of hardware and software coordinating mechanisms.*

Mintzberg (1983) distinguishes between technology and technical system. To Mintzberg, technology is the knowledge base of the organization, and the technical system is the set of instruments used in the operations of a company. "Accountants, for example, apply a relatively complex technology (that is, the base of knowledge), with a very simple technical system — often no more than a sharp pencil." In my framework, Mintzberg's "technology" is equivalent to our "knowledge and information," and his "technical system" is equivalent to my "technical coordinating mechanisms."

Savage (1990) argues that connectivity and interfacing are necessary but not sufficient conditions for integration. He uses the following example to demonstrate the importance of agreed upon definitions and context:

> "... it is possible for me to call someone in a foreign country. [Suppose the person answering the phone]... speaks English, even in a faltering way... [and] says, 'I see a bear out my window.' If I were to reply, 'I'd love to see a bear, please shoot it for me,' what should I expect to get in the mail? A snapshot of the bear, or a stuffed bear? The telephone line provides connectivity, and I can interface using the language, but integration comes when there is an agreed-upon set of definitions and the context is understood."

Thus, the categories in Figure 3.7 simply name the technical tools being used; they do not *a priori* guarantee the quality or amount of information and knowledge that flows. However, a testable hypothesis is whether there is an association between the sophistication of technology used and the richness and usefulness of information and knowledge being transmitted.

Cohen (1992) discusses "natural idioms" as attributes of communication tools in his simulation model of the performance of a virtual design team (VDT). Natural idioms include words, schematics, plans, drawings, numbers, and letters. Each type of information processing tool (face-to-face meetings, electronic transfers, physical transfers) has a different ranking of these idioms in terms of their capacity to transmit *richness* or *cognitive complexity* of information in the context of that tool. The match between the idiom and the actors' capabilities, together with the priority of the design decision to be made, combine to determine the information processing tool that will be used to address a design decision. This conception of differential ordering of the coordination mechanisms as a function of context will be an important consideration in future development of the technical coordination mechanisms component of the integration framework.

Though Quality Function Deployment (QFD) was not used by any of the projects included in this study, it does bear mentioning in the context of technical integration. The QFD, or "House of Quality" (Hauser 1988) (Akao 1990) technique is a structured tool for identifying the need to pass information between functions, between disciplines, and through time, and revealing areas where conflicts exist that are in need of a trade-off or other resolution decision. Akao calls QFD a method for "integrating customer requirements into process design." Starting with very explicit knowledge about the customer's requirements and customer evaluations of alternatives, engineering requirements are matched to customer requirements in a matrix format. Relationships of the customer requirements to the engineering requirements, and each engineering requirement to every other engineering requirement are evaluated as having either a positive or negative relationship. For example, a customer requirement for a car door that is easy to close has a negative relationship with the door seal resistance that was included in the design to prevent rain leakage (Hauser 1988).

QFD is an elegant and apparently effective method for increasing integration in the process of creating relatively standardized manufactured products like cars and camcorders. Akao (1990) describes Taisei's and Shimizu's use of QFD in the design and layout of standardized prefabricated and multiple-family dwellings. However, in the context of non-standard industrial facilities, it is questionable whether QFD would be viable. Many more cars and camcorders than complex industrial facilities are produced on the basis of a single QFD undertaking, even though the scope of the QFD analysis might be similar. My estimate is that a complex industrial facility might involve 10,000 customer requirements and 10,000 engineering requirements which would generate one matrix with $10^8$ cells and one with $10^8/2$ cells to be evaluated in just the first step of the QFD process. This may be too many relationships to justify the analysis if the results are relevant only to a single, non-standard facility. Perhaps a larger level of granularity could be used, though this could possibly detract from the technique's usefulness. Another uncertainty regarding its applicability is its ability to manage the requirements of the *multiple* customers of an industrial facility in contrast to the *individual* consumers of manufactured products.

QFD's applicability as a technical coordinating mechanism for facility development is a promising and worthwhile area of research. The CII has recently published a summary of interviews with four companies in manufacturing and service industries, and have derived a set of issues affecting the applicability of QFD to engineering and construction (Oswald 1992). In the virtual design team (VDT) performance simulation model, Christiansen (1992) has implemented QFD to evaluate design task and information dependencies for two types of standardized industrial projects. The first implementation is an electrical substation and the second is a subsea satellite for oil production. The satellite application uses three matrices, each $35^2$ cells in size. His application bodes well for future experimental applications and increased understanding regarding the costs and effects of coordinating the flow of knowledge and information in this manner.

## A FRAMEWORK OF INTEGRATION IN INDUSTRIAL FACILITY DEVELOPMENT

We have now reviewed the origins, definitions, and some operational issues for five aspects of integration in the industrial facility development process. These occupy three primary dimensions (vertical, horizontal, and longitudinal), each of which can be further described by two sets of coordinating mechanisms (organizational and technical). Although the founding ideas for each of these five components were well established in the literature, their fragmentation prevented researchers from using them as a basis of analysis for the facility development process as a whole. Creating a new synthesis of these components results in the framework shown in Figure 3.8.

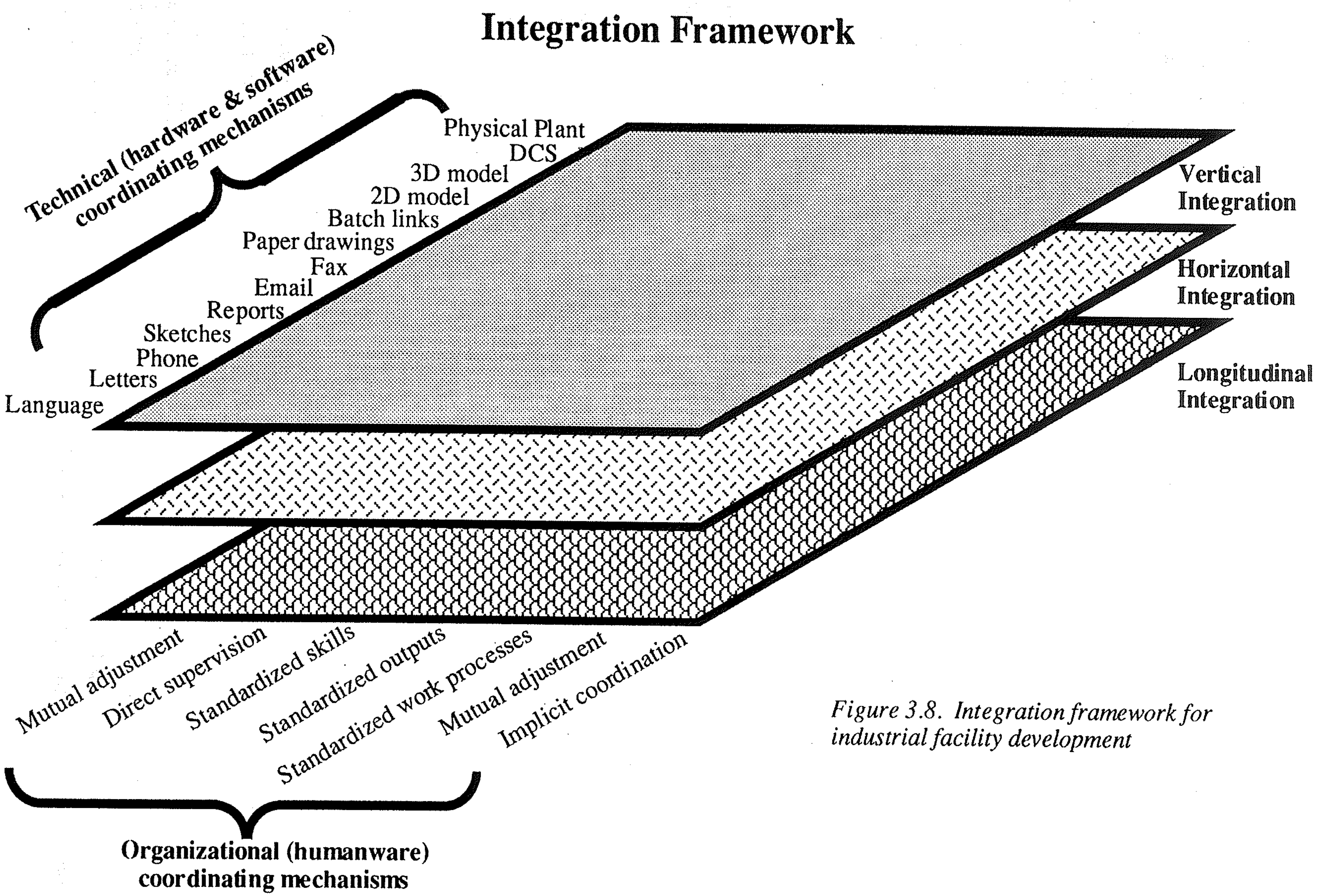


*Figure 3.8. Integration framework for industrial facility development*

One issue with the framework is the distinction between vertical and longitudinal integration. I prefer to think of vertical integration as strictly between functions, not between time phases. Time dependencies in information flow are issues of longitudinal integration. I think it is important to break vertical and longitudinal integration apart like this rather than treating them as a single dimension because in a single dimension the effects of integration over time and between functions are confounded. However, it is more natural for people with long experience in the engineering and construction industry to think of vertical integration as between phases, where phases are dominant activities over a certain duration. This issue indicates that the two dimensions are likely to be somewhat correlated.

### The challenge of a dynamic project organization

In the context of superprojects, Levitt (1984) discusses the importance of recognizing that the structure of project organizations needs to change as projects move from inception to completion because successive stages of completion have different coordination needs. His general sense is that design is composed of reciprocally interdependent tasks requiring sophisticated coordination techniques such as mutual adjustment, whereas construction's sequentially interdependent tasks require less sophisticated techniques such as direct supervision. Levitt challenges researchers to increase their understanding of existing organizational forms and to define new forms that better address coordination of design and construction. It is this type of research challenge that the proposed framework, with additional development, may enable future researchers to address, by relating variables in the longitudinal and vertical dimensions with organizational means of coordination. Ordering the coordination mode components (e.g. in terms of cost of implementation) may enable us to gain a more structured understanding of the tradeoffs between more expensive coordination techniques and the benefits of improved facility quality.

### Coordination theory as an alternative framework

The literature on coordination theory provides a different, though not incompatible, framework for analyzing complex processes. Malone (1991) defines coordination as "the act of managing interdependencies between activities" to achieve goals. Several types of interdependencies are identified, including resource interdependencies and timing interdependencies. A key difference between coordination theory and the integration framework presented above is that coordination theory focuses on optimization of decision making, whereas this framework focuses on gross information flow. As elegant as coordination theory is, the level of detailed observation that would be required in an empirical study founded on coordination theory is not compatible with the level of analysis or scope of this study. In the domain of facility engineering, possibly hundreds of thousands of decisions are made in the course of the development of a single facility, numbers which make impractical the application of this theory in this case.

### The framework of integration in the context of prior work

Throughout this chapter I have discussed the work of many researchers in the domain of facility development who have addressed the issue of integration. From this diverse body of literature I have demonstrated the requirement for a unifying, cohesive integration framework. I described how elements from these diverse studies are encompassed in the new framework. This framework accommodates and extends the breadth of issues addressed by prior researchers by defining and incorporating vertical, horizontal, and longitudinal integration, and to a lesser extent, technical and organizational integration. In summary, Figure 3.9 places the new framework (shown at the right side of the figure) in the context of other researchers in the field of engineering and construction management.

**Researcher and Year**

| Integration Component | Williamson (1979)<br>Stinchcombe (1985) | Vanegas (1988) | Fischer (1989) | Williams (1990) | Sanvido (1990) | Fruchter, Khedro, others (1990-92) | Thomas (1991) | Tatum, Nam (1989) (1992) | Koskela (1992) | Cohen (1992)<br>Christiansen (1992) | Fischer, Kunz (1993) | Teicholz, Fischer (1993) | Fergusson (1993) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Vertical** | XX | XX | XX | XX | XX |  | X | X | X |  | X | X | XX |
| **Horizontal** |  | X | X |  | X | XX | XX |  |  | XX | XX | X | XX |
| **Longitudinal** |  |  |  |  |  |  |  | X | XX |  | X | X | XX |
| **Organizational** | XX |  |  | XX |  |  |  | XX | XX | XX |  | X | X |
| **Technical** |  |  | XX | XX |  | XX |  | XX | X | XX | XX | XX | X |

**Legend:**
X = weak emphasis
XX = strong emphasis

*Figure 3.9. The three integration dimensions and two modes of coordination, as defined in this study, have been addressed by several prior researchers in the field of engineering and construction management. The column on the right demonstrates the breadth of integration components addressed by the integration framework developed in this chapter.*

In addition to drawing from the background literature in engineering and construction, I have also tied the definitions of the dimensions of integration to their roots in organization and economics theory, manufacturing, and quality management. This synthesis is demonstrated in Figure 3.10.

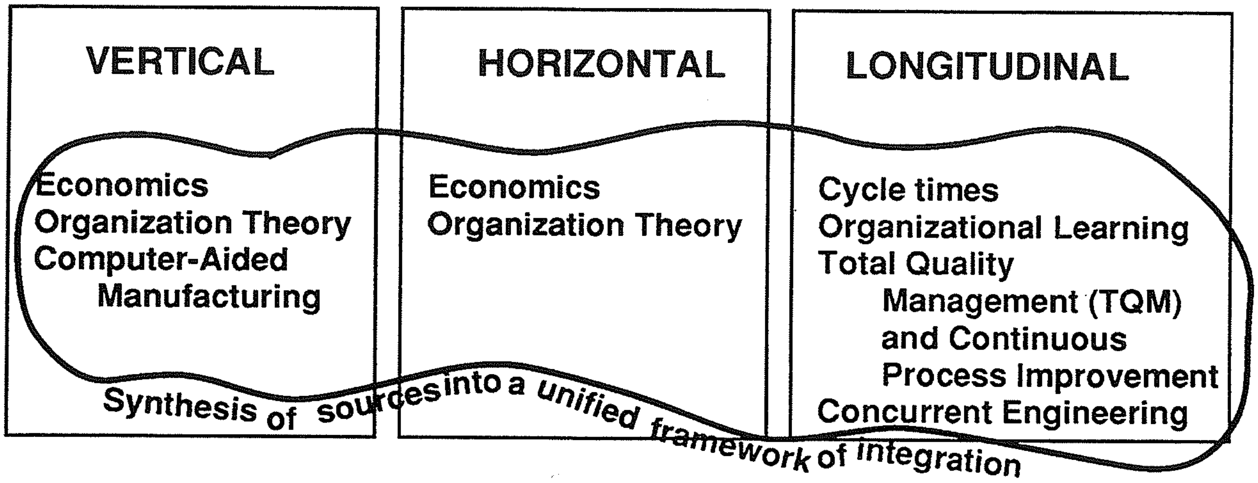


*Figure 3.10. In addition to drawing from the engineering and construction literature, the integration framework synthesizes ideas from economics and organization theory, manufacturing, and quality management.*

The industrial facility quality characteristics developed in Chapter 2 and the integration framework developed in this chapter will form the basis for the design of the measurement instruments for quality and integration described in the next chapter. Chapter 4 begins with descriptions of overall methodological approaches to research, followed by creation of the measurement instruments for quality and integration data collection. Next, the development and validation of summary measures are described. Then my overall modeling approach is presented, and the advantages in this context of using a structured integration framework. The chapter concludes by describing the advantages and disadvantages of the study's design.

# *Chapter 4 — Methodology*

This chapter is divided into six parts. The introduction discusses how to create and measure a concept. The second part addresses how facility quality, defined as customer satisfaction with the completed facility, is measured in this study. The third part describes how vertical, horizontal, and longitudinal integration are measured. Fourth, I discuss several methods of creating summary measures. Next, I give some background regarding the statistical model that is used in chapter 6 to predict industrial facility quality from integration measurements. Finally, I describe the overall design of this study, the samples of owner representatives and industrial facilities selected, as well as how I mitigated potential sources of bias resulting from these choices.

## CREATING AND MEASURING CONCEPTS

There are two main concepts in this study; facility quality and integration. The definition and measurement of these concepts is a substantial part of this research effort. Chaffee (1991) and Cacioppo (1982) provide methodological underpinnings for concept creation and measurement, the first by means of explication theory, the second by means of example.

In his book *Explication*, Chaffee (1991) describes the process of scholarly research. Concept explication is the purpose of such research. In the creation of a concept, one usually starts with a loose or fuzzy idea. Through an iterative cycle of interrelated steps, the concept is gradually detailed and refined until it reaches a point of stable usage in the scholarly literature. In this process, knowledge is generated. Explication of a concept is not completed over the course of a single study; rather it is pursued over an evolving course of research.

The first step in the cycle is the identification of an interesting, though perhaps ill-defined or fuzzy idea or term. At some level, the researcher should be able to think of it as a variable. Through a literature review which reveals the historical origins and evolutionary path that this and related ideas or terms have taken through time, the investigator tentatively chooses a particular characterization of the concept that best suits the goals of the research. The literature should be sorted and categorized to reveal meaningful divisions in types of studies. Meaning analysis of the tentative concept is accomplished either by *distillation* or by *list creation.*

The next, and perhaps most difficult step is the creation of an empirical definition of the concept which provides the link between the world of ideas and the world of observation. This process of "operationalization" is the creation of measures. There are often compromises made at this stage. For example, one might only be able to develop a measure for part of a concept. Often, one develops "auxiliary theories" to link implementable measures with the concept of interest. In parallel with developing the measures, statistical models that reflect the structure of the theory are identified for use in data analysis. The definition of the concept is reviewed and perhaps modified at this stage, based on several judgments regarding the specificity of the definition, and again, usage of key terms in the literature. The appropriate operational procedures, or study designs, are examined next, with the objective of ensuring that the type of study undertaken (laboratory experiment, longitudinal study, survey, etc.) can be expected to capture the variation that the researcher wishes to observe. Once data collection is complete, the operational procedure is evaluated as to whether it contributed to or hindered the observation of variation. Finally, validation and reliability assessment of the concept's operational definition occurs.

This cycle should not be considered a series of linearly linked steps, but rather an interconnected web of intellectual challenges with feed-forward and feedback loops connecting many of the stages. The process of explication occurs gradually over the course of a program of research. In a single study, one can expect to address several but not all of the stages of concept explication. In summary, a concept is an interesting idea at the focus of a research effort. Over the course of literature review, creation of measures, study design, data collection, statistical analysis and modeling, and the initiation of further studies, the idea achieves better definition of what it is and what it is not. In the process, the explanatory power of the concept increases, and knowledge is generated.

Operationalization of a concept means the creation of instruments to enable structured observation of the world, with the intent of gathering data in experiments or in natural settings in order to test hypotheses about the concept. Measurement is the use of these instruments to gather data. In order to claim that a concept can be measured using a particular instrument, one ought to implement and test it in a series of several different studies. Cacioppo and Petty (1982), in their psychology studies of the "need for cognition

(i. e. the tendency for an individual to engage in and enjoy thinking)," provide researchers with an excellent model of how to measure a concept. In a series of four studies, the authors demonstrate that a concept, the need for cognition, exists and can be measured. Using a series of increasingly sophisticated study designs, the authors gradually refine and validate their concept to the point that the reader is convinced of its existence and importance in explaining human behavior. In the first study, they use a questionnaire-style instrument containing a list of items that on their face seem likely to differentiate between people with high and low needs for cognition. Their subjects fall into two groups of people that are assumed to differ on the concept: a group of university professors, and a group of factory assembly line workers. After gathering the data, they select items to include in further studies that differentiate well between the groups, and perform a factor analysis which shows that these items load on a single factor. They create a summary scale composed of these items. In the second study, the items are administered to a more homogenous group, and the factor loadings of the items in the second study are compared to the loadings in the first study to show their similarity in structure. In addition, correlations of the need for cognition scale with measures of other concepts are shown to be coherent. For example, general intelligence had a significant but weak correlation with the need for cognition, while test anxiety did not. In the third study, the need for cognition again correlates weakly with intelligence, and has a negative correlation with dogmatism, or close-mindedness. In the fourth study, students were given two number-circling tasks, one with difficult instructions, and one with easy instructions, then the subjects were asked about their enjoyment of the respective tasks. In addition, the measures from the previous studies were replicated.

I derive three key lessons from Cacioppo and Petty's methodology. As well as attempting to replicate prior results, subsequent studies should use additional measures to broaden the scope of related phenomena that can be explained by the concept. In this way, the bounds of knowledge surrounding a concept are gradually expanded. Secondly, studies that concern the same concept should employ different designs and respondent groups to ensure that replicated results are not an artifact of the design. Finally, a list of items administered in questionnaire format to different groups of respondents is a good starting point for selecting items to include in a summary statistic.

Both Chaffee and Cacioppo and Petty serve as ideal models for quantitative research of fledging concepts. In Chapters 2 and 3, for quality and integration respectively, I addressed the first several steps of Chaffee's process of explication from the selection of a focal concept through meaning analysis. The meaning analysis for facility quality was accomplished by means of *list generation*, and for integration by *distillation*. The remainder of this methodology chapter describes the operationalization and measurement of these concepts, as well as appropriate statistical summaries and models for analyzing the data.

## MEASUREMENT OF CUSTOMER SATISFACTION

Chapter 2 established a definition for industrial facility quality as customer satisfaction with the completed facility. But how can customer satisfaction be measured? Traditional attributes that engineers are accustomed to measuring such as dimension, weight, ductility, cost and duration cannot be easily translated to the realm of measuring human attitudes toward facility quality. Instead, we may defer to expertise developed in the fields of sociology and psychology on attitude measurement.

Dawes (1985) gives an enlightening overview of the many approaches to attitude measurement, distinguishing between representational and nonrepresentational techniques. Representational methods include magnitude techniques such as Thurstone's paired comparisons (Thurstone 1928), interlocking techniques such as Guttman scaling (Guttman 1944), proximity techniques, and unfolding techniques. These techniques attempt to represent both the orders and specific consistent distances on a scale between different observed behaviors or objects. On the other hand, nonrepresentational measurement is not based on the assumption of consistent distances between points on a scale. For example, the interpreted distance between 2 and 3 on a Likert scale (nonrepresentational) may vary from person to person and may be influenced by the item being measured. In contrast, the difference between 2 and 3 ounces on a balance scale (representational) is consistent regardless of who performs the measurement and what type of item is being measured on the scale.

Importantly, nonrepresentational measures, like representational ones, have been shown to demonstrate both internal and external predictability. Internal predictability refers to the ability to replicate results on similar scale, and external predictability is the capacity to "predict dissimilar behaviors (e.g. from rating scale responses to voting). Hence the basis for all measurement is empirical prediction" (Dawes 1985). Seiler (1970) concludes that the external predictability of representational (Thurstone scale) versus nonrepresentational

(Likert Scale) is comparable. Indeed, Likert himself argued, and other studies have verified, that his scale meets or surpasses the reliability of the Thurstone method with greatly reduced effort and fewer statistical assumptions (Likert 1932) (Seiler 1970).

The semantic differential technique is a heavily used nonrepresentational measurement method in the fields of sociology and psychology, but is used in a limited form in marketing research. Osgood (1957) developed the semantic differential as a by-product of investigating semantic meaning. His research determined that simple equal-appearing-interval rating scales with bipolar adjectives as anchors (e.g. good-bad, hot-cold, beautiful-ugly) could be used to capture the meaning of semantic objects. Furthermore, his research identified three clear dimensions of meaning: 1) evaluative, 2) potency, and 3) activity. Pure rating scales along these dimensions (such as good-bad for evaluative, powerful-powerless for potency, and active-passive for activity) can economically and reliably capture the essence of a person's attitude toward an object (Heise 1970). Developed in the 1950s, semantic differential rating scales soon became enormously popular among attitude researchers (Summers 1970), and continue in their popularity today.

The evolution and refinement of attitude measurement evident in the above discussion forms the basis for this study's implementation of the measurement of customer attitudes.

## Operationalization of Industrial Facility Quality Concept

To measure attitudes about industrial facility quality, the semantic differential scale was chosen for this study because of its simplicity and flexibility. As Ventre (1990) points out, there is a tradeoff between elegance of measurement and the applicability of a measurement method. One of the goals of this study is to produce results that are immediately applicable to current practice by EPC professionals and facility owners. A straightforward, easily understandable technique is required in this context, even if the trade-off involves the possible introduction of some random error into the data. The semantic differential scale introduces some error into the data by assuming an interval scale, rather than an ordinal scale. At worst, this type of error will cause us to find a statistically non-significant result when a true effect exists in reality (Type II error). This is therefore a very conservative approach, as Bohrnstedt (1970) attests:

> "By assuming interval measurement where only ordinal measurement exists, some measurement errors will occur. The result of errors generally is the attenuation of relations among variables. That is, one's apparent results will be more attenuated than they are in reality. Thus, it is unlikely that the decision to assume interval measurement when it does not exist will lead to the spurious overestimation of results."

It was recognized at the inception of this study that the concept of industrial facility quality was highly complex and composed of many underlying factors. Indeed, (Garvin 1984) identifies no less than eight dimensions of manufactured product quality: performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality. Although our concept of industrial facility quality does not necessarily align with Garvin's eight dimensions, it is made even more complex by the fact that there are several, perhaps many, customers of a single facility, each with different priorities and varying roles in the facility development process.

The strategy for capturing this complexity is based on the notion that each individual has a different conception of industrial facility quality as shown schematically in Figure 4.1, which is an adaptation of a Venn Diagram (Tabachnick 1989). The concept of quality for each person is shown as a large circle. Overlapping the large circle are ovals representing facility characteristics. The fraction of the circle's area that is overlapped by each oval is an indication of how important that characteristic is to the person's overall concept of the facility's quality. Measurement error, which is discussed in the Additive Index Creation section later in this chapter, is represented by the portion of the ovals lying outside the large circle.

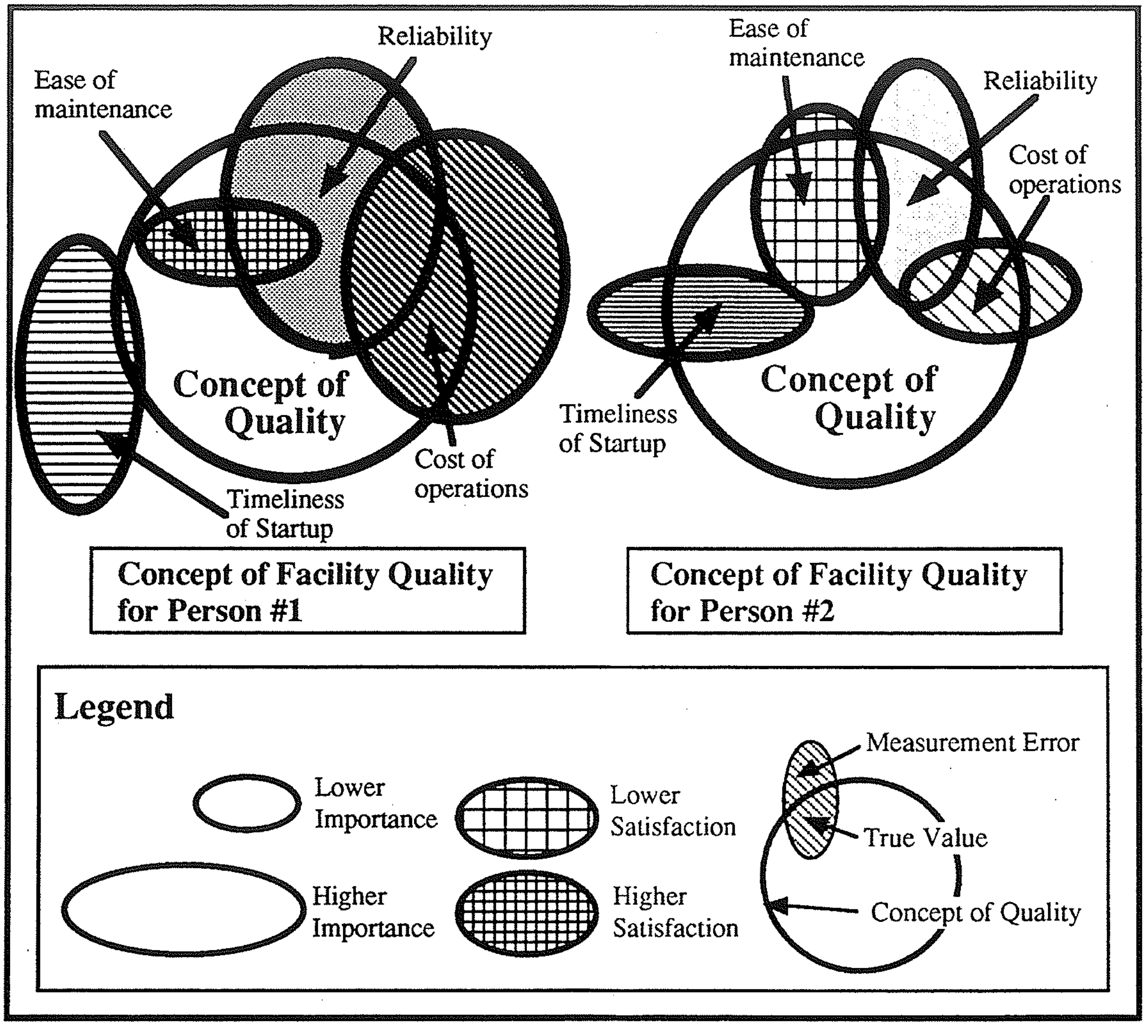


*Figure 4.1. Schematic Representation of Concept of Quality. Each large circle represents a hypothetical individual's concept of industrial facility quality. Ovals represent facility characteristics which comprise that individual's concept. The fraction of a circle's area that is overlapped by each oval indicates how important that characteristic is to the person's overall concept of facility quality.*

To implement a measurement system, we utilized the list of industrial facility characteristics presented in Table 2.A of Chapter 2. Table 2.A is a comprehensive enumeration of useful product attributes that together comprise the concept of industrial facility quality. These items were used as the quality characteristics (semantic objects) that were rated by respondents in owner organizations. The clarity and completeness of the items in Table 2.A was validated during the administration of the questionnaire by requesting respondents to point out items they felt were ambiguous, and to write in additional characteristics upon which they judged the quality of their facility. Three adjustments were made to the list on this basis, as detailed in Appendix A.

Two semantic differential rating scales were constructed for each characteristic as shown in Figure 4.2. One rating scale measured the evaluative dimension of the characteristic (low satisfaction-high satisfaction), and the other measured the potency of the characteristic (low importance-high importance). Since an industrial facility is inanimate, the action dimension of meaning was deemed irrelevant and was not measured. My approach differs from the approach taught in marketing research (Kinnear 1983) (Tull 1987) because I attempt to measure not only the evaluative dimension of owner attitudes, but the potency dimension as well.

To visualize these dimensions in terms of Figure 4.1, the importance dimension is the relative size of each oval. The satisfaction dimension is pattern intensity, where a perfectly satisfying characteristic is completely black. For example, "ease of maintenance" is more important to person #2 than to person #1, but person #1 is more satisfied with "ease of maintenance" than person #2. Statistical variance of importance items can be thought of as the diversity in oval sizes from person to person on the same characteristic. Similarly, statistical variance of satisfaction items is the diversity of pattern intensities from person to person on the same characteristic. Statistical correlation between two characteristics is consistency in the relative size of the two ovals from person to person for importance characteristics, or consistency in the relative pattern intensities from person to person on satisfaction characteristics.

**Profitability of Plant**

| Importance Scale | | | | | Satisfaction Scale | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| (low) | | | | (high) | (low) | | | | (high) |

*Figure 4.2. Two Semantic Differential Scales for the Semantic Object "Profitability of Plant." Respondents in owner organizations rated semantic objects such as "Profitability of Plant" on the importance and satisfaction scales shown above. The importance scale measures the potency dimension of the object's meaning, while the satisfaction scale measures the evaluative dimension of meaning.*

## MEASUREMENT OF INTEGRATION

In Chapter 3, I derived an integration framework composed of the main subconcepts of integration: vertical, horizontal, and longitudinal, each having organizational and technical coordination mechanisms. The subconcepts were synthesized from organization theory and economics, as well as prior work in the field of engineering and construction project management. This section describes how these subconcepts were transformed into three practical measurement instruments to gather vertical, horizontal, and longitudinal integration data, respectively, from industrial facility projects. Additional measures for these subconcepts are presented in Appendix A. Several of these measures were used for validation efforts, and the remainder are reserved for future analysis. The three measurement instruments presented below were selected for the analysis of the impact of integration on industrial facility quality presented in Chapter 6.

### Vertical Integration

Vertical integration is the flow of knowledge and information between project functions. The first challenge to overcome in creating a measurement instrument of vertical integration is to make these abstract functions identifiable to respondents. People are not accustomed to thinking of the facility development process in terms of functions, so it is important to provide them with familiar manifestations of these functions. In order to approximate the hypothesized concept of *knowledge and information flow between functions* in the facility development process, the measurement instrument focuses on *knowledge and information flow between the project participants* that are most closely associated with the functions.

The functions in the facility development process discussed in Chapter 3 included strategic business planning, engineering, permitting, manufacturing and fabrication, construction, start-up, and operations. The main participants representing these functions are the owner project management team, the prime engineering design organization, engineering subcontractors, the equipment and material vendors, regulatory agencies, the construction project management firm, the prime construction contractor, the construction subcontractors, and the operations and maintenance group in the owner organization. The link between which participant performs which function is not clear cut, and indeed the greater the vertical integration on a project, the more blurred the distinctions will be between participant and function.

Every one of these nine participant groups are not necessarily present for every project because project structures vary. Each project has unique factors such as contracting strategy, scope, objectives, and owner preferences which influence the project structure and hence the presence or absence of particular participants. For example, some projects have no construction project manager firm; others have no engineering subcontractors or no prime construction contractor. Therefore, the instrument for measuring information flow between these nine entities must be flexible enough to accommodate all possible project structures.

To accomplish this, a matrix was created which juxtaposed each participant with the other eight participants. Each pair of participants thus created can be thought of as a relationship in which knowledge and information flowed between the two participants in some manner. The maximum total number of potential relationships was 36 if all nine participant groups were represented in the project structure. This is because a 9 x 9 matrix yields 81 intersections, but 9 of these intersections pair participants with themselves, so they are not counted. Of the remaining 72 pairs, half are duplicates, which are also not counted, yielding a total of 36. Thus the formula to determine the number of relationships, R, from the number of participants, n, is:

$$\mathbf{R} = \frac{\mathbf{n^2 - n}}{\mathbf{2}} \qquad (4.1)$$

This equation parallels Galbraith's (1977) formula for the number of communication channels between individuals in a non-hierarchical organization.

When presented with the matrix, the respondent's first task was to determine if one (or more) of the nine participants listed was not represented in the respondent's project. If so, all relationships involving this participant were eliminated from consideration, resulting in a reduction in the total number of relationships to 28 if there are eight participants[1], or 21 if there are seven participants[2].

Then, for each remaining relationship, the respondent was asked to make two simple ratings. First, the respondent was asked, "For a *hypothetical* project of this type and with

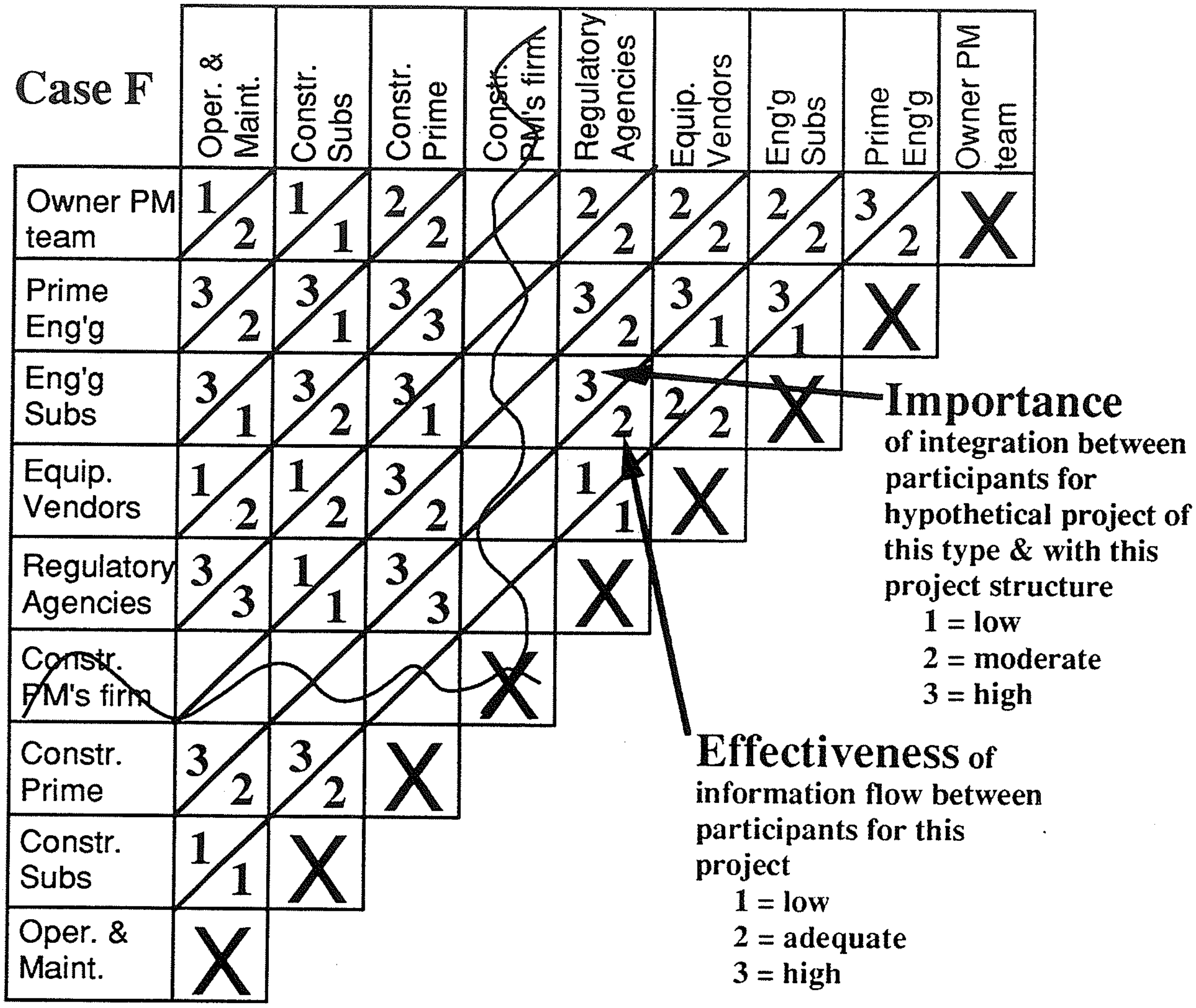
---

[1] $(8^2 - 8)/2 = 28$

[2] $(7^2 - 7)/2 = 21$

this project structure, how *important* is the integration (defined as the sharing of knowledge and information by technical and organizational means) between each pair of participants?" The ratings for this item were *low importance* (1), *moderate importance* (2), and *high importance* (3). Next, the respondent was asked, "For this *particular* project, how *effective* was the integration between each pair of participants?" The ratings for this item were *low effectiveness* (1), *adequate effectiveness* (2), and *high effectiveness* (3). The purpose of asking the respondent to think in terms of a *hypothetical* project for the importance rating was to minimize the influence of the respondent's hindsight on the importance rating. An example of the measurement instrument and the response for Case F is shown in Figure 4.3.

This matrix instrument was used to collect vertical integration data from one to four people in the project organization. In order to provide as consistent a viewpoint as possible across cases, I chose to use the responses given by the operations managers in the analysis of the vertical integration data. However, in five cases data were not collected from this participant, so the data from a surrogate respondent as close as possible in job function to the operations manager were used.



**Case F**

| | Oper. & Maint. | Constr. Subs | Constr. Prime | ~~Constr. PM's firm~~ | Regulatory Agencies | Equip. Vendors | Eng'g Subs | Prime Eng'g | Owner PM team |
|---|---|---|---|---|---|---|---|---|---|
| Owner PM team | 1 / 2 | 1 / 1 | 2 / 2 | | 2 / 2 | 2 / 2 | 2 / 2 | 3 / 2 | X |
| Prime Eng'g | 3 / 2 | 3 / 1 | 3 / 3 | | 3 / 2 | 3 / 1 | 3 / 1 | X | |
| Eng'g Subs | 3 / 1 | 3 / 2 | 3 / 1 | | 3 / 2 | 2 / 2 | X | | |
| Equip. Vendors | 1 / 2 | 1 / 2 | 3 / 2 | | 1 / 1 | X | | | |
| Regulatory Agencies | 3 / 3 | 1 / 1 | 3 / 3 | | X | | | | |
| ~~Constr. PM's firm~~ | | | | X | | | | | |
| Constr. Prime | 3 / 2 | 3 / 2 | X | | | | | | |
| Constr. Subs | 1 / 1 | X | | | | | | | |
| Oper. & Maint. | X | | | | | | | | |

**Importance** of integration between participants for hypothetical project of this type & with this project structure
1 = low
2 = moderate
3 = high

**Effectiveness** of information flow between participants for this project
1 = low
2 = adequate
3 = high

*Figure 4.3. Measurement instrument for vertical integration and responses for Case F. The respondent indicated that no Construction Project Management (CPM) firm participated in this project, so all relationships involving the CPM firm were eliminated from consideration. The remaining relationships were rated in terms of the importance and effectiveness of knowledge and information sharing between the two participants.*

## Horizontal Integration

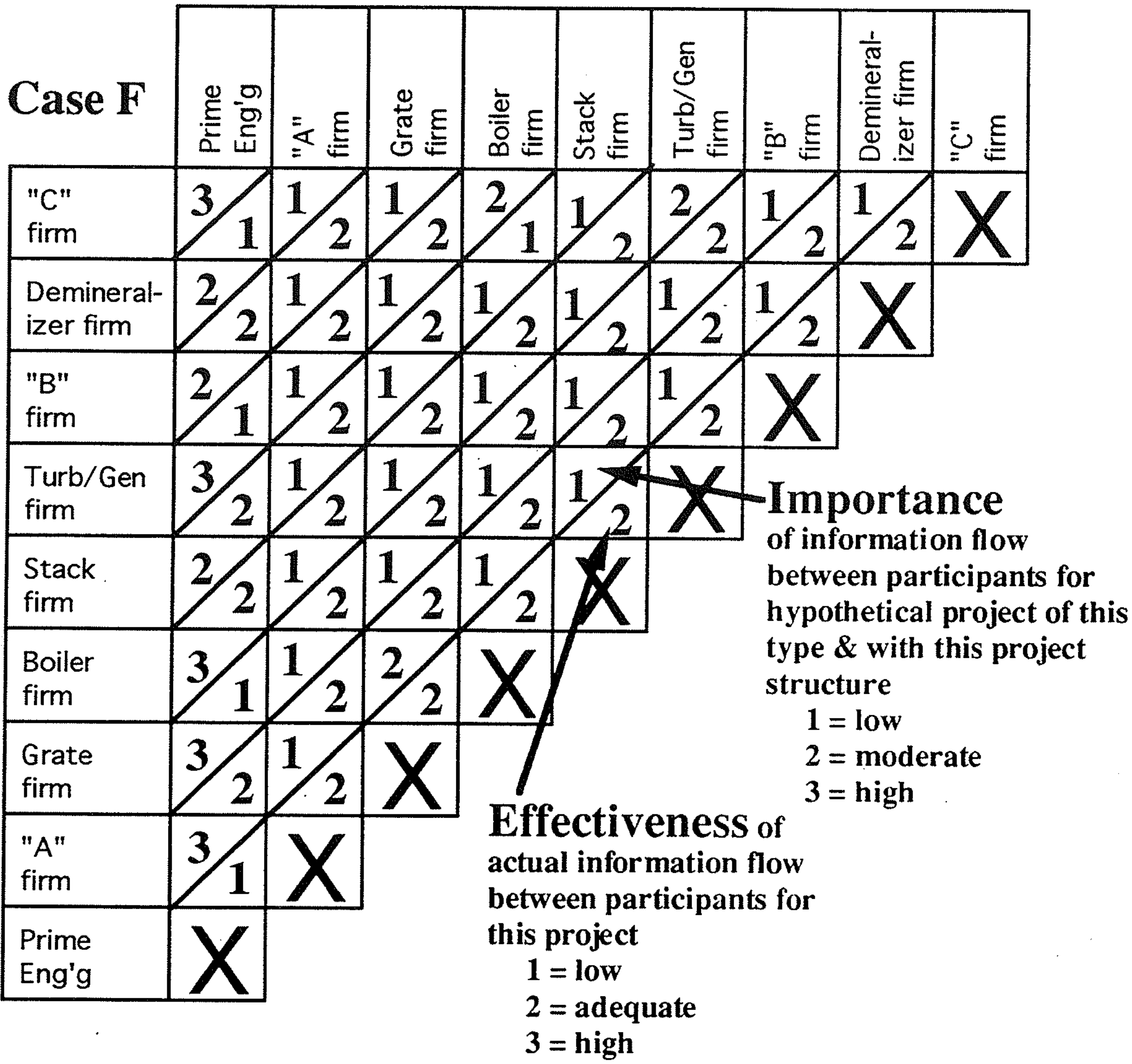
Horizontal integration is the flow of knowledge and information between disciplines or specialties. As in the case of vertical integration, the first task is to embody an abstract notion, *specialty*, in an easily recognizable form. I chose *the firm* performing the specialized work as this embodiment, and respondents were asked to rate information flows *between firms doing specialized work.* If all the specialized work was performed within the prime engineering firm, the instrument did not capture variation in this dimension.

The next step in implementing the concept of horizontal integration poses the same difficulty of varying project structure as does the case of vertical integration. Due to varying contracting strategies, project complexity, and other factors, the number of firms performing specialized work varies greatly for different projects. Therefore, it was not possible, as it was with vertical integration, to start with a predefined list of possible specialties that could be adjusted by the respondent. Instead, the respondent must generate this list from memory. In order to have reasonable limits on this onerous task, the respondent identifies only those firms that have some element of engineering design work. Thus the vertical range addressed by the measure is constrained primarily to the engineering function.

Except for the use of *firms* rather than *participants*, and the use of a *respondent-generated list* rather than a *predefined list*, the format of the instrument to measure horizontal integration is similar to that used to measure vertical integration. A matrix with variable size is constructed depending on the number of specialized firms involved in the engineering of the facility. Substituting the number of firms for the number of participant groups, n, the number of intersections in the matrix follows Equation 4.1, above.

This study uses this measure of horizontal integration between firms in its model of the impact of integration on quality. The questionnaire also included a measure of horizontal integration between design participants within the prime engineering and design firm, but this measurement instrument failed because it assumed wider-spread usage of CAD than was actually the case for these projects.

When presented with the measurement instrument, the respondent's first task was to make a list from memory of all the subcontractors or vendors that performed significant engineering work on the industrial facility. If the list contained more than 10 firms when complete, the respondent was asked to identify the 10 most important so that the completing the ratings in the resulting matrix would not over-tax the respondent's patience. Next, the interviewer constructed the matrix by re-listing these firms starting with the prime engineering design firm followed by as many as 10 vendors and engineering subcontractors, creating R intersections as defined previously in Equation 4.1. The interviewer then asked the respondent to rate importance: "For a hypothetical project of this type, with this project structure, how *important* was the flow of information between each pair of design/engineering participants shown in the matrix?" The ratings for this item were *low importance* (1), *moderate importance* (2), and *high importance* (3). Next, the respondent was asked, "For this *particular* project, how *effective* was the information flow, that is, in both directions in a rapid and accurate manner, between each pair of participants?" The ratings for this item were *low effectiveness* (1), *adequate effectiveness* (2), and *high effectiveness* (3). An example of the measurement instrument and the response for Case F is shown in Figure 4.4.



| **Case F** | Prime Eng'g | "A" firm | Grate firm | Boiler firm | Stack firm | Turb/Gen firm | "B" firm | Demineral-izer firm | "C" firm |
|---|---|---|---|---|---|---|---|---|---|
| "C" firm | 3/1 | 1/2 | 1/2 | 2/1 | 1/2 | 2/2 | 1/2 | 1/2 | X |
| Demineral-izer firm | 2/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | X | |
| "B" firm | 2/1 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | X | | |
| Turb/Gen firm | 3/2 | 1/2 | 1/2 | 1/2 | 1/2 | X | | | |
| Stack firm | 2/2 | 1/2 | 1/2 | 1/2 | X | | | | |
| Boiler firm | 3/1 | 1/2 | 2/2 | X | | | | | |
| Grate firm | 3/2 | 1/2 | X | | | | | | |
| "A" firm | 3/1 | X | | | | | | | |
| Prime Eng'g | X | | | | | | | | |

**Importance** of information flow between participants for hypothetical project of this type & with this project structure
1 = low
2 = moderate
3 = high

**Effectiveness** of actual information flow between participants for this project
1 = low
2 = adequate
3 = high

*Figure 4.4. Measurement instrument for horizontal integration and responses for Case F. The respondent indicated that in addition to the prime engineering design firm, eight firms contributed significant engineering work to this project. These relationships were rated in terms of the importance and effectiveness of information flow between the two participating firms.*

Using this instrument, horizontal integration data was collected from the engineering project manager. Most engineering project managers belonged to engineering organizations outside the owner organization, though in three cases the engineering project manager belonged to the owner organization.

It is not common for concepts to be directly measurable. We can argue, however, that a closely related phenomenon or state that *is* directly measurable may exhibit almost the same variance as the concept we truly wish to observe but cannot. This is essentially what took place in the development of the horizontal and vertical measurement instruments above. For vertical integration, participant groups were a surrogate for facility development functions. For horizontal integration, firms that performed engineering work were a surrogate for disciplines or specialties. For the next concept, longitudinal integration, a similar approach is necessary because of the gap between the theoretical concept and what is directly observable.

## Longitudinal Integration

Longitudinal integration is defined as the flow of knowledge and information over time. The origins of the concept in organizational learning and cyclical process improvement techniques described in Chapter 3 lend some guidance as to its implementation. The owner organization controls the finances and writes the main contracts in a project, so is in the most powerful position to influence project organization, structure, and overall execution strategies. Therefore, the general ability of the owner organization to incorporate experience and knowledge gained from prior projects and other sources into its capital project development process is conceptually a key manifestation of longitudinal integration. We can imagine that the greater this general ability, the greater the level of longitudinal integration affecting a single project. But how might this ability be measured?

Certain tools popular in North American businesses today are designed to incorporate experience and knowledge into the business procedures of the company in a formal manner. Logically, companies whose employees are well trained in using these tools are in a better position to actually do so than companies whose employees are not trained in the use of these tools. Such tools include Total Quality Management or Control (TQM or

TQC), formal process improvement techniques (such as CPI or PDCA), Quality Assurance (QA), and statistical process control (SPC).

Therefore, as an approximation of a project's actual longitudinal integration, the capacity of the owner organization for longitudinal integration given its experience with relevant tools is our target of measurement. Respondents were presented with a list of popular quality management programs, including those listed above, and were asked, "For how many years has the owner/operator organization used each of the following quality programs?" They were also asked to state during which prior years each program was used in order to check whether the program was still ongoing at the time of facility startup. An example of the measurement instrument and the response for Case H is shown in Figure 4.5. To provide a consistent viewpoint across all cases, the respondents to this question were the operations managers. A slightly modified question with the same response categories, was asked of the respondent completing the owner representative section of the questionnaire, "For how many years has the owner organization used each of the following quality programs?" However, because the job function of the owner representative varied greatly from case to case, these data were not used in the analysis.

| | Number of years | Which years (e.g. 1980 to 82) |
|---|---|---|
| Statistical Process Control (SPC) | 0 | |
| Quality Assurance (QA) | 15 | to present |
| Total Quality Control (TQC) | 4 | to present |
| Total Quality Management (TQM) | 3 | to present |
| Plan, Do, Check, Act (PDCA) Cycle | 1 | to present |
| Continuous Process Improvement (CPI) | 0 | |
| Quality Performance Tracking System (QPTS) | 0 | |
| Quality Function Deployment (QFD) | 0 | |
| Other____________________ | 0 | |

**Case H**

*Figure 4.5. Measurement instrument for longitudinal integration and responses for Case H. The respondent indicated that the owner organization has experience with four of the quality management programs listed. The duration of the programs extended to the interview date.*

Other longitudinal variables were measured, but the types of responses were descriptive text and binary categories, which each pose problems for inclusion in a quantitative model. In order to quantify descriptive text, it must be semantically analyzed by the researcher, a process which is very prone to biased results. Binary variables do not contain enough variation for use in a model with so few cases.

The above section and the one prior to it described the data collection instruments for the concepts of quality and integration, respectively. The intention of these instruments is to translate the abstract concepts of vertical, horizontal, and longitudinal integration into tools for the structured observation of events and outcomes of facility development processes. As a prelude to how the data collected with these instruments will be used in analyses, the next section discusses how data from closely related questions regarding a single concept can be combined to form powerful summary measures.

## DEVELOPING SUMMARY MEASURES

When designing survey instruments to gather data, it is important to use multiple measures concerning a single concept, each with a somewhat different nuance of meaning to tap a somewhat different area of variation. A set of closely related measures that sufficiently cover the concept of interest should be used so that these measures can be combined or summarized to reduce random error and increase the explanatory power of the data. Additional measures that are not quite so closely related can be used for validation purposes by means of bivariate correlations.

There are two general methods by which data can be combined to achieve greater power: additive index creation, and scale construction by factor analysis. There are hybrid forms of these as well. The method of greatest interest for this research is that of additive index creation because of this study's small sample size. In its pure form, it will be used to create summary measures of facility quality and longitudinal integration in the next chapter. In a hybrid form, it will be used to create ratio measures of vertical and horizontal integration.

### Additive Index Creation

During the analysis phase of research, additive indices are often used to reduce noise and thus improve reliability of data (Babbie 1983) (Bohrnstedt 1970). Indices are used extensively in the social sciences to provide convenient, powerful, and reliable summaries of measured data.

All measured data is composed of two parts: variation due to the concept being measured, and random variation. Random variation is often called noise or random error. An additive index reduces noise in data because random variation associated with each term tends to average to zero when summed across all terms. The random variation associated with each term averages out because the error is *random and normally distributed*, and thus equally distributed between positive and negative effects. In mathematical terms, where $\varepsilon_i$ is the noise associated with the ith variable and $X_i$ is the true value associated with the ith variable,

$$\varepsilon_1 + \varepsilon_2 + ... + \varepsilon_i < |\varepsilon_1| + |\varepsilon_2| + ... + |\varepsilon_i|. \qquad (4.2)$$

The additive index, A, where

$$\mathbf{A} = X_1 + \varepsilon_1 + X_2 + \varepsilon_2 + ... + X_i + \varepsilon_i, \qquad (4.3)$$

has less error than the total absolute error associated with the individual variables because random error tends to average out between positive and negative effects.

Items are often selected for inclusion in an index based on some rating of their importance. The advantage of this technique is that more important items tend to yield more accurate responses. If items are ambiguous or unimportant to respondents, they are more likely to be careless or uncertain in their responses, thus introducing error into the measurement.

Items chosen for inclusion in an index should correlate quite highly because they are assumed to be measuring the same concept. An item that does not correlate highly should be dropped from the index because it is contributing error (i.e. variation unrelated to the concept of interest) to the measure. Inter-item correlation and item-to-whole correlation can be used to check for such anomalous items.

Another excellent tool for index construction is the Cronbach's alpha statistic (Cronbach 1951). Cronbach's algorithm analyses the reliability, or the absence of random error, in a set of items to be added into an index. The statistic ranges from 0 to 1, with 1 indicating perfect reliability. Indices with a Cronbach's alpha between .7 and .8 are considered to have acceptable reliability.

A hybrid form of an additive index is created when numerous binary (e.g. two-category) items are combined. For example, take the case of a series of ten questions, each with a positive or negative response. The number of positive responses can be counted to create a summary index. However, a Cronbach's alpha statistic cannot be computed for such indices because they are composed of binary items. Another technique is to count the number of positive items then divide them by the total number of items to compute a percentage of positive items.

## Scale Construction from Factor Analysis

Another method of combining data uses factor analysis to weight each variable before combining them into a single measure. The difference between the term "index" and "score" is that an index is a summation of raw or standardized items, and a score is a summation of weighted items.

Factor analysis starts with a set of related variables. The algorithm allocates the variance of each variable into one or more factors. Each factor has an eigenvalue which can be used to estimate and compare the relative importance of the factors. Researchers usually expect to find one and only one dominant factor from a set of closely related variables. When one dominant factor is found, it is assumed to represent the concept under study. The factor analysis procedure yield "loadings on the factor" between -1 and 1 for each variable. The variables are multiplied by these loadings before being added into the composite score.

The drawback to factor scores is that a large number of cases are needed to produce both definitive eigenvalues as well as the weights or loadings. Although this is an elegant and well established method to create composite measures, it is not appropriate to apply in a study such as this in which the cases are relatively few.

## Validation of Measures and Indices

The need for validation of measures and indices used in the investigation of non-physical phenomena is dictated by the relative youth of the social sciences compared to the physical sciences. Both the measurement instruments as well as the theoretical concepts used in studying non-physical phenomena are, in general, less accurate and less reliable than their counterparts in the physical sciences. These limitations, however, should not halt critical investigation of the non-physical world, though these limitations should be addressed through careful validation of measures and concepts. (Bohrnstedt 1970).

Bohrnstedt gives a general definition of validity as "the degree to which an instrument measures the construct [i.e. concept] under investigation." He decomposes validity into three types: content, construct, and criterion. "Content validity refers to the degree that the score or scale being used represents the concept about which generalizations are being made." Construct validity determines a theory's ability to explain variance in the measured variables. Criterion validity refers to the association between different measures of the same or related concepts. (Bohrnstedt 1970).

Content validity is evaluated by the congruence of a study's definition of a concept with the definition of the concept in prior studies, related literature, and common usage of a term. The goal is disciplined definition of the breadth and depth of a concept. In addition to prior studies and related literature, open ended questions can be used in a study to probe respondents' ideas associated with a concept. Such data might cause a researcher to modify the concept's definition.

Construct validity concerns the question of whether one's hypotheses are correct regarding the structure of a concept or the relationship between concepts. It is evaluated on the strength of theoretical arguments in conjunction with statistical evidence, measurement methodology, and experimental design. Construct validity is generally developed by convergent results found over the course of many studies.

Criterion validity is assessed by the degree of association between measures of related concepts. Concepts that are related theoretically may be expected to correlate statistically when measured in a field setting. Measures that are highly related theoretically should have higher correlations, whereas measures that are only partially related are expected to demonstrate lower correlations. Chaffee (1989), Babbie (1989), Dawes (1985), and Bohrnstedt (1970) each advocate this class of validation analysis as fundamental to solid research methodology. Their basic approach is termed "bivariate correlation" between the researcher's index and a related measure. These methodologists caution that the second measure, or "criterion," is often an inferior measure of the concept than the composite index which is the object of the validation effort. When this is the case, lower correlations are an expected consequence. A primary consideration, as detailed in Campbell and Fiske's (1959) landmark work on validation, is that the measures used for validation employ substantially different measurement methods. In the case of indices constructed from attitude measures, Dawes (1985) suggests their validation by correlation with representational measures.

Other taxonomies of validity are popular, including Cook (1979), who discusses internal and external validity, and Campbell (1959), who discusses convergent and divergent validity. The essential theme in all these methodological studies is that researchers must think critically about the strengths and weaknesses of their concepts and measures, and wherever possible, substantiate their chosen measurement approaches by employing common sense, statistical tools, and disciplined reasoning.

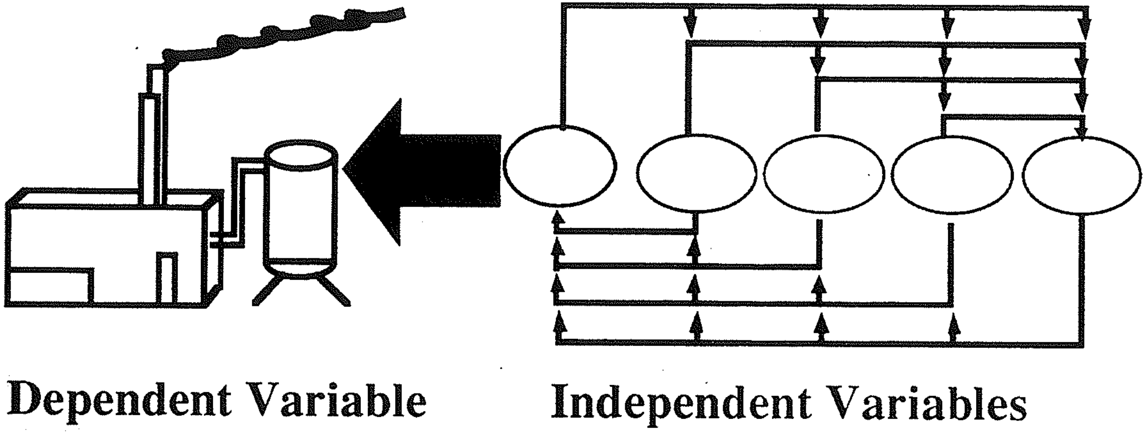
## REGRESSION APPROACH TO PREDICTING FACILITY QUALITY

The thesis of this dissertation is that industrial facility quality is determined by the level of integration in the facility development process, and that this integration takes three forms: vertical, horizontal, and longitudinal. If observed and modeled in a structured fashion, integration levels could be used to monitor facility development processes, and adjusting these levels could lead to achieving higher quality facilities. This view of the impact of integration on facility quality is a cause and effect view because I theorize that integration levels during project execution are a major causal force in customer satisfaction with the completed facility. The cause and effect viewpoint is also supported by the fact that the integration occurs first, well before the facility has been in a mode of sustained operations.

The multiple regression model is a statistical equation which is ideally suited to cause and effect models. It is commonly used as a tool to predict the value of a dependent (outcome) variable using measured values of independent (explanatory) variables. In this study we have measured values for the causal variables of vertical, horizontal, and longitudinal integration, as well as measured values for the effect variable, industrial facility quality. The regression equation, where Q is quality and V, H, and L are vertical , horizontal, and longitudinal integration respectively, may be stated as:

$$Q = \beta_0 + \beta_V V + \beta_H H + \beta_L L + \varepsilon \qquad (4.4)$$

Q, V, H, and L are measured values. The $\beta$ ("beta") terms are generated by a computer algorithm that seeks to find a best fit "curve" by minimizing the distance ($\varepsilon$) between the dependent variable and weighted independent variables in four dimensions. $\beta_0$ is the constant term, and $\beta_V$, $\beta_H$, and $\beta_L$ are beta coefficients, or weights. $\varepsilon$ is termed the residual. The parallel structure between the thesis of this research and Equation 4.4 is evident in Figure 4.6.



$$\text{Quality} = \beta_0 + \beta_V V + \beta_H H + \beta_L L + \varepsilon$$

*Figure 4.6. Can facility quality be predicted by the vertical (V), horizontal (H), and longitudinal (L) dimensions of integration?*

A regression equation is considered to be of good fit, predictive, or useful by three criteria. First, the independent variables must explain a certain amount of the variance in the dependent variables. The statistic that tells us this is the adjusted R squared ( $R^2$). An adjusted $R^2$ of .20 means that 20% of the variance in the dependent variable can be explained by the independent variables. The second important statistic is the F value for the overall equation. According to the distribution curve of the F statistic, the number of variables in the equation, and the number of cases in the study, the F statistic will have a certain probability, p, associated with it. Since this is an exploratory study with rough, "first cut" measurement instruments, a p value of .10 or less will be considered statistically significant. Finally, the t statistic associated with each beta coefficient must be statistically significant ($p<.10$).

Certain assumptions are made when developing a regression equation. The dependent variable is assumed to be normally distributed. The independent variables are assumed to be just that: independent. To ensure this, there are several types of checks that can be made, including correlation analysis, and evaluation of changes in $R^2$ with the stepwise removal of the variables from the equation. There should be no bivariate outliers in the plots of the each independent variable with the dependent variable because of the inordinate influence of such outliers on regression results (Belsley 1980). Finally, the residuals (the difference between the actual and predicted values) are expected to be randomly (normally) distributed.

Independent variables are chosen to be included in a regression equation based on two primary criteria. The first is the theoretical value of the variable. Is it representative of the concept of interest? The second consideration is predictive value. Is the variable significant in the regression equation? If a variable does not meet these two criteria it should not be included in the equation. However, it should be noted that sometimes regression equations drive theories rather than vice versa. The number of independent variables in a regression equation is dictated by theory, parsimony, and the number of cases. Tabachnick (1989) recommends a minimum of five cases for every one independent variable.

It is beyond the scope of this research to consider for possible inclusion in the regression model all the integration variables for which data was collected. Using the criteria of theoretical value and predictive power, and after generating numerous models, I selected three independent variables for the analysis to demonstrate a proof of concept of the measurement and regression model approach.

## DESIGN OF THE STUDY AND POTENTIAL SOURCES OF BIAS

Seventeen (17) industrial facilities were selected for inclusion in this study. The facilities had all been operating for between nine months and six years, and had initial capital costs between $10 million and $1 billion U. S. dollars. They represented a variety of process industries: power and cogeneration plants (6), chemical manufacturing (4), pulp and paper (4), water and waste water treatment (2), and hardware manufacturing (1). The population is heterogeneous in the sense that five industries are represented, yet homogeneous in the sense that they are all industrial facilities. The heterogeneous nature precludes us from using narrow objective data such as availability or start-up duration to compare the plants directly because each industry has unique norms for these measures. However, the homogeneous nature enables us to apply the rating scale measurement technique outlined in the Measurement of Customer Satisfaction section of this chapter.

The plants were selected by contacts within owner and engineering companies. In most cases, the contacts selected two projects in which their companies had been involved. In order to guard against the tendency of people to "show off" only their best projects and to ensure variance in the data, the contacts were requested to provide what they judged to be one higher quality plant, and one lower quality plant. Contacts had either expressed a prior interest in participating in the study, or had been contacted because of their company's affiliation with CIFE, and thus were inclined to permit me access to their organization and information. Typically, the contact provided me with the names of two people in the owner organization: an owner representative that had been involved in the project; and the chief operator of the plant (plant manager, production manager, etc.). After interviews with these two people to gather quality and integration data, snowball sampling (i.e. using members of a special population to identify others of that population) (Kish 1965) was used to identify, typically, between zero and three more respondents per facility. These respondents provided facility quality data only and included strategic, project management, and operations personnel. Readers are cautioned that the results presented in Chapters 5 and 6 may reflect a gender bias: all contacts were men, as were 52 of the 53 respondents in the owner organizations.

In the early stages of this research, before the development of the integration framework presented in Chapter 3, I identified about 60 or 70 detailed hypotheses regarding the impact of integration on facility quality. I pared these down to 40 hypotheses using a ranking technique to determine which ones would most likely yield interesting or important results. These hypotheses fell into a simpler framework which I have since abandoned because it had little explanatory power and was not based on any integration traditions developed in the literature. I developed measurement questions to gather integration data that could be used to test each hypothesis.

The integration data was obtained during interviews of four key people involved in the development of each facility: owner representative, engineering project manager, construction project manager, and plant manager. Designing the study to include these four people ensured that data throughout the development stages of the facility life cycle could be gathered. An integration questionnaire was used to guide the interviews and obtain measurements for integration variables in all three dimensions of the integration framework presented in the Chapter 3. Each interview was approximately 4 to 6 hours in duration. In some cases, the owner representative and the plant manager were the same person. In other cases, information provided by the four key participants was supplemented by additional interviews. Approximately 60 people contributed to the integration data.

A questionnaire-based data gathering approach for the purpose of statistical analysis was chosen as the research methodology rather than a case study approach. A case study approach would have had the advantage of providing more detailed insight into the effects of particular decision making events on plant quality. However, using more gross observations combined with statistical techniques to analyze project data allows us to overcome many of the biases and limitations of human cognitive processes, including anchoring and adjustment, recency, conservatism, etc., that would be operative if the interviewees were asked to give verbal, interpretive accounts of prior events (Kleinman 1991) (Slovac 1977).

These biases are particularly relevant to facility development projects because such projects are relatively lengthy in duration. An extremely experienced project manager might only manage 3 to 8 large projects in a career. Even with the best of experience and intentions, human cognitive limitations could easily lead to the individual presenting erroneous conclusions to the researcher regarding the effects of integration from the sample of projects with which he or she is directly familiar. Therefore, we chose to ask factual rather than interpretive questions, e.g. "How many times did you use X?" rather than "Why did you use X instead of Y?"

Conducting interviews in person or by telephone may introduce error into the data because of the interviewee's natural tendency to try to "help" the researcher. The interviewee may consciously or subconsciously interpret subtle cues in the interviewer's demeanor, or try to guess the hypotheses under study, leading to answers that contain error. I attempted to mitigate these "demand characteristics" by refraining from discussing my research objectives with the respondents until after the relevant questionnaire section was complete. In addition, I was careful to control my verbal inflection. I memorized additional instructions for certain questions, and attempted to repeat these verbatim each time. The separation of interviews regarding quality from interviews regarding integration also contributed to the mitigation of this potential bias.

To avoid direct biasing of the data, the interviewee completed the questionnaire form, while I took only supplementary notes during the interviews.

Another potential bias derives from the timing of the study relative to the facility life cycle. Because we wished to obtain plant quality data from plants in the operations stage, the plants that we included in the study had been in operation for between six months and six years. Therefore, when responding to questions regarding events that had occurred several years previously, selective recollection influenced by post-project events may have contributed bias. This time lag between the events under study and the collection of the data may also have introduced error because of the reduced ability of the interviewees to recollect certain aspects of the project accurately. This type of error is called maturation (Cook 1979).

Another possible source of noise in the data is history (Cook 1979). Although we make an implicit assumption that each project had equal access to technical and organizational innovations, the fact that one project was completed 5-1/2 years earlier than another belies this assumption. Technology and organizational tools had been changing during that period, so that tools used in later projects were not available for previous ones.

The potential sources of bias and error discussed above are issues of internal validity. The most problematic source of external validity is the small sample size used in the study. Ideally, we would have liked to include at least thirty projects in the study. Budget constraints precluded us from including more than seventeen. Therefore, we must use caution when extending or generalizing the findings of the integration part of the study. In addition, the projects included in the study were by no means a random sample of the population of all plants that have started up between 2 and 7-1/2 years previous to the publication of this dissertation. Indeed, I would guess that these projects are of better-than-average quality, if not excellent plants, as compared to the industry norm. The lack of a random sample limits our ability to generalize the findings of this research, a problem of external validity.

This chapter described the methodology I used in designing the study, designing the measurement instruments, gathering the data, and analyzing it. In Chapter 5 I analyze the industrial facility quality data, and in Chapter 6 I analyze the integration data and the impact of integration on industrial facility quality.

## *Chapter 5 — Analysis of Industrial Facility Quality*

This chapter analyzes the facility quality data, and Chapter 6 analyzes the impact of integration on quality. This division reflects the two levels of analysis used in this study. This chapter analyzes differences in quality perspectives according to an individual's role in the owner organization. Here, the individual is the level of analysis. The next chapter concerns the impact of integration on the quality of an industrial plant. In that discussion, the level of analysis is the project or plant.

Our analyses in five areas help establish industrial facility quality as a conceptually defined and measurable concept. These areas of analysis are 1) group distinctions, 2) attitude differences *between* owner groups, 3) high importance and low satisfaction items *within* owner groups, 4) construction of a summary quality index and 5) validation of the index based on its correlation with a representational measure.

### GROUP DISTINCTIONS

When this research was conceived, I assumed that there was one, and only one, "customer" or "owner" viewpoint of facility quality. However, during the course of data gathering, it became apparent that people with different roles in the owner organizations often have substantially different definitions of facility quality. Specifically, after completing interviews for the first two projects in the study, I hypothesized that project managers were more satisfied with the plants than other people in the owner organization.

The number of individuals in this sample is 53, and they all belong to owner organizations. As a working hypothesis, we have classified people in the owner organization post-hoc into 3 groups, Project Management (n=12), Strategic (n=8), and Operations (n=33), defined as follows:

*Project Management:* From year to year, the full time responsibilities of a person in this category involve facility engineering or construction, and the person's financial accountability for the facility tapers off at mechanical completion. The person typically begins working on a new facility project when the current one is completed.

*Strategic:* The Strategic person has financial (profit and loss) responsibility for the plant, and may oversee operations of more than one plant. This person contributes to the strategic technical and/or business direction of the company, and typically has depth of experience in operations of more than one plant. The financial accountability of people in both this group and the next typically increases at mechanical completion.

*Operations:* People in this category currently oversee no more then one plant, and may oversee just a portion of a plant. They work on day-to-day production operations.

As the first step in analyzing the data, the mean importance value and the mean satisfaction value for each group was calculated for each of 29 of the 32 facility quality items listed in Table 2.A in Chapter 2, such as profitability of plant, meeting production output specifications, etc. The other three items were not suitable for analysis as detailed in Appendix A. The results of these calculations are shown in Figure 5.1, which lists the facility characteristics at the left of the figure, and shows mean values for the operations, strategic, and project management groups in the left, center, and right columns, respectively. The characteristics are ordered from top to bottom by mean importance of pooled responses from all three groups. Satisfaction means are indicated by striped bars and importance means are indicated by black bars.

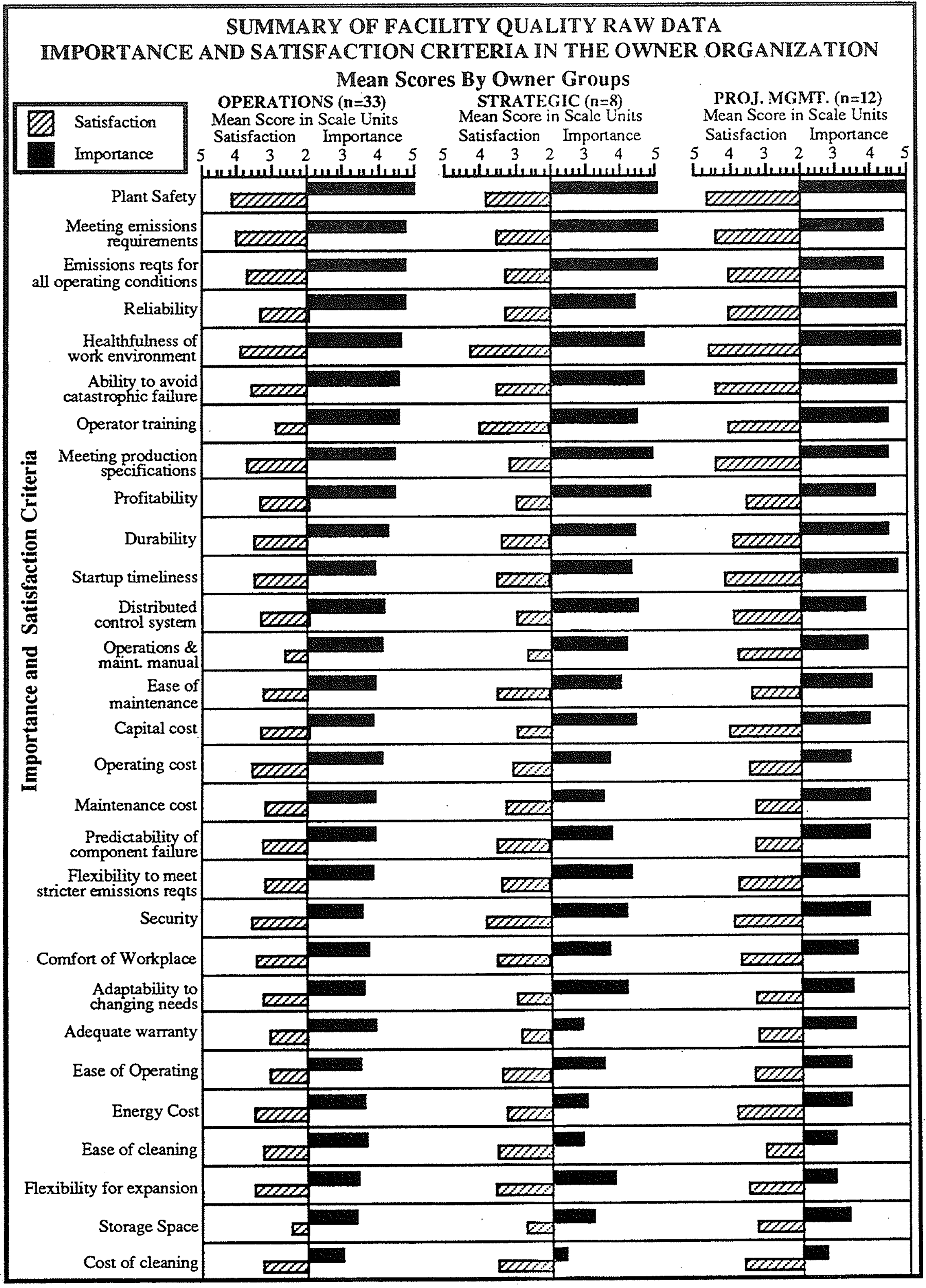


*Figure 5.1. Summary of Facility Quality Raw Data. Mean scores by owner groups for 29 facility quality characteristics.*

To test whether attitudes about facility quality are reliably different between the three groups, ANOVAs (ANalysis Of VAriance) were used to compare the importance and satisfaction group means, $\mu$, of these facility quality items[1]. Project management means, operations means, and strategic means for each item were compared to determine whether these means differed significantly. Because this is an exploratory study using preliminary measurement techniques, a relatively high significance level of $p<.10$ was chosen for this analysis.

The null hypotheses are that there is no difference between the three groups' mean scores on each item, i. e., $\mu_1=\mu_2=\mu_3$. Based on the F-statistic, we rejected the null hypothesis for 4 of the 29 importance comparisons and 10 of the 29 satisfaction comparisons.

Although the significant F-statistics tell us that differences between means exist, they do not tell us between which particular groups the differences exist. To determine specifically which groups exhibit these differences, the Least Significant Difference (LSD) statistic (Ostle 1988) is used. For example, the F-test may tell us that the statement $\mu_1=\mu_2=\mu_3$ is false. The LSD test can tell us specifically that $\mu_1\neq\mu_3$. Based on the LSD statistic, 6 importance differences and 17 satisfaction differences were obtained, as shown in Table 5.A, below. These differences are detailed in Figure 5.2 in the next section.

| **Comparisons:**<br>**Item type:** | Operations vs. Proj. Mgmt. | Strategic vs. Proj. Mgmt. | Operations vs. Strategic | Significant LSD totals: |
|---|---|---|---|---|
| Importance items: | 3 | 1 | 2 | 6 |
| Satisfaction items: | 8 | 8 | 1 | 17 |

*Table 5.A. Number of Significant (p<.10) Specific Group Differences in Facility Characteristics Between Three Owner Groups.*

These test results show that although there are few importance differences between the groups, there are substantial differences in satisfaction levels between Project Management and both the Operations and Strategic groups. The number of satisfaction differences, 8 of

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[1] ANOVA enables us to avoid one aspect of the problem of multiple comparisons because only 29 comparisons are made for importance and satisfaction measurements of each characteristic rather than the 87 that would be required using the t-test of mean differences. However, 29 is still a large number of comparisons. If these variables were independent, we could use Bonferroni's adjustment to reduce the probability level, p. However, the variables are not independent, so the problem of multiple comparisons remains an unresolved issue for this study.

29 for the Operations vs. Project Management relationship, and 8 of 29 for the Strategic vs. Project Management relationship suggest that these groups have significantly different definitions of industrial facility quality. Project Management has different standards than the other two groups. This is confirmed by two sign tests comparing Project Management mean satisfaction with the 29 items to Strategic and Operations means, respectively. The null hypothesis is that there is no difference in satisfaction between the two pairs of groups, and the alternative hypothesis is that Project Management means exceed those of the other two groups. The results of the sign test are displayed in Table 5.B, below, which shows that Project Management means exceeded Operations means for 27 of the 29 satisfaction items, and exceeded Strategic means for 24 of the 29 satisfaction items. We conclude that Project Management has a significantly different definition of industrial facility quality than Strategic and Operations.

| **Comparisons:** | Proj. Mgmt. mean is greater than Operations mean | Proj. Mgmt. mean is greater than Strategic mean |
|---|---|---|
| **Number of sign differences:** | 27 of 29**** | 24 of 29**** |

**** indicates significance at p<.001; $p = \dfrac{\sum_{i=m}^{n} \frac{n!}{i!(n-i)!}}{2^n}$.

*Table 5.B. Sign Tests for the Differences in Satisfaction Item Means for Project Management Compared to Operations and Strategic Groups.*

However, the differences in satisfaction means between the Strategic and Operations groups are few compared to the differences in means between either of these two groups and the Project Management group. Therefore, although the differences between Strategic and Operations should be highlighted and discussed, it may be appropriate in future research to combine Strategic and Operations people into a single "Permanent Facility Responsibility" group. This option is explored briefly in Appendix B, and simulation method for verifying group cohesiveness is presented in Appendix C.

## ATTITUDE DIFFERENCES BETWEEN THREE OWNER GROUPS

Given the working hypothesis that these three distinct viewpoints regarding satisfaction with facility quality exist in the owner organization, the differences between them will now be examined in more depth. Based on the F-test, the significant ANOVA results comparing group means on each facility characteristic that were summarized in Table 5.A are now presented in detail in Figure 5.2. Note that because of our hypothesis that project management means would exceed operations and strategic means of satisfaction scores, one-tailed tests were performed in these cases. However, the importance comparisons between all groups and the satisfaction comparisons between the operations and strategic groups were performed using two-tailed tests because there was no prior expectation as to whether one group would exceed another.

Statistically significant differences on the basis of the Least Significant Difference (LSD) statistic are indicated by one asterisk (*) for $p<.10$ and two asterisks (**) for $p<.05$ at the end of the vertical bars in Figure 5.2. The items are positioned from left to right in rank order of importance based on the means of all 53 responses for each item.

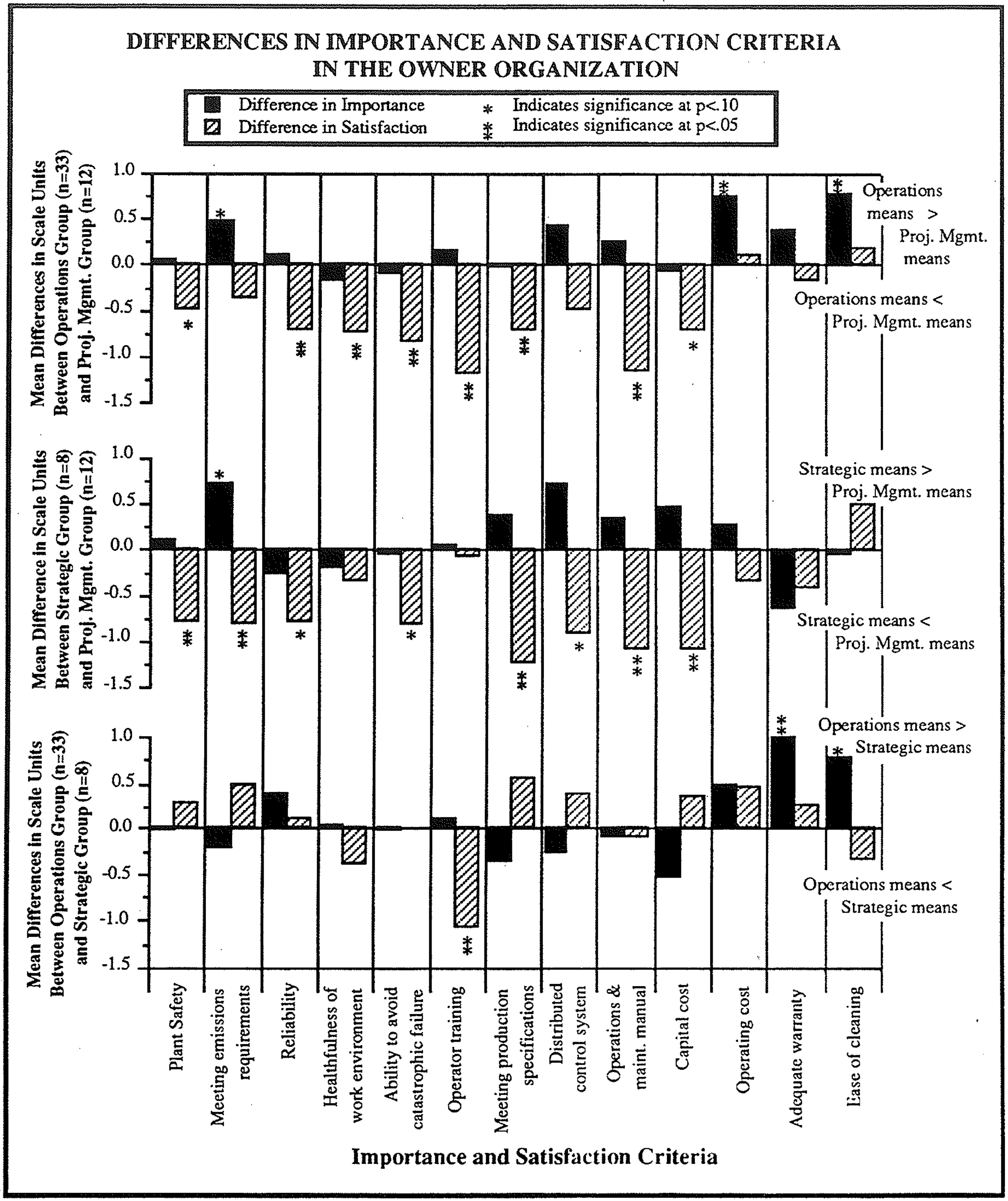

*Figure 5.2. Differences in Importance and Satisfaction Criteria. Each of the three horizontal bar charts compares two owner groups. Each black bar shows the difference in the two groups' importance averages on a single variable. Likewise, the striped bars show differences in satisfaction.*

*Operations Group vs. Project Management Group:* As shown in the upper bar chart of Figure 5.2, there are three facility characteristics that are more *important* (shown by *'s at the end of the *black* bars) to operations personnel than to project management in this study. The operations group places a greater *importance* on the ability to meet emissions requirements for all waste types, cost of operating, and ease of cleaning.

Meeting environmental regulations is obviously of great concern from the operations perspective because of the combined potential of public safety consequences, heavy regulatory fines and detrimental public relations that could result from noncompliance. Cost of operating is likewise more important to the operations group, perhaps because these people are accountable for setting and meeting operations budgets. Ease of cleaning, though not relatively as important as many other characteristics, is of understandable concern in maintaining "housekeeping" standards and a safe working environment.

Though not shown in Figure 5.2 because the item did not quite reach statistical significance, owner project managers rated timeliness of start-up much higher in importance than did the operations group. This is a reasonable result because project management people are generally focused on schedule deadlines, whereas operations personnel, knowing that they are responsible for the plant on a permanent basis, tend to focus their concerns on the long term operating capability of the plant.

Operations has a lower average *satisfaction* level (shown by *'s at the end of the *striped* bars) than project management on 8 items. These are plant safety, plant reliability, healthfulness of worker environment, the ability to avoid catastrophic failure of major components, training of operators, the ability to meet production output specifications, useful operations and maintenance (O & M) manual, and capital cost.

Plant safety, healthfulness of worker environment, and the ability to avoid catastrophic failure might be termed "operator well-being" variables. Operations people are less satisfied than project management on these items, perhaps because being on site, they have found themselves at greater personal risk when failures do indeed occur. We might group training and O & M manual together as "how-to" variables. It is rather alarming that the people responsible for running these enormous, complex facilities have low satisfaction with the "how-to" operations instruction they receive at turnover. Plant reliability and meeting production specifications, two items measuring the basic functionality of the plant, also demonstrate significantly lower satisfaction levels for the operations groups relative to project management, perhaps due to an over-optimistic perception by project management regarding the performance of the plants they deliver to their internal customers. Lower satisfaction with capital cost may indicate a concern with value received for the money.

Storage space was an "almost significant" item for which operator satisfaction again was lower than project management satisfaction. While being a rather low importance item overall, it is mentioned here because it surfaced time and again during interviews as an item that had received little attention during design but that now was a persistent, irritating problem.

*Strategic Group vs. Project Management Group:* As with the operations perspective, the strategic perspective varies significantly from project management. The second-from-left column of the middle bar chart in Figure 5.1 shows that meeting emission requirements for all waste types is more *important* to strategic personnel than to project management. Being responsible for the plant's business performance, strategic people understand the true magnitude of the costs that can be associated with environmental non compliance.

Strategic people have a statistically significant lower level of *satisfaction* than project management with respect to eight facility characteristics. In addition to seven items in common with the Project Management vs. Operations differences (plant safety, meeting emissions requirements for all waste types, plant reliability, the ability to avoid catastrophic failure of major components, meeting production output specifications, useful operations and maintenance (O & M) manual, and capital cost), the eighth item is Distributed Control Systems (DCS). These items are indicated by asterisks (*) at the ends of the *striped* bars of the middle bar chart in Figure 5.2.

Project management's markedly higher satisfaction with critical items such as reliability and ability to meet production output specifications may indicate a misperception regarding the actual performance of the plant. Conversely, the strategic perspective is much less satisfied with DCS than project management, perhaps because these systems do not perform to expectations. As plant complexity continues to increase, the DCS has become more and more essential to plant operation by guiding optimization of industrial process performance and reducing labor requirements. The gap between the two groups on plant safety and the usefulness of the operations and maintenance manual may exist because these items are difficult to judge from the shorter-term project management perspective. The lower satisfaction of the strategic perspective than the project management perspective with capital cost may indicate the strategic person's desire to achieve a better return on investment, while project management's goal is to meet budget objectives.

Taken together, the differences in satisfaction described above suggest that owner project managers may not have an accurate conception of the performance of the new facilities that they "deliver" to their organization. Project managers are the owner organization's crucial liaison with the larger facility development team which includes engineering, vendor, construction, regulatory, and other organizations. Owner project managers need to communicate the priorities of the owner organization as a whole. It is therefore essential that they develop a deep, sensitive understanding of what constitutes satisfaction in the eyes of the people in their organizations that have long-term financial accountability and operations responsibilities for these facilities.

Many of the projects in this study had no post start-up reviews to provide feedback to the project team. If one or more reviews were held, they typically focused on *project* performance rather than *facility* performance. These meetings are typically held shortly after start-up, with operations and strategic representatives often not even present. In addition, because project managers are typically extremely valuable personnel in the owner organization, as soon as mechanical completion is accomplished they are often transferred to the next capital project in progress. Under these circumstances, it is not surprising that project managers' perceptions of facility quality are typically focused on the "front end" of the facility life cycle rather than being aligned with the perceptions of others in their organization.

*Operations Group vs. Strategic Group:* The operations group gives a significantly higher weight to the *importance* of adequate warranty and ease of cleaning than the strategic group. Operations people bear the responsibility of keeping the plant running on a day-to-day basis. When something goes awry, it is their responsibility to get things running smoothly again. It is thus not surprising that they exceed the strategic group with respect to equipment warranty expectations. Ease of cleaning, while not a particularly important item, does contribute to a safer, more pleasant working environment.

The only significant difference in *satisfaction* averages between these two groups involves training of operators. While all three groups concur on the *importance* of operator training, operations people themselves are very dissatisfied. The inclusion of training as one of the facility quality characteristics is a recognition that the capital investment made by owner organizations in a plant includes not only hardware investment, but human investment as well.

The implications of the differences between groups uncovered in this section will be discussed in more depth in Chapter 7. In summary, these differences indicate areas in which goals and expectations within the owner organization are not aligned, and the contrast between the three groups' definitions of industrial facility quality.

## HIGH IMPORTANCE, LOW SATISFACTION ITEMS WITHIN GROUPS

The previous section examined differences *between* groups by comparing mean values of single items. Another way to gain insight into the data is to identify items high in importance and low in satisfaction *within* each group. To do so, the 29 items are ordered from highest to lowest in terms of both satisfaction and importance within each group. Items which are ranked high in importance and low in satisfaction for each group indicate facility characteristics for which customer expectations are not being met. These areas should be targeted for improvement efforts by owners as well as contractors. This target area is highlighted by the curved outline in Figure 5.3.

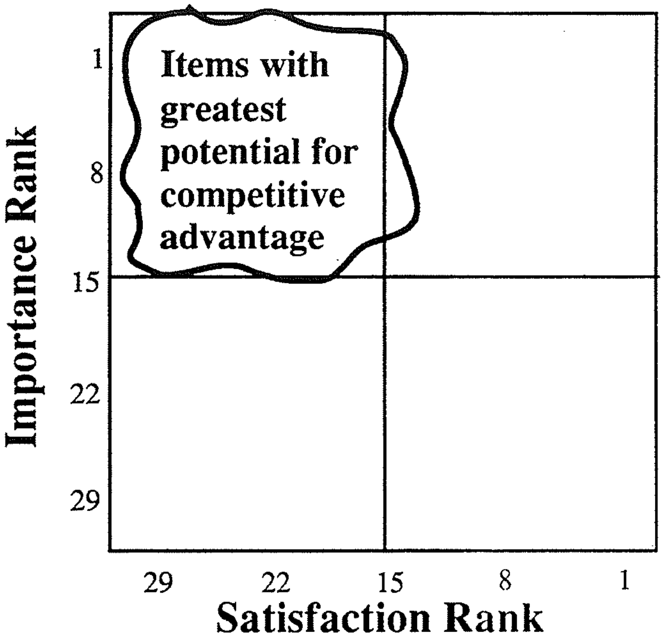

*Figure 5.3. Facility characteristics which are ranked high in importance but low in satisfaction are items which demonstrate the greatest potential for competitive advantage for both owner and EPC organizations. 1 is the highest rank and 29 is the lowest.*

Table 5.C, below, portrays items ranked high in importance and low in satisfaction based on item averages within each group. The table is divided into three main vertical sections, one for each of the owner viewpoints. Note that operator training (in the Operations Viewpoint column) has the very largest difference in rank order of all the facility characteristics.

| Operations Viewpoint | | | Strategic Viewpoint | | | Project Mgmt. Viewpoint | | |
|---|---|---|---|---|---|---|---|---|
| Facility Quality Characteristic | Import -ance Rank | Satis- faction Rank | Facility Quality Characteristic | Import -ance Rank | Satis- faction Rank | Facility Quality Characteristic | Import -ance Rank | Satis- faction Rank |
| Reliability | 3 | 15 | Mtg emissions requirements (all operating conditions) | 3 | 18 | Reliability | 4 | 9 |
| Training of Operators during Startup | 7 | 29 | Meeting Production Output Specifications | 4 | 21 | Profitability of Plant | 11 | 19 |
| Profitability of Plant | 9 | 16 | Profitability of Plant | 5 | 23 | Ease of Maintenance | 12 | 22 |
| Useful O & M Manual | 13 | 30 | Distributed Control System (DCS) | 9 | 24 | Cost of Maintenance | 14 | 27 |
| Cost of Maintenance | 16 | 24 | Reliability | 10 | 17 | Ability to predict failure of major components | 15 | 24 |
| Warranty | 18 | 25 | Capital Cost | 12 | 25 | | | |
| | | | Useful O & M Manual | 16 | 29 | | | |

*Table 5.C. Facility Characteristics Ranked High in Importance and Low in Satisfaction by Three Groups in the Owner Organization. The items listed in this chart are areas in which competitive advantage might be gained by organizations demonstrating superior competence.*

The items shown in Table 5.C have possible implications for both owner organizations and EPC firms. These areas of high importance and low satisfaction to the owner organization may be very productive areas in which to focus improvement efforts in order to achieve an edge over competitors. Particularly, training of operators and useful operations and maintenance manuals are two areas where gains could be made with relatively little effort. Meeting emissions requirements is an area where owner companies may have more practical expertise and know more about future requirements than typical engineering organizations. Therefore, one strategy for improving customer satisfaction in this area would be to proactively tap the expertise existing within the owner organization. Reliability is also a prime target, since it is a high importance, low satisfaction item for all three groups.

## DEFINING A SUMMARY INDEX FOR FACILITY QUALITY ASSESSMENT

Although the above analysis of the many components of facility quality gives us useful and interesting insights, it does not readily enable us to assess overall facility quality. We have seen the contrasts in definitions of plant quality within owner organizations. Thus it would be beneficial to have a single coherent measure that describes overall plant quality, while nevertheless preserving the diverse individual perspectives in owner organizations.

Both business and measurement needs are addressed in the creation of a summary measure. In his discussion of the use of quality measurement to develop and evaluate strategic business goals, Akao emphasizes the importance of developing broad summary measures to evaluate the outcome of key elements of a business strategy (Akao 1990). The performance of an organization's capital investment in a new industrial plant is frequently such a key element. However, we lack summary statistics with which to make these comparisons and evaluations of project success. A summary quality measure would allow managers to compare varied, complex facilities on a simple, straightforward basis. In addition, a summary measure could be used as a dependent variable to assess the impact of various facility development strategies on the outcome of the product.

As detailed in Chapter 4, the creation of additive summary indices reduces the random error, or noise, in data. This is because random error is normally distributed and tends to average out to zero over several items.

Both the business need for a simple evaluative measure and the research need to reduce noise prompted me to develop a summary index that incorporates the most relevant information regarding facility quality. This simple additive index is the sum of each individual's standardized scores of six facility characteristics ranked as among the twelve most important, on average, by all the respondents in all three owner groups. Equation 5.1 formulates the Additive Satisfaction Facility Quality Index:

$$Q = S_{\text{Safety}} + S_{\text{Reliability}} + S_{\substack{\text{Ability to avoid} \\ \text{catastrophic failure}}} + S_{\text{DCS}} + S_{\substack{\text{Operator} \\ \text{training}}} + S_{\substack{\text{Meeting prod-} \\ \text{uction output} \\ \text{specifications}}} \qquad (5.1)$$

where Q is the additive satisfaction facility quality index score, and S is the standardized satisfaction rating for the indicated item.

The Cronbach's alpha statistic indicates the level of random noise or error in the data comprising an index. It is calculated based on inter-correlations between the items. The statistic ranges between 0 and 1, and larger numbers indicate less error. Cronbach's alpha for the Additive Satisfaction Facility Quality Index is 0.77, which indicates that this is a reliable, interpretable index (Cronbach 1951). Adding certain additional items to the index might increase its Cronbach's alpha statistic slightly, but parsimony would be sacrificed.

The index is representative of the broad spectrum of plant quality issues, and represents key interests of all three owner groups. All six of the items, which are safety, reliability, ability to avoid catastrophic failure, distributed control systems (DCS), operator training, and meeting production output specifications appear in Figure 5.2, indicating that these items maintain key differences in opinions between the three owner groups. Four of the six items also appear in Table 5.C, indicating that these items have important competitive implications. Thus, the index has good conceptual strength with respect to preserving key differences, conveying important aspects of competitiveness, and providing broad coverage of the diverse aspects of facility quality.

Because of the differences in quality perspectives in owner organizations, it is important to select a consistent viewpoint when using the index to compare facilities. We recommend using the plant manager's index because he or she is likely to be able to give an accurate assessment of all facility quality characteristics of the plant, whereas other people in the owner organization may lack knowledge regarding one or more characteristics. In this study, the plant manager was a viewpoint for which we had data across all cases, so the plant manager's assessment of plant quality is used when the plant is the level of analysis.

## VALIDATION OF ADDITIVE SATISFACTION FACILITY QUALITY INDEX

As detailed in Chapter 4, the validation of nonrepresentational measures such as our Additive Satisfaction Facility Quality Index by significant correlation with representational measures is recommended by Dawes (1985). In this study we collected "objective" representational data on percent availability, start-up duration, and ratio of actual production to planned capacity. Percent availability is defined as hours of uptime / (uptime + unscheduled downtime) for the most recent year. Start-up duration is defined as the period in days from mechanical completion to sustainable commercial production.

However, of these three objective measures, percent availability and start-up duration are not suitable for index validation because the data collected in this study using these measures differ significantly between industries. For example, the average availability for power plants is 98.1% and the average for chemical plants is 86.9%. Because of the large difference between these means, comparing the plants on the basis of availability would be like comparing "apples to oranges." The third representational measure, the ratio of actual production to planned capacity, is not significantly related to industry type and so may be used for index validation. Unfortunately, this measure has limitations stemming from the fact that it measures a different, though related concept than that of overall industrial facility quality.

In general terms the ratio of actual production to planned capacity may be thought of as measuring whether "the plant we bought is producing as much as we thought it should be capable of producing." To the extent that this concept is similar to the concept of quality as customer satisfaction with the broad range of plant characteristics, we can expect the index to correlate with this ratio. Obviously, however, there is much more to facility quality than the concept that this ratio represents. For example, crucial facility characteristics such as plant safety, operator training, and maintainability are unrelated to the ratio. In addition, using the ratio as a quality indicator could give misleading results because it does not account for planned extra capacity which could be a crucial component of a strategic business plan. Factors unrelated to plant quality, such as general market demand for the plant's output, also influence the ratio values. Therefore, we can expect a significant modest correlation, but not a high correlation, between the ratio and the index. Although we fully recognize the shortcomings of the ratio as a measure of plant quality, it is in keeping with the methodological importance of index validation to determine whether it explains a significant percentage of the variance in the Additive Satisfaction Facility Quality Index .

To construct the ratio, the actual production figure was obtained from the plant manager. The planned capacity figure was obtained from the engineering project manager. There were three cases with missing values (leaving 17-3=14 cases) and one outlier, a power plant (with an index value of -4.87 and a ratio value of .24), leaving 13 cases to analyze. The null hypothesis is that the quality index and the actual / planned ratio are uncorrelated.

We reject the null hypothesis ($r^2$=.23; $p<.05$), and as expected, there is a significant modest correlation (r) between the index and the ratio of actual production to planned capacity. The $r^2$ value indicates that about 23% of the variance in the Additive Satisfaction Facility Quality Index can be explained by the ratio measure. This relationship is shown in Figure 5.4 which plots the Additive Satisfaction Facility Quality Index against the ratio of actual production to planned capacity.

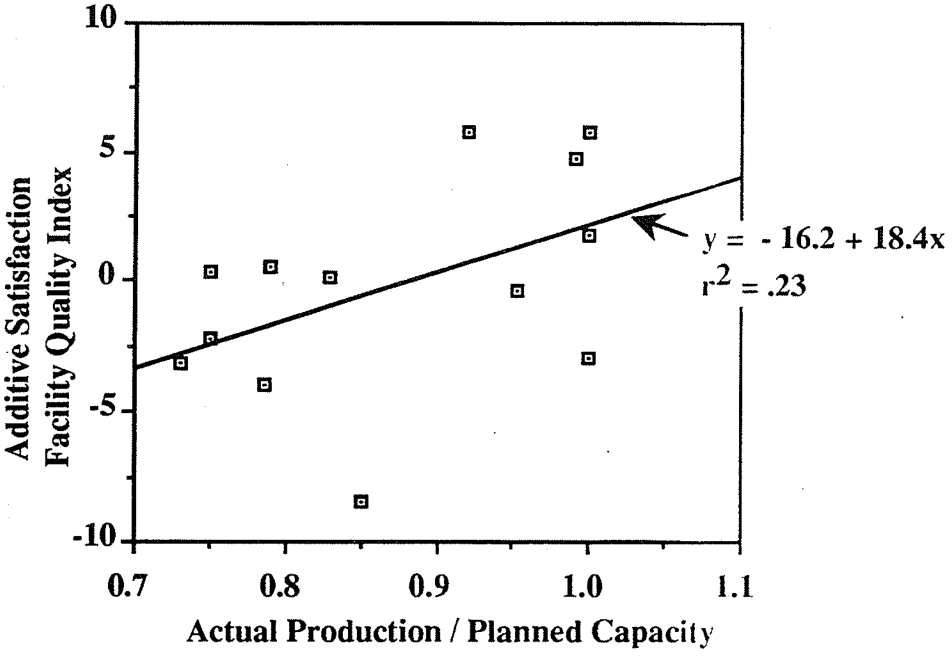

*Figure 5.4. Validation of Additive Satisfaction Facility Quality Index by bivariate correlation with the ratio of Actual Production to Planned Capacity. Excluding the outlier, the correlation is significant, and 23% of the variance in the two measures is shared, ($r^2$ = .23; $p<.05$).*

Interestingly, the index also performs well ($r^2$ = .25, $p<.05$) when the outlier is included in the analysis, suggesting that it might be valid for a greater range of facility quality than was emphasized in this study. However, because of the potential of outliers to influence results inordinately (Belsley 1980), the conservative strategy is to eliminate the outlier.

The correlation of the Additive Satisfaction Facility Quality Index with the ratio of actual production to planned capacity contributes to this summary quality index's validity because 23% of their variance is shared. A Venn diagram depicting this relationship is shown in Figure 5.5. It is clear that a wider range of facility quality aspects exist in the index than in the ratio measure. This fact lends credence to our assertion that the additive index is a richer and more useful representation of an individual's concept of industrial facility quality than the ratio measure.

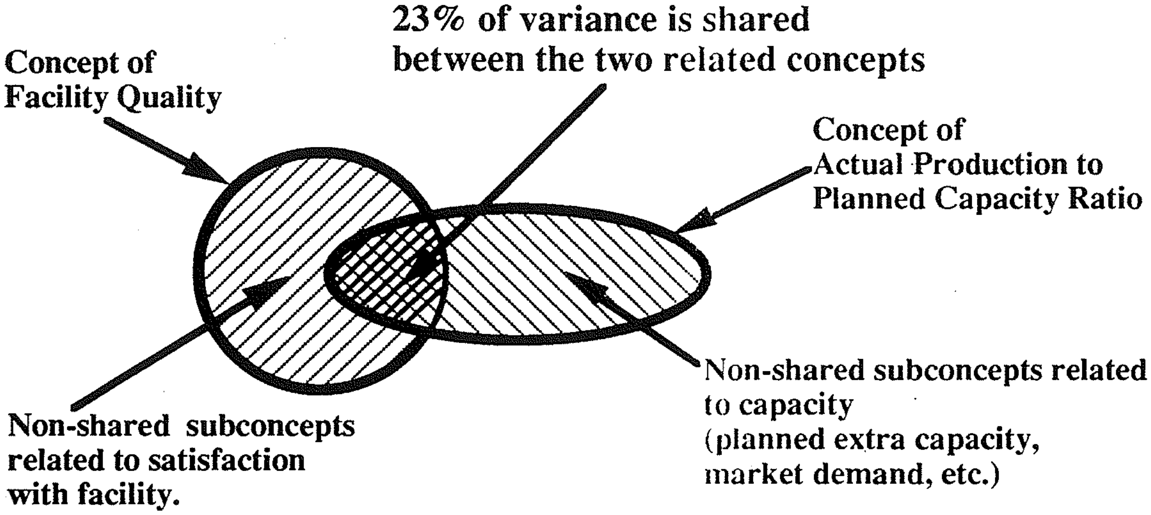

*Figure 5.5. This Venn diagram shows the 23% shared variance between the related concepts of facility quality and the ratio of planned capacity to actual production. The non-shared facility quality subconcepts are richer in explanatory power and of a wider range than the non-shared subconcepts in the ratio measure. Thus we believe that the additive index is the richer and more accurate representation of an individual's concept of industrial facility quality.*

This chapter makes significant progress toward achieving the first of the three research objectives stated in Chapter 1, "*to establish the meaning and measurement of industrial facility quality.*" The definition of facility quality as customer satisfaction with the list of facility characteristics and their measurement by means of semantic differential scales successfully distinguished between different owner groups. Cacioppo and Petty use a similar criterion to argue that their list of items successfully represented and measured the "need for cognition" concept. In addition, the significant bivariate correlation of the Additive Satisfaction Facility Quality Index with the roughly related ratio of actual production to planned capacity supports the ability of the measurement approach to capture relevant variation.

In the following chapter, I turn to an analysis of this study's other main concepts of interest, integration in the facility development process and its impact on industrial facility quality.

# *Chapter 6 — Analysis of Integration and the Impact of Integration on Industrial Facility Quality*

This chapter analyzes the integration data collected from the 17 projects. First, in a fashion parallel to the analysis of the quality data, I develop summary measures for the vertical data, the horizontal data, and the longitudinal data collected using the measurement instruments shown in Figures 4.3, 4.4 and 4.5 of Chapter 4. In two cases I further substantiate the measures using bivariate correlation to assess the degree of association between the measure of interest and another roughly related measure. After the development of the three summary integration measures is complete, they will be used to create a regression model that predicts facility quality as measured by the Additive Satisfaction Facility Quality Index.

It should be noted that one pulp and paper project and one power project had more than one missing independent variable. Therefore, these projects were not included in either the development of the summary measures or the regression model.

## A SUMMARY MEASURE FOR VERTICAL INTEGRATION

Vertical integration data was collected by means of the matrix shown in Figure 4.3. The first step in interpreting this data is to focus only on the integration between non-trivial pairs of participants. The reason for doing this is to improve reliability, that is, reduce error. Relationships that were rated "low" in importance can be assumed to have more error (variation unrelated to true effectiveness) in the associated effectiveness rating. Therefore, we will only focus on pairs of participants for which the importance of integration between them was rated "high" or "moderate." I shall call these pairs the "important relationships," and symbolize the number of these relationships by $M_V$.

Next, a differentiation can be drawn between relationships that exhibited effective or favorable vertical integration, and those that were suboptimal or unfavorable. Deciding what constitutes "unfavorable" is a matter of choosing between two alternatives. The first alternative is to classify only the pairs that were rated "low" in effectiveness as being unfavorable. That is, we would identify relationships that were rated "high " or "moderate" in importance and "low" in effectiveness. However, that classification scheme deprives the analyst of valuable variance in the data. A second alternative is to recognize that some relationships were rated "high" in importance but only "adequate" in effectiveness, and that this combination of ratings also signifies a suboptimal vertical integration. Since this option captures more variation in the data, it is better suited to our needs. I will therefore classify these three combinations of importance and effectiveness ratings as *unfavorable* relationships, and symbolize the number of these relationship by $U_V$. The remaining relationships will be termed *favorable*.

Thus the percentage of important relationships in the matrix that exhibited unfavorable vertical integration is the ratio of $U_V$ to $M_V$, and this ratio is at the heart of the summary measure of vertical integration. However, rather than having a low percentage represent high integration and a high percentage represent a low integration, the ratio of $U_V$ to $M_V$ is subtracted from 1, as shown in Equation 6.1:

$$\mathbf{V = 1 - \frac{U_V}{M_V}} \tag{6.1}$$

This summary measure, V, approaches 1 as vertical integration increases, and approaches 0 as vertical integration decreases. A return to Figure 4.3 provides an example. To obtain $M_V$, we determine the number of important relationships by counting the number that are rated "moderate" or "high" in importance. There are 21 of these. To obtain $U_V$, we determine the number of unfavorable relationships by counting relationships rated "moderate" in importance but "low" in effectiveness and relationships rated "high" in importance but "low" or "adequate" in effectiveness. There are 13 of these. The other 8 relationships will be termed "favorable." The ratio of $U_V$ to $M_V$ is thus 13/21 or .62. It is now an easy matter to calculate V as .38.

Because this summary measure of vertical integration is a ratio, a quantitative estimate of its reliability such as that provided by Cronbach's alpha statistic is unavailable. However, we can attempt to validate that the vertical integration measure, V, indeed measures what it purports to measure by correlating it with other variables that, on their face, tap this same concept. This is a matter that I would like to address in future research.

A set of findings that emerge from additional analysis of the vertical integration data warrants further discussion. Effective information flow between particular project participants discriminates between higher and lower quality plants, thus suggesting that these relationships should be the focus of attempts to improve vertical information flow in project organizations. Eight such key relationships are shown in Figure 6.1. In this figure, the length of each bar represents the *difference* between the quality means of projects with a "favorable" vertical integration rating for that relationship (upper dot), and projects with an "unfavorable" vertical integration rating for that relationship (lower dot). Using one-tailed t-tests because higher vertical integration is predicted to result in higher quality, these eight differences are all significant at p<.10. A brief discussion of each of these relationships follows.

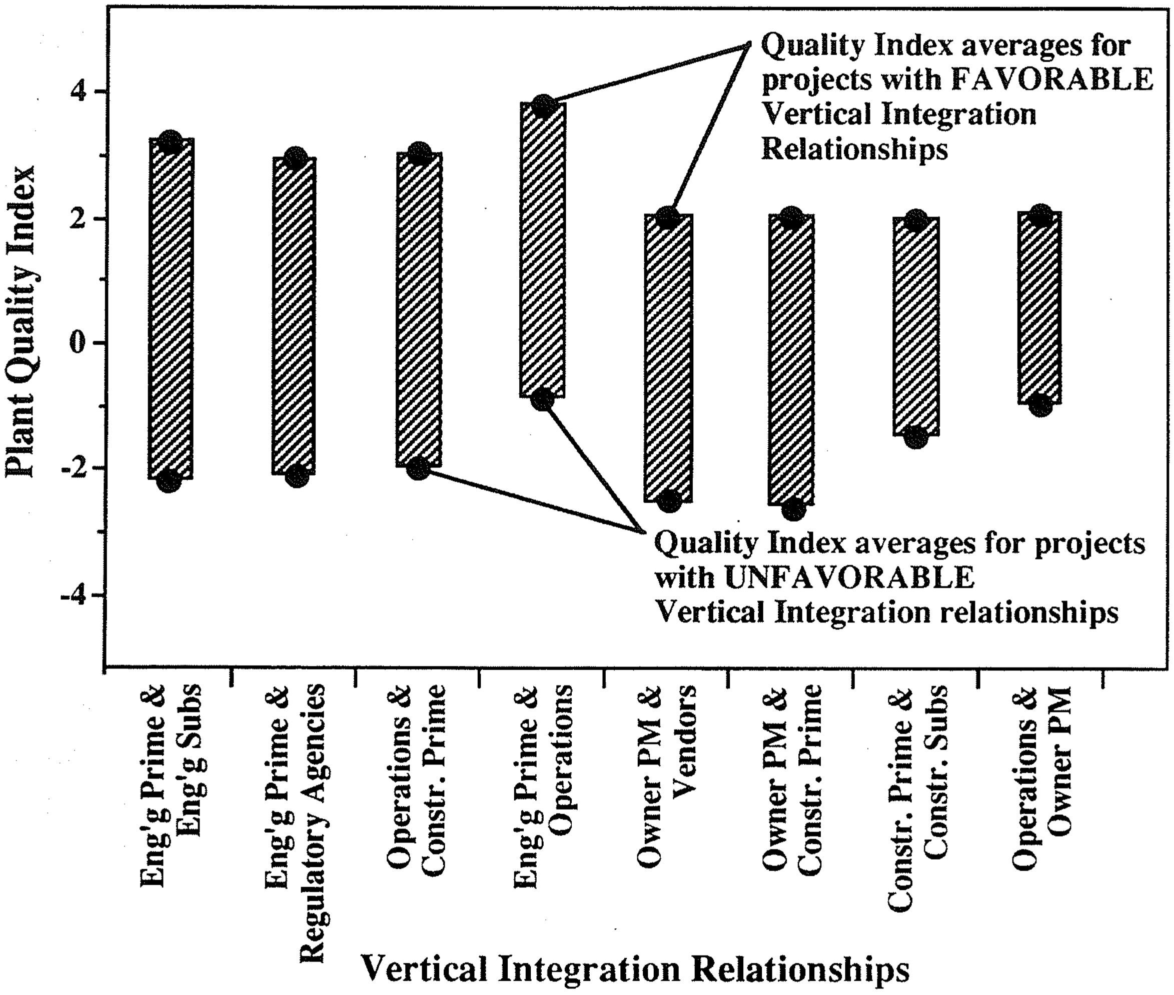

*Figure 6.1. Plant quality differences by favorable vs. unfavorable integration relationships. All differences are significant, p<.10.*

Some relationships which one might expect to appear in this chart do not actually appear, such as that of that of the Engineering Prime and the Construction Prime. One might conclude that vertical integration between these two is not sufficient to achieving a higher quality facility. An alternative explanation is that given the small sample size, this pair may not have exhibited enough variance across cases for a comparison to have been made. For example, vertical integration between them may have been favorable in all but one or two cases.

### Engineering Prime with Engineering Subcontractors

In general, the engineering prime has control over the design of the plant as a whole. In the majority of cases, part of the design involving "core" disciplines is done in-house. Other specialized work such as that for the structural system, distributed control system, cooling system, electrical system, etc. is often subcontracted. The engineering prime must convey the overall concept of the design as well as details to these engineering subcontractors. In addition, the prime often plays the role of a coordinator or mediator between all of the engineering subcontractors.

Thus it has a hierarchical (functional) relationships with the subcontractors to whom it delegates work and between which it coordinates, as well as horizontal (interdisciplinary) relationships in the sense of exchanging data between disciplines. It is the hierarchical, or functional sense of the relationship that I am concerned with here, which is uncovered by treating all the engineering subcontractors as a single group rather than individual firms.

A failure to convey overall concepts and levels of uncertainty of the design to the engineering subcontractors could have adverse effects on the quality of the plant. A subcontractor can conform to the contract specification, but the design created may still not contribute optimally to the operational whole. More knowledge and information needs to flow than that conveyed by even the most carefully written specifications. In the "unfavorable" cases in this study we can conclude that the effectiveness of vertical integration was not good enough. Ways to increase both the flow and its effectiveness are important challenges for the facility development process.

### Engineering Prime with Regulatory Agencies

This is an interesting relationship because it is so often blamed for causing "unforeseen" project delays, which in turn can impact the timeliness of startup, the profitability of the plant, meeting production output specification, etc. Although it is frequently the owner organization's responsibility to obtain permits from regulatory agencies, the engineering prime must be an expert negotiator and advocate for the owner during the permitting process. One key to good negotiation skills is being prepared and researching the other party, especially when one is negotiating from a position of lesser power. These considerations argue for the need for the engineering prime to proactively keep abreast of current and changing regulations, and to cultivate informal channels of communication.

In addition, in order to provide the client with a design that meets often-changing environmental emissions regulations, the prime engineer should keep abreast of anticipated legislation as well as advancing technology in this area. In these ways, the engineering prime can bridge the functional gap between regulatory agencies advocating the interests of the public, and the owner's interests in developing a safe, profitable plant.

### Operations with Engineering Prime
### Operations with Construction Prime
### Operations with Owner Project Management

These three different relationships each have one party in common: the operations group in the owner organization. The juxtaposition of this group with arguably the three most powerful or influential groups in a traditional project organization suggests the importance of "operability" in achieving quality in industrial facilities.

Project-oriented people frequently express the sentiment that operators always want to "gold plate" the design. However, operators contend that they could save their company large sums of money if they were to be given more discretion during the facility development process. The operator's rich knowledge and longer term perspective can provide a needed contrast to the shorter term budget and schedule objectives of project-oriented people. Engineers and project managers take deserved pride in their education, knowledge and ability to provide elegant solutions to complex problems. They must remember, however, that they generally do not have in-depth knowledge and experience of plant operations, and therefore must seek the participation of operations personnel to design world class plants.

### Owner Project Management with Vendors

Increasing vendors' opportunity to exchange knowledge and information with the owner project manager seems to be a promising strategy to increase the quality of industrial facilities. To implement this strategy, the owner project manager might proactively address issues such as, "Is the vendor capable of cooperating with us in terms of timeliness of delivery and product reliability?" "Will the equipment mesh with the functioning of the overall facility as a whole?" Addressing such issues in an active way, rather than using the traditional approach of relying on specifications to communicate expectations is one way to increase vertical integration between these two participants.

### Construction Prime with Construction Subcontractors
### Construction Prime with Owner Project Management

The fact that the prime construction contractor's integration levels with both the construction subcontractors and the owner project manager are good distinguishers between higher and lower quality plants will come as no surprise to most industry professionals. The key challenge for these professionals is to determine innovative ways to ensure and enhance the flow of knowledge and information between these key participants to achieve higher quality facilities.

In conclusion, this section has highlighted eight pairs of functional participants in the facility development process whose integration levels were shown to be significant differentiators between higher and lower quality plants. While some of these relationships come as no surprise to veterans in the field, the emerging importance of operability and vendability knowledge in the facility development process is analytically justified.

## A SUMMARY MEASURE FOR HORIZONTAL INTEGRATION

The matrix shown in Figure 4.4 was used to collect the horizontal integration data. We develop the summary measure for horizontal integration in a manner very similar to that of vertical integration. First, to improve reliability, all of the non-trivial pairs of participants are selected. These are the pairs of participants for which the importance of integration between them was rated "high" or "moderate." These "important relationships" are symbolized by $M_H$.

Next, within these important relationships, we differentiate between those which are effective, or "favorable," and those which are suboptimal, or "unfavorable" with respect to horizontal integration. The same decision rule is used as that with which the vertical integration measure was created. That is, we identify relationships that were rated "high " or "moderate" in importance and "low" in effectiveness, and those that are rated "high" in importance and "adequate" in effectiveness. These are termed the *unfavorable* relationships symbolized by $U_H$. The remaining relationships are termed *favorable.*

The ratio of $U_H$ to $M_H$ is the percentage of important relationships in the matrix that exhibited unfavorable horizontal integration. Again, rather than having a low percentage represent high integration and a high percentage represent a low integration, the ratio of $U_H$ to $M_H$ is subtracted from 1, as shown in Equation 6.2:

$$\mathbf{H = 1 - \frac{U_H}{M_H}} \tag{6.2}$$

This summary measure, H, approaches 1 as horizontal integration increases, and approaches 0 as horizontal integration decreases. Figure 4.4 provides us with an example. To obtain $M_H$, we determine the number of important relationships by counting the number that are rated "moderate" or "high" in importance. There are 11 of these. To obtain $U_H$, we determine the number of unfavorable relationships by counting relationships rated "moderate" in importance but "low" in effectiveness and relationships rated "high" in importance but "low" or "adequate" in effectiveness. There are 7 of these. The other 4 relationships will be termed "favorable." The ratio of $U_H$ to $M_H$ is thus 7/11 or .64. Thus H is .36.

As was the case with vertical integration, this summary measure of horizontal integration is a ratio, so a quantitative estimate of its reliability such as that provided by Cronbach's alpha statistic is not available. However, we can assess its criterion validity by correlating it with another variable that, on its face, partially taps this same concept. The measure we selected to validate the summary measure of horizontal integration is the total number of firms doing a substantial amount of design engineering work on a project, as identified by the engineering project manager.

We expect a negative correlation because the greater the number of firms the lower we would expect the level of horizontal integration to be. More firms implies a more decentralized (fragmented) project organization, thus more difficulty in coordinating with each other, resulting in more incidences of failure to communicate. With 3 missing values and one outlier which were not included in the correlation calculations (Belsley 1980), we had 11 cases to analyze.

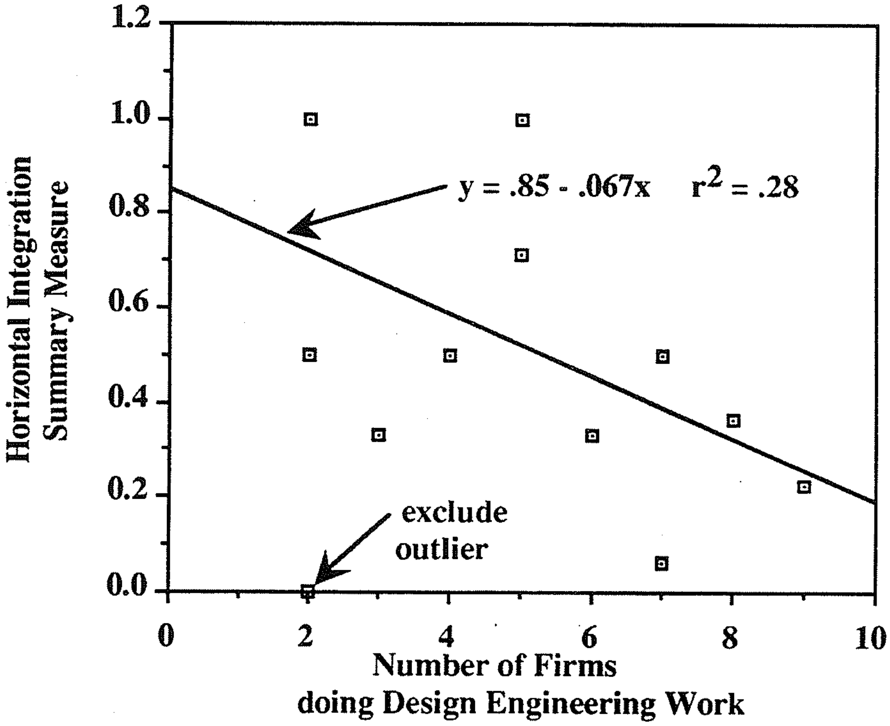

*Figure 6.2. Validation of the summary measure of horizontal integration by bivariate correlation with the number of firms doing engineering work. Excluding the outlier, a power plant, the correlation is significant, and 28% of the variance in the two measures is shared, ($r^2 = .28; p<.05$).*

The result of the analysis is shown in Figure 6.2. We found a significant negative correlation between the number of firms doing engineering work and the summary measure of horizontal integration ($r^2 = .28$; $p<.05$). This correlation lends validity to the summary measure of horizontal integration.

## A SUMMARY MEASURE FOR LONGITUDINAL INTEGRATION

The instrument I used to collect the data that will be aggregated into a summary measure of longitudinal integration is depicted in Figure 4.5. This instrument operationalizes the concept of *flow of knowledge and information across time* by capturing the extent to which the owner organization has the formal tools to learn and improve its major facility projects over time. Of the nine items, only the first six will be used in the summary measure because no respondents had used the Quality Performance Tracking System (QPTS) or Quality Function Deployment (QFD), and responses in the "Other" category were not pertinent.

The other six items can be thought of as falling into a rough order of sophistication in the use of quality management techniques. The least sophisticated technique is Quality Assurance (QA) which is the use of inspection to ensure conformance to standards. Quality Assurance has been popular for decades among organizations in the United States. More sophisticated than Quality Assurance are Total Quality Control (TQC) and Total Quality Management (TQM). These two acronyms mean essentially the same thing, though TQC seems to be a more popular term in Japan, and TQM seems to be a more popular term in the United States. Perhaps this reflects the American workers' sentiment that they would rather be "managed" then "controlled." TQM and TQC are philosophies which seek to improve an organization as a whole by removing systemic barriers to improved products and services. TQM and TQC are typified by Deming's 14 points to lead organizations "out of the crisis" caused by a reliance on inspection to achieve quality (Deming 1986).

The next level of sophistication is that represented by the Plan, Do, Check, Act cycle (PDCA) and Continuous Process Improvement (CPI). Again, these terms are very similar in meaning, the first being the popular Japanese term, and the latter the popular American term. PDCA and CPI refer to the incremental improvement of repetitive work processes using a suite of analytical tools. Statistical Process Control (SPC) is one of these tools and represents the highest level of sophistication in this hierarchy. SPC is used to measure and trend variation in repetitive work processes, so that variation can be pinpointed and reduced.

These items represent a variety of the formal tools an organization possesses that enable it to transfer knowledge and information through time, both from project to project, and within a single project.

Constructing an additive index is appropriate for these items because, on their face, they all measure closely related aspects of the same concept. Before adding the raw data items, however, they were reduced by the duration between the month of plant start up and the interview month. Therefore, the items were adjusted to reflect usage of the six programs in the years prior to plant start-up. Then, to limit the influence of any one item, and to reflect the notion of an organization's learning curve for each item (Katz 1982), a cap of 5 years was placed on each item. Because TQM is so closely related to TQC, and likewise PDCA with CPI, only the maximum of the two responses for each was used. Equation 6.3 shows the calculation for the summary index of longitudinal integration, after the raw data was corrected as described above:

$$\begin{aligned} \mathbf{L} = \ &\mathbf{min\ (QA\ or\ 5)\ +} \\ &\mathbf{min\ (\ (max\ (TQC\ or\ TQM)\ or\ 5)\ +} \\ &\mathbf{min\ (\ (max\ (PDCA\ or\ CPI)\ or\ 5)\ +} \\ &\mathbf{min\ (\ \ SPC\ or\ 5)} \end{aligned} \tag{6.3}$$

This index has a Cronbach's alpha statistic of .80 indicating that this is a highly reliable index with low error and high inter-item correlations.

In order to assess the criterion validity of this summary measure, bivariate correlation was used with a second measure which was the sum of two items. The first is the average number of prior projects on which each pair of main participants (owner, engineering prime, construction prime and construction project manager) had worked together over the 10 year period prior to the project under study. The second was the average number of prior projects on which the prime engineering organization had worked together with each of the firms doing substantial engineering work, again over the 10 year period prior to the project under study. In constructing the averages, a cap of 20 projects was used for each relationship. On its face, this measure relates well to the concept of longitudinal integration. Lessons learned and knowledge of each other's styles of working embody the idea of the flow of knowledge and information through time. This measure is also reminiscent of Kleinman's concept of implicit coordination[1] (1992) though it concerns *organizations* rather than *people* working together on prior projects.

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[1] Ideally I would have liked to have used the number of projects worked on together over the *5* year period prior to the start of the project in keeping with Katz's findings. However, it was the *10* year period which was actually measured. Dividing this figure by two to get an estimate for the 5 year period would have no impact on this variable's correlation with longitudinal integration.

These items, which would be expected to positively correlate, do indeed demonstrate this relationship ($r^2 = .54$, $p<.01$) as shown in Figure 6.3, lending further validity to the summary measure of longitudinal integration.

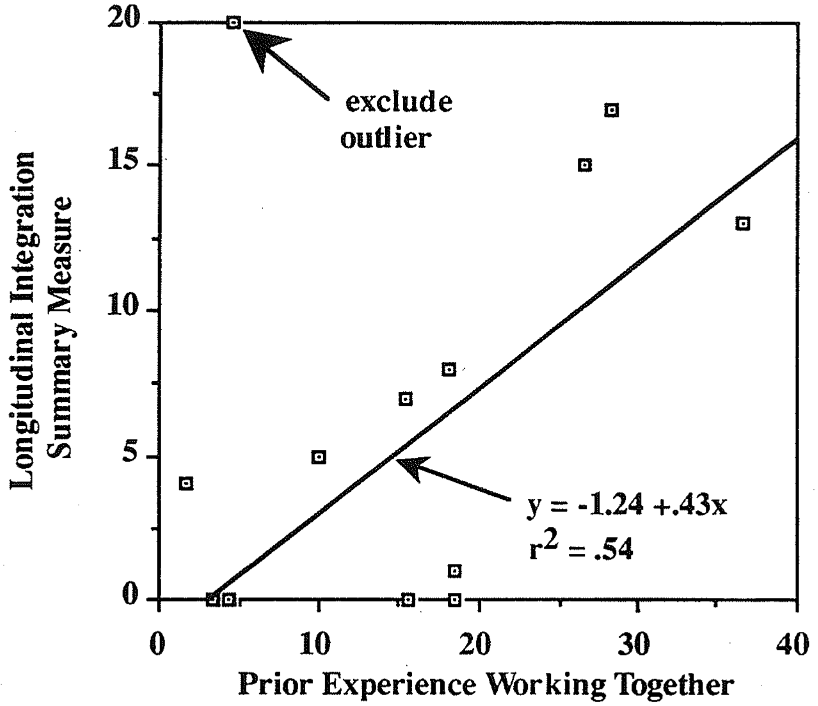

*Figure 6.3. Validation of the longitudinal integration index by bivariate correlation with a measure of prior experience. Excluding the outlier, a pulp and paper project, the correlation is significant, and 54% of the variance in the two measures is shared,* ($r^2 = .54; p<.01$).

## THE THREE SUMMARY MEASURES IN THE CONTEXT OF THE INTEGRATION FRAMEWORK

This section briefly discusses how the three summary measures of integration developed above relate to the integration framework presented in Chapter 3 and depicted in Figure 3.8.

The measure of vertical integration encompasses most of the functions in the facility development process. Exceptions are the functions of Financing and Strategic Planning. Despite these omissions, the functions seem rather well accounted for. In terms of modes of coordination, the data collection instrument's wording ("sharing of knowledge and information by technical and organizational means") includes at least some component of both organizational and technical modes of coordination. Thus, the scope of the measure appears to represent the pertinent concepts.

The use of an instrument that measures information flow between firms, as that for horizontal integration does, necessarily precludes the assessment of information flow between disciplines within the prime engineering organization. However, there is some likelihood (though no certainty) that information flow between specialized firms would be more challenging than information flow within a firm. Thus the summary measure we developed taps a component of horizontal integration that may represent an area of higher risk to project success. This measure maintains breadth at the expense of depth, and this is a reasonable strategy given that it seems to be a good idea to monitor areas of higher risk. Because the wording of the instrument did not specify the means of coordination used, it is ambiguous with respect to the concepts of organizational and technical modes of coordination. Therefore we cannot draw conclusions with respect to these two concepts.

Longitudinal integration, as a concept, concerns both the within-project and project-to-project time horizons, and the longitudinal integration measure taps both of these. In terms of the coordination modes, it emphasizes organizational modes of coordination. It measures years of experience of using one or more quality management techniques, which themselves promote humanware tools of coordination such as group brainstorming, consensus building, customer orientation, etc. The use of statistical process control introduces an element of technical coordination, in its use of math and graphs to portray process variance.

On the whole, then, we can conclude that the summary measures of integration are fairly well representative of the framework of integration presented in Figure 3.8. Where the measures fall short, it is because reasoned trade-offs have been made. The framework will now be the basis for the development of a predictive model of quality based on integration.

## A STATISTICAL REGRESSION MODEL FOR PREDICTING THE IMPACT OF INTEGRATION ON INDUSTRIAL FACILITY QUALITY

The thesis of this dissertation is that industrial facility quality is determined by the level of integration in the facility development process, and that this integration takes three forms: vertical, horizontal, and longitudinal. If observed and modeled in a structured fashion, integration levels could be used to monitor facility development processes, and to adjust these levels to achieve higher quality facilities.

This section describes the development of a regression model for predicting industrial facility quality. It starts by evaluating the suitability of each variable for inclusion in the model, then presents the model itself, followed by an analysis of the residuals. The section concludes with a brief discussion of the model's implications.

The dependent variable is the plant manager's additive satisfaction index of plant quality. The distribution of this variable is shown in Figure 6.4. Because of the small sample size (n=15), the distribution deviates somewhat from normal, though not to a worrisome degree. Regression is very robust in this regard (Tabachnick 1989).

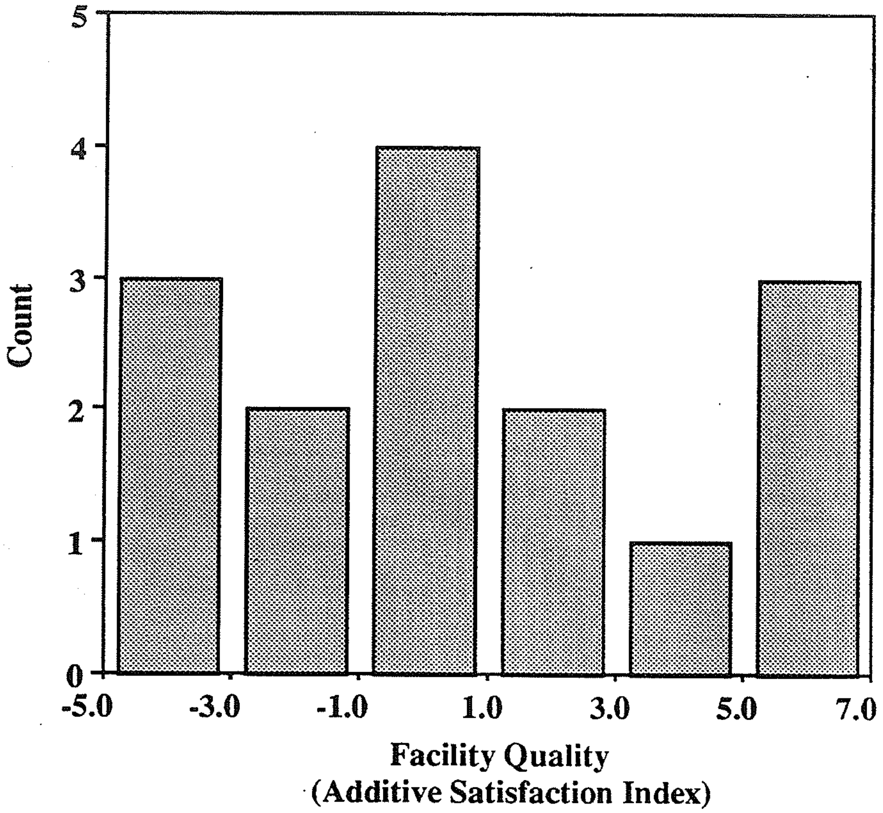

*Figure 6.4. Histogram of the dependent variable, Facility Quality n=15. In the regression model, this variable is assumed to be normally distributed.*

The bivariate plots of each independent variable with facility quality are made with two purposes in mind. First, we wish to evaluate the degree of association between the variables. On their face, do the independent variables seem to be correlated with the dependent? In addition, we wish to check for outliers. The bivariate plots of vertical, horizontal, and longitudinal integration, respectively, with quality are presented in Figures 6.5, 6.6, and 6.7.

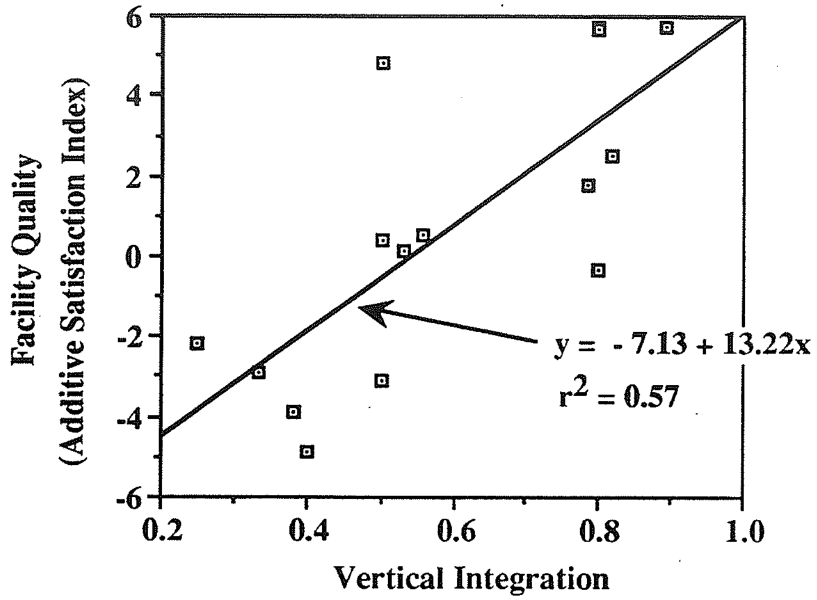

*Figure 6.5. Bivariate correlation of vertical integration with facility quality. The two variables have a positive, strong association with no outliers, ($r^2$ = .57, p<.001).*

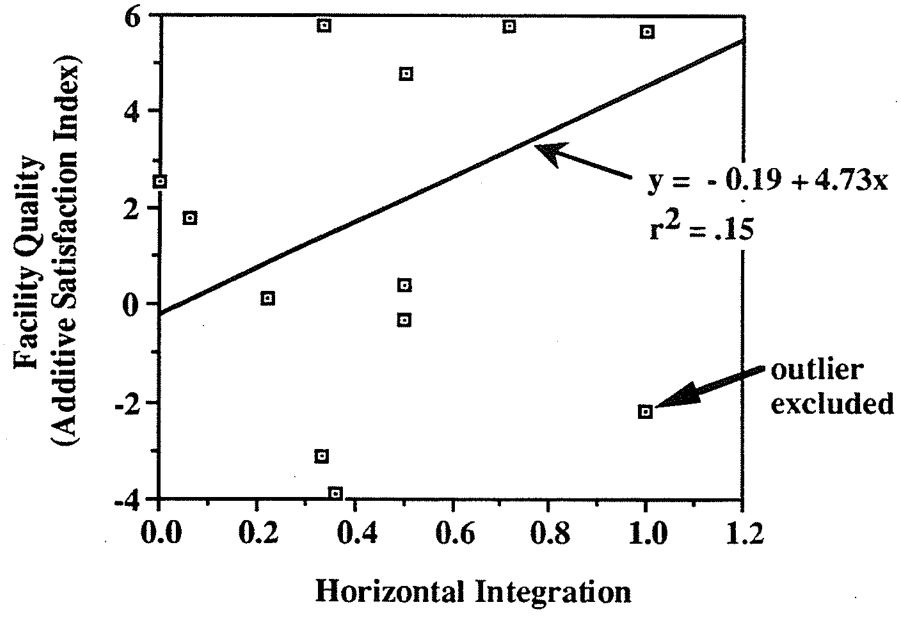

*Figure 6.6. Bivariate correlation of horizontal integration with facility quality. The plot identifies one outlier, which is not included in the $r^2$ calculation. The two variables have a positive association, ($r^2$ = .15, p < .15).*

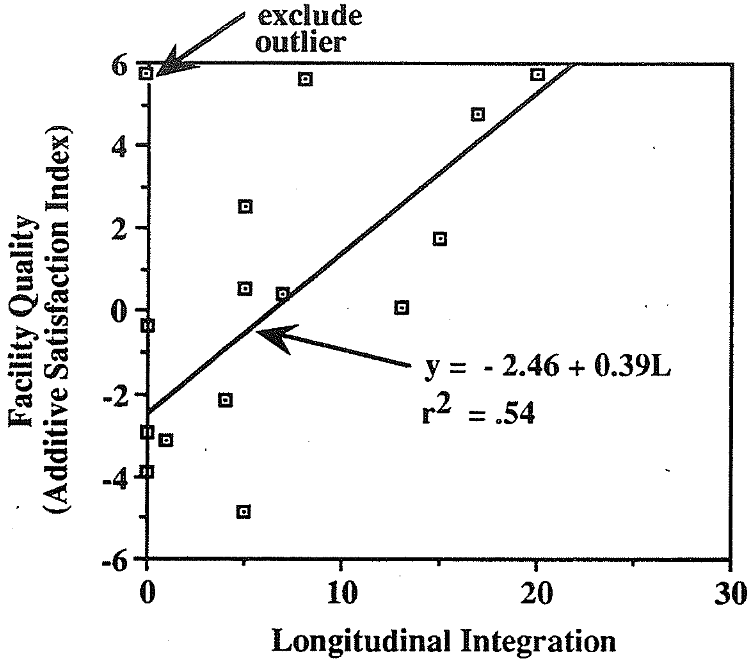

*Figure 6.7. Bivariate correlation of longitudinal integration with facility quality. The plot identifies one outlier, which is not included in the* $r^2$ *calculation. The two variables have a positive, strong association,* ($r^2 = .54, p<.001$).

All correlations are positive, the expected direction of association. The correlations of vertical and longitudinal with quality are significant, though the horizontal integration and quality association falls somewhat short of significance (p<.15). No outliers are identified from the plots of vertical integration with quality, though one was identified in the horizontal vs. quality plot and one was identified in the longitudinal vs. quality plot. The horizontal integration outlier's value seems higher than warranted by the actual project. It may contain error because the engineering project manager was among the study's very first interviewees, and, being less practiced, I may have caused him to respond in a "defensive" manner. The longitudinal integration outlier's value may be due to the fact that the plant manager was new to the company. He had been recruited specifically to help design and operate the new plant, and may not have been familiar with the history of quality management programs in the company. Other respondents in the company indicated that quality management programs were in use. These cases were excluded from the respective correlation calculation of horizontal and longitudinal integration with quality in Figures 6.6 and 6.7, above. In the regression analysis, the average (mean) value for horizontal and longitudinal integration, respectively, will be substituted for these cases' original outlier values. This technique of "mean substitution" will be used for the three missing values of horizontal integration as well.

As an initial check for the problem of multicollinearity, which occurs when two or more independent variables are highly correlated, Table 6.A presents the correlation matrix for the independent variables, with the outliers on horizontal and longitudinal treated as a missing values. The correlations are not significant, suggesting that the three dimensions are truly independent or orthogonal. This, combined with the fact that the independent variables correlate positively with the Facility Quality Index, strongly supports the theoretical model of integration developed in Chapter 3. It also supports my measurement approach: if the integration dimensions had been highly correlated, we might suspect that we merely had measured the same concept (e.g. the general happiness of the plant manager) three different ways.

| | **Vertical** | **Horizontal** | **Longitudinal** |
|---|---|---|---|
| **Vertical** | 1.00 | 0.13 | 0.39 |
| **Horizontal** | 0.13 | 1.00 | -0.11 |
| **Longitudinal** | 0.39 | -0.11 | 1.00 |

*Table 6.A. The correlation matrix of the independent variables shows that there are no significant correlations between them. Multicollinearity does not appear to be a concern.*

As a more rigorous check for multicollinearity, I performed three regressions, each of which attempted to predict one independent variable from the other two. In no case did the $R^2$ exceed .15, an assurance that multicollinearity does not affect the beta values of the regression equations presented below. As a conservative rule-of-thumb, any $R^2$ below .50 indicates multicollinearity is of no concern.

To this point we have been checking the suitability of the dependent and independent variables for inclusion in the regression equation. All variables do indeed seem suitable, and meet the assumptions and requirements of this statistical technique. We are therefore ready to proceed with the regression analysis itself.

The regression analysis produces a very strong model ($F = 21.9$; $p<.001$; adjusted[2] $R^2 = .82$), which is shown in Figures 6.8 and 6.9. The regression equation itself is presented in Equation 6.4, and the standardized regression equation in Equation 6.5.

$$Q = -9.0 + 9.4V + 4.8H + 0.3L + \varepsilon \tag{6.4}$$

$$Q_s = .54V_s + .32H_s + .52L_s + \varepsilon_s \tag{6.5}$$

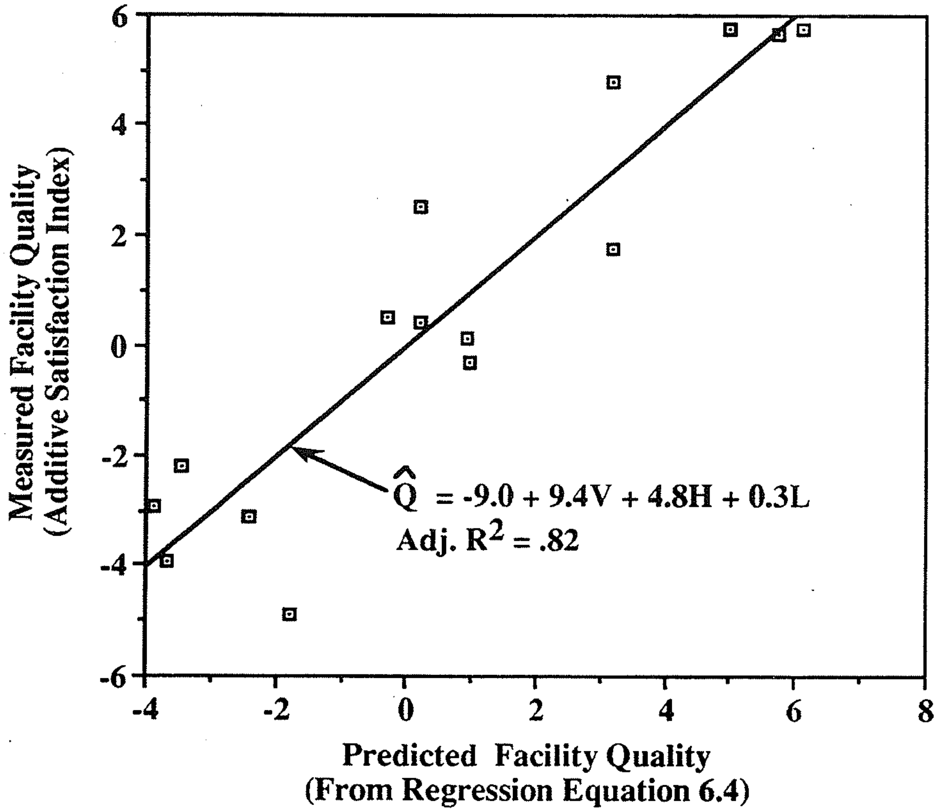

*Figure 6.8. The regression of vertical, horizontal, and longitudinal integration with facility quality. Actual (nonstandardized) values of the variables are assumed in the equation. 82% of the variance in plant quality can be predicted by the integration parameters.* ($F = 21.9$; $p<.001$; adjusted $R^2 = .82$).

The regular regression equation (Equation 6.4 and Figure 6.8) is used for prediction of quality using the actual (nonstandardized) values of the independent variables. The

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[2] The adjusted $R^2$ reduces the amount of explained variance for regressions in which there are relatively few cases, and thus a high unadjusted $R^2$ is relatively easy to obtain.

constant has a negative sign because the values of all the independent variables are greater than or equal to zero, and plant quality values range from about -5 to +6.

The standardized regression equation (Equation 6.5 and Figure 6.9) can be used to compare the relative importance of the three types of integration in achieving facility quality. Because this equation uses standardized scores for the variables (ranging in general from +3 to -3) there is no constant term. The s subscript indicates the variables are standardized.

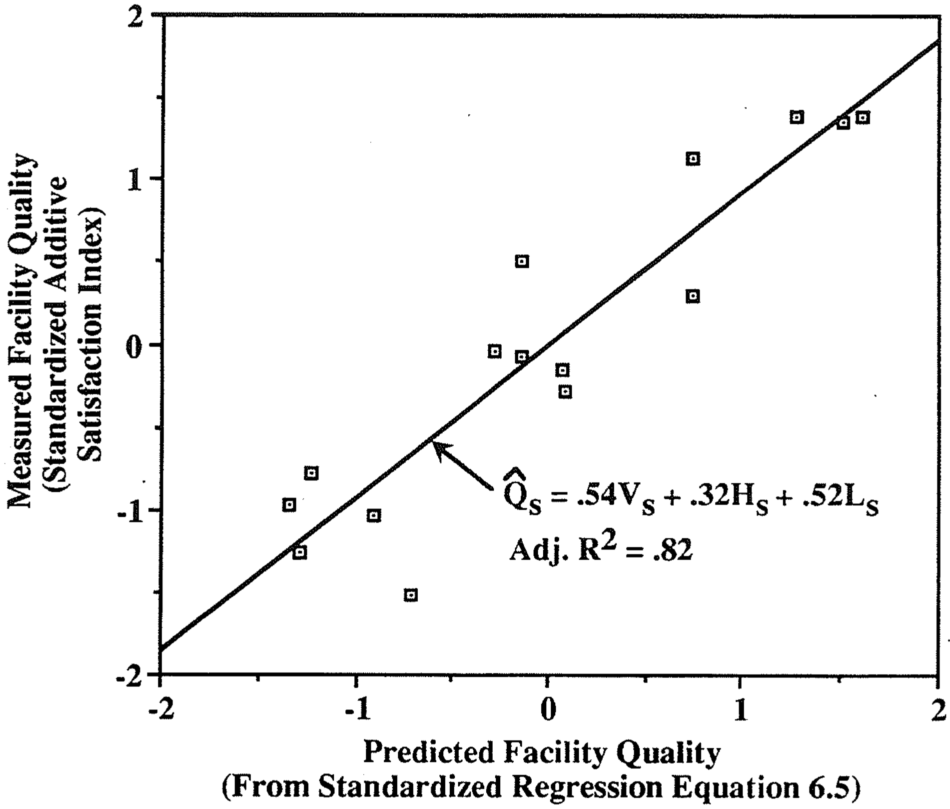


*Figure 6.9. The regression of vertical, horizontal, and longitudinal integration with facility quality. Standardized values of the variables are assumed in the equation. Otherwise, the graph is identical to Figure 5.12. The standardized beta coefficients, .54, .32, and .52 for vertical, horizontal, and longitudinal integration, respectively, suggest the relative importance of integration in these three dimensions for developing a high quality plant.*

The check for heteroskedasticity in Figure 6.10 shows no pattern in the residuals, so we can conclude that the regression assumption of normally distributed error is met.

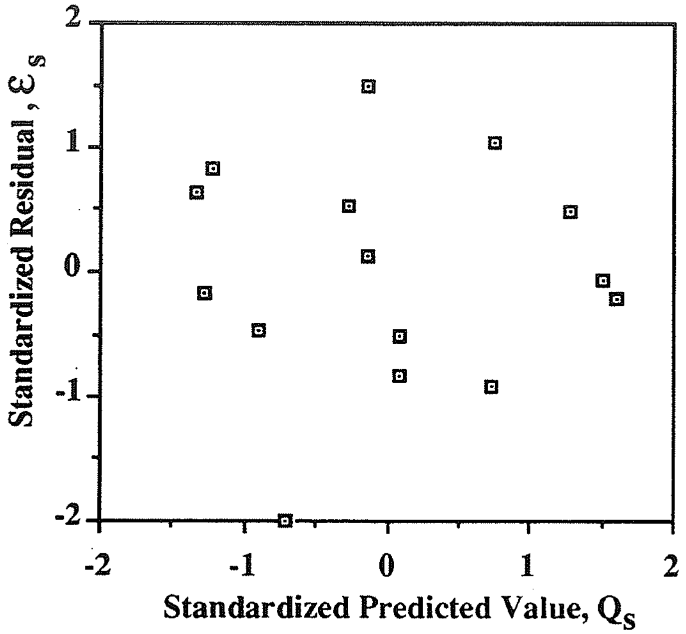


*Figure 6.10. The residuals form a patternless cloud, allowing us to conclude that our model is not affected by problems of heteroskedasticity.*

The model's standardized beta coefficients (.54, .32, and .52 for vertical, horizontal, and longitudinal integration, respectively) are also significant. The probability, p, of Type I error (predicting a relationship when none in fact exists) for vertical and longitudinal integration is $p<.01$, and for horizontal, $p<.05$.

Vertical and longitudinal integration appear to be about equally important dimensions, having respective standardized weights of .54 and .52 in the regression equation. This suggests that a company's most effective quality improvement investment is in cross functional and cross temporal information flow. Horizontal integration is less influential, with a standardized weight of .32. The implication of these weights is that emphasizing vertical and longitudinal integration is a good strategy for both EPC and owner organizations that wish to improve the quality of their industrial capital facilities. Integration research programs and funding agencies, which seem to favor horizontal integration studies, should suitably balance these efforts with investigations into the vertical and longitudinal dimensions.

We have shown that plant quality can be successfully predicted by means of a regression equation in which 82% of the variance in plant quality is explained by the three integration parameters. This lends strong credence to the hypothesized relationship between process integration and product quality. As complex as the facility development process is, the integration framework is an excellent filter through which to view it. We have shown that integration can be measured. If it is monitored with an eye to increasing it, we can adjust the structure of our project organizations and work processes to create better quality facilities. And that, after all, is our ultimate goal.

# *Chapter 7 — Conclusions and Contributions*

The analyses presented in the two preceding chapters suggest several conclusions and recommendations in the areas of quality, integration, and the impact of integration on quality. In addition, based on the definitions, measurement approaches, and predictive regression model developed in the course of this research, the research makes contributions to knowledge in the field of engineering and construction management. These conclusions and contributions are discussed in this chapter.

## CONCLUSIONS AND IMPLICATIONS

The following four subsections provide the reader with a summary of the results of this study and the conclusions that may be drawn from them. These conclusions have implications for industrial facility development and the participants in this process.

### Facility Quality as a Source of Competitive Advantage

In the 1970s, Japanese automobile manufacturers capitalized on product quality as a market niche created by outdated business practices in the rest of the auto industry. Today, progressive companies involved in industrial facility development have a similar opportunity to forge ahead of their competition.

The first step is recognizing that there are multiple viewpoints of industrial facility quality in owner organizations. Viewing quality as *customer satisfaction* rather than *conformance to requirements* makes evident the possible existence of multiple customers. From the standpoint of an organization that plans to become more competitive, it is essential to recognize who it is, exactly, that must be satisfied. This study identifies three types of customers in an owner organization, as supported by two different analyses. The numerous differences in facility quality criteria were shown in Table 5.A. The analysis of sign differences in Table 5.B points to dramatic differences in evaluation of facility quality by different groups within the owner organization. The groups have markedly different priorities and levels of satisfaction with facility characteristics, and in essence, different definitions of facility quality.

One of the most dramatic differences is that owner project managers have a much more optimistic view of the quality of facilities than those people who work with these facilities on a day-to-day basis and who are responsible for their profitability. Project managers, however, are typically the project participants who communicate the priorities and expectations of the owner organization to other project participants such as vendors and engineering and construction contractors. If the owner's project manager does not have a clear understanding of the attitudes of the organization's strategic and operations people towards completed facilities, then there is less likelihood of producing a new facility that satisfies them in the long term. This is true even when project-oriented objectives such as schedule, budget, and start-up deadline are met.

The importance and satisfaction quality differences among owner groups highlight areas for improvement. Organizations can narrow the gaps between groups, such as those shown in Figure 5.2, by increasing their understanding of the underlying causes of differences in attitude, and taking steps to help the participants align their goals. The mean difference technique used to create Figure 5.2 is a way to pinpoint conflicts in owner organization priorities that typically cause difficulties and change orders in project execution. Resolving these differences through alignment of attitudes would logically lead to smoother project execution and a better product.

Identifying facility characteristics that demonstrate high importance and low satisfaction ratings is another opportunity for attaining competitive advantage. These items indicate areas in which customer expectations are not being met. Examples of such characteristics are shown in Table 5.C. Both owner and EPC firms could gain competitive advantage by addressing these attributes. EPC firms could differentiate their services on the basis of these items, and owners could likely improve their operations and profitability. Particularly, more in-depth equipment operation training programs and better equipment operations and maintenance manuals appear to be easily and relatively inexpensively implementable goals. Improving plant reliability is another very important (though perhaps more difficult) goal, but one that could have tremendous payoffs. Even a fraction of a percentage point increase in process production could mean a welcome increase in profitability.

The observation that there are multiple viewpoints of quality in owner organizations has important implications for both EPC firms and the owners themselves. Improvements in assessing owner requirements, priorities, and expectations are needed in the facility development process. In particular, the needs of the operations group should be reflected in design. We hear over and over again from EPC firms about how poorly owner organizations communicate their priorities regarding new facilities. Owners complain about facility deficiencies after their completion. This research suggests that a small investment in measuring and understanding these attitudes pro-actively could have a high return. The return for EPC firms would be in achieving customer satisfaction and repeat business. The return for owner organizations would be the attainment of facilities that truly meet the expectations of *all* the stakeholders in the owner organization, from maintenance personnel to the chief executive officer.

## Measurement of Facility Quality

This dissertation has demonstrated a rudimentary technique for measuring attitudes about facility quality from the owner perspective. It must be kept in mind that this was a preliminary study, the first of its kind. As such, there are certainly ways in which it can be improved to obtain more accurate, more easily interpretable data. In Appendix B, I present ideas for a revised questionnaire regarding industrial facility quality. They incorporate several improvements suggested by the data gathering and analysis experiences in this study. These improvements include longer scales, better question wording and format, more questions regarding characteristics of particular interest such as reliability, better ways for classifying the respondents in owner organizations, and clearer definition of some terms.

However, despite the rough edges of the current study, its method of using attitude scales is straightforward enough for owners and EPC firms to adapt to their own applications such as benchmarking for continuous process improvement. In addition, it is a suitable technique for academic research because it allows the collection of meaningful data while potentially avoiding the necessity of gathering proprietary data such as return on investment, annual profits from the plant, etc.

Many of the facility quality characteristics presented in Table 2.A demonstrated an ability to differentiate between different groups. Following the model of Cacioppo and Petty (1982), the ability of items to distinguish between groups validates that these items are indeed measuring the concept of interest. Like Cacioppo and Petty, I retained six of these items to use in the additive satisfaction index.

I validated the completeness of the list of facility characteristics by the use of write-in characteristics which respondents were instructed to consider after rating the items that appeared on the questionnaire. Responses indicated that an "architectural image" item should be added as a facility characteristic in future studies. Other than that item, no other write-in item appeared more than once, which substantiates the validity of the list as a whole. In a combined sense, the items acceptably represent the concept of facility quality for industrial process plants. The items are further defined and critiqued in Appendix A.

I found only one "objective" representational measure, the ratio of actual production to planned capacity, to be appropriate for comparing facility performance. Other "objective" measures, while they may be appropriate for assessing facilities within single industries such as chemical manufacturing or power generation, cannot be used to compare the diverse collection of facility types represented in this study. The ratio measure, despite its inability to account for planned extra capacity and other quality characteristics, was useful in validating the additive satisfaction quality index of subjective, nonrepresentational measures.

The summary index is a concise measure for comparing industrial facilities as products of the EPC process. Owners could use this or a modified index to assess the quality of their own operating facilities. EPC firms could adapt the index to assess their own performance in providing facilities that satisfy their range of customers in the owner organization, from the project management contacts they work with on a daily basis, to the division manager who will be responsible for the long-term profitability of the plant. Using the summary index would allow both owners and EPC firms to track their improvement in producing quality facilities over the coming years.

The summary index is composed of six items that significantly distinguish between owner groups as shown in Figure 5.2. In addition, four of these items are high importance, low satisfaction items drawn from Table 5.C. Thus the index represents issues pertinent to a variety of participants in the facility development process. Tracking facility quality improvements by means of this measure will require key aspects of industry competitiveness to be addressed in a substantive way. In a world where the word "quality" is often cynically associated with expensive consultants touting the words of the most recently fashionable guru, I prefer the type of insights derived from the rational approach to measurement and analysis presented in this dissertation.

### The Dimensions of Integration

I developed a framework of integration in the facility development process by distilling the work of prior researchers in the field of engineering and construction management and augmenting this with ideas from organization theory and economics. The framework is broad enough to encompass the variety of traditional uses of the term "integration." It provides a simple yet powerful common lexicon for academics and industry professionals alike to describe phenomena and principles in the facility development process. The vertical, horizontal, and longitudinal dimensions, with organizational and technical means of coordination, comprise a unified and internally consistent theoretical model that can be readily applied to describe and analyze a project.

Based on the definition of integration as *flow* of information and knowledge, detailed hypotheses can be phrased in terms that all civil engineers are comfortable with: turbulence, density, viscosity, purity, velocity, pressure, etc. (E.g., "the information flow from participant "a" to "b" is turbulent at high velocities.") Like Galbraith (1973), I view knowledge and information as fluid commodities flowing through channels of communication.

The measurement and analysis of vertical integration between industry functions highlighted eight pairs of participants between whom the flow of knowledge and information is a significant differentiater between higher and lower quality products, as shown in Figure 6.1. Several of these relationships are commonly cited as being very important to project success, but others receive very little attention in the literature. For example, the relationship between the engineering prime and regulatory agencies is the second best quality differentiater among these vertical integration relationships. There are many examples of how a conflict with a regulatory agency had a detrimental impact on a project. Usually these conflicts are written off as "external influences," or "beyond our control." However, this analysis suggests that such problems could potentially be mitigated by an effective flow of knowledge and information between the functions.

In addition, the importance of integration between the equipment vendors and the owner project management is highlighted by my method. Since process equipment can be in the range of 50 to 75% of a plant's capital cost, this is a critical area for additional study. Likewise, the interactions of the owner's operations people with both the engineering and construction prime emphasize the importance of incorporating "operability" knowledge if the facility development process is to result in a plant of high quality.

Horizontal integration, especially by technical means of coordination, has been a heavily studied form of integration over the past few years. It is an appealing notion that the widespread problems in the facility development process can be solved by technical means, especially by concentrating on information and knowledge exchange between the traditional specialties. As engineers, we are easily seduced or even bewitched by the latest advances in technology which seem to promise a step forward in addressing our industry's ills. Unfortunately, in our engrossing romance with technology, we may be overlooking other fundamental answers which involve more leadership, and perhaps a break with past traditions. (It is far easier to buy computers than it is to change the structure of project organizations.) I am by no means advocating that we shun technological solutions; far from it. But the full potential of the tools cannot be realized if we don't first master the understanding of how the ways that information flows in a project affect the quality of the product it produces (NNI 1989). My humble suspicion is that the human and organizational challenges are harder to implement but may pay greater dividends. The relationship between technical and organization means of coordination deserves more attention. The essential thing is to gain an understanding of how to invest resources wisely toward achieving the overarching goal: improving facility quality.

We saw in Chapter 6 that when used in the main regression equation, this measure is a significant predictor of facility quality, but that it actually had less influence on the achievement of plant quality than integration in the vertical and longitudinal dimensions in this study. Although it would be unwise to base far-reaching policy on just a single study such as this, the lower weight calculated for the horizontal integration variable suggests that efforts in other dimensions of integration and understanding the relationship between technical and organizational modes of coordination merit as much, if not more, attention.

The composition of the index measure for longitudinal integration links this research with a large body of quality management practice in industry. The components of quality assurance, quality management, structured process improvement, and statistical methods for analyzing process variance foster a culture in the owner organization which embraces continuity and improvement over time. The success of these practices in driving the owner organization to create a better facility development process is supported by the correlation between the longitudinal index and facility quality. These results are especially interesting in light of the recent backlash against quality management programs as being wasteful of company resources (Schaffer 1992) (Naj 1993). Of course, results based on such a small study should be interpreted with caution, but they do suggest that owner organizations with well established quality management programs will have more success in developing high quality industrial facilities than those that do not.

Currently, owners and service organizations in the EPC industry spend millions of dollars annually on such quality management efforts. This research project suggests a way to monitor improved quality due to those efforts. Though the impact on facility quality of the use of quality management tools in contractor organizations was not specifically analyzed in this study, we might expect a parallel, though less dramatic effect than that which was observed for the owner organization. This expectation derives from the fact that owner organizations have much more control of the overall structure of the project organization than do contractor organizations, and their culture would have a greater influence on project structure decisions.

In addition, the method of validation by bivariate correlation of the longitudinal integration index with another measure of longitudinal integration, the prior experience variable, gives me confidence that I am indeed measuring the concept of longitudinal integration. The significant correlation ($r^2$=.54; $p<.01$) between these two variables lends credence to this component of the integration framework.

## The Impact of Integration on Industrial Facility Quality

Our purpose in developing a statistical regression model that predicts facility quality based on measuring the flow of knowledge and information in the facility development process was to test the whether the thesis of this dissertation could be supported empirically. The test showed that the thesis could indeed be supported, and with a high level of confidence. I found that 82% of the variance in facility quality could be explained by the integration parameters. These results should guide industry professionals to focus on enhancing knowledge and information flows when designing project structures and contract incentives.

These highly successful results suggest that a deeper analysis of integration as a determinant of facility quality is a worthwhile pursuit. With a larger sample of projects, more subtle concepts within the framework of integration could be tested. Recommendations for further study in this area are discussed in the last section of this chapter.

In this study, the regression weights in the model ($\beta_V = .54$, $\beta_H = .32$, $\beta_L = .52$) suggest that vertical and longitudinal integration have the highest influence on quality, and horizontal has less influence. The lesson for industry professionals is that the ideal facility development process strives to achieve high levels of integration in all three dimensions, though recognizing that perhaps horizontal integration has the least influence. Future study will allow us to determine these relative weights with more certitude with the refinement of measurement instruments and experimental designs.

## CONTRIBUTIONS TO KNOWLEDGE

### Point of Departure

This study extends the literature in three areas of the engineering and construction domain: quality, integration, and the impact of integration on quality.

In the area of quality, this study investigates product quality rather than process quality as the focus of inquiry, and customer satisfaction rather than conformance to requirements as the definition of quality. In this context, Stokols (1990) has evaluated offices and Preiser (1988) has studied housing and offices. The current study adds industrial process facilities to these other types of facilities studied. By using an attitude measurement technique, Stokols provided a starting point for the quality measurement methodology developed in this dissertation.

In terms of integration, this study extends the organizational theory literature by adding an empirical study of vertical and horizontal integration in the domain of engineering and construction to the many other industries represented in this literature Blair (1983). It gathers the diverse uses of the term "integration" in our industry, and ties them together in a comprehensive framework. Whereas other work such as Williamson (1979), Stinchcombe (1985), Vanegas (1988), Fischer (1989), Tatum (1989), Williams (1990), Thomas (1992), Nam (1992), Khedro (1992), Teicholz (1993), and others, discuss integration or related themes, their approaches are less comprehensive, focusing on less well defined, and usually narrower, types of integration. The comprehensive framework presented in this study enables the recognition, measurement, and comparison of different types of integration.

My use of a structured theoretical process framework to predict facility quality is unique in the engineering and construction domain, with one exception: Alarcón-Cárdenas and Ashley's (1992) General Performance Model (GPM) to evaluate project execution strategies in terms of several project outcomes. Within the GPM, various execution strategies interrelate to impact project outcomes of cost, schedule, start-up effectiveness and, most important to our purposes, facility quality. The knowledge that drives the model is to be provided by industry experts. At this point, the model exists in a theoretical state, but once it is built and loaded with expert knowledge, it will be utilized to predict the effects on facility quality that result from different project execution strategies such as incentives, team building, and organizational structure. My work complements the GPM by utilizing a statistical regression model to predict facility quality from integration parameters. Although both models are predictive in nature, the GPM uses expert opinions regarding executions strategies as its driver, while mine uses measured integration data from actual projects. It will be instructive to both teams of researchers to compare the results of these two predictive models.

## Contributions to Knowledge

By means of meeting the three research objectives, this study makes five specific contributions to knowledge in the field of engineering and construction management. The three objectives were 1) to establish the meaning and measurement of industrial facility quality, 2) to establish the meaning and measurement of integration in the industrial facility development process, and 3) to increase understanding of how integration in the facility development process impacts the quality of the operational facility. The five contributions resulting from meeting these objectives are discussed below.

1) **Definition of quality for industrial facilities.** I developed and validated a formal definition of industrial facility quality as customer satisfaction with a comprehensive list of facility characteristics. This definition led to the identification of three groups in owner organizations, each with a different perception of quality. Based on these differences, I extracted a set of key facility characteristics (shown in Figure 5.2) that highlight areas in which owner organizations should strive to align internal goals to gain potential competitive advantage.

2) **Quality measurement.** Based on data gathered using the semantic differential technique, I identified a set of facility characteristics that were rated as high in importance but low in satisfaction by people in owner organizations. Drawing from this set and the set generated by the items' ability to distinguish between owner groups, I developed the additive satisfaction index as a summary measure of industrial facility quality. I validated that this measure is representative of the concept of facility quality by correlating it with a related, though weaker measure of quality ($r^2=.23$, $p<.05$).

3) **Definition and framework of integration.** By distilling and synthesizing ideas from theories of organizations, process coordination, and economics, as well as prior work in the field of engineering and construction management, I developed a conceptual model of integration. This framework has three dimensions of integration and two means of coordination. It defines integration as the flow of information and knowledge, and takes a full life cycle view of the industrial facility development process.

4) **Integration measurement.** I combined research methodology traditionally used in the social sciences with knowledge of the facility development process to create data collection instruments corresponding to the concepts of the vertical, horizontal, and longitudinal dimensions of integration. They were developed and implemented to measure variance in the flow of knowledge and information in the facility life cycle. In addition, I created measures that summarized the data to form a single variable for each dimension.

Experience gained in the study with respect to questionnaire item development and determining what and how information can be gathered quickly and accurately from busy industry professionals will contribute to the methodology adopted for data collection in future studies. Ideas for data collection instruments which advance the integration questions used in this study are suggested in Appendix B.

**5) Statistical regression model to predict the impact of process integration on industrial facility quality.** I created a statistical regression model to predict the impact of facility development process integration on industrial facility quality. The regression model parallels the process-product viewpoint taken in this study, with the process characteristics represented by a structured framework of independent variables, and the product by the dependent variable. Statistically, the model is highly significant (adj. $R^2 = .82, p<.001$). The three measures of the three dimensions of integration are all useful predictors. The model can be used by industry professionals to evaluate whether information flows in their own projects are leading to high quality facilities.

These five contributions to knowledge add to our fundamental understanding of the facility development process. I see each of these contributions as first steps in an important line of research. As the definition and measurement of process integration, facility quality, and the impact of integration and quality are rigorously refined and tested in ensuing work, our mastery of the complexities of the facility development process will grow. This growth will be to the ultimate benefit of facility owners as well as engineering and construction organizations.

## FUTURE RESEARCH

There are several types of future studies that would build on the results of this research. Some studies would attempt to replicate the results of this one using different samples and improved measurement techniques. Other studies would explore ideas and issues raised in the course of this research in greater depth.

Triangulation is the process by which studies concerning a similar concept use different methodologies to gradually converge on a unified theory. No one study is capable of addressing all threats to validity. There are always trade-offs between internal and external validity. Of course, the results of related studies are not *a priori* expected to converge. Divergent results serve to strengthen theory and are just as important as convergent results in the pursuit of knowledge. Regardless of whether their results converge or diverge from this study, ensuing studies should be designed to address the weak areas of validity in this one.

To address the limited generalizability of the results of this study, future studies employing survey methods should attempt to sample *randomly* the population of completed industrial facilities. Although it is often difficult to obtain organizational access, this is an achievable goal. The payoff of generalizability of results would be well worth the effort. In addition, in order to take advantage of a wider range of the powerful multivariate statistical techniques to gain deeper insights of the data, a larger sample (n = 30 or 40) of projects should be utilized.

Future research should improve upon the measurement techniques described in this paper. Ideas for questionnaire items which address some of the methodological shortcomings in this study are presented in Appendix B. In particular, a better method of measuring importance, scales with finer granularity, and more precise question wording should be used. Several questions should be used to get data regarding critical characteristics such as training and reliability. The relationship between technical and organizational modes of coordination and the three dimensions of integration should be explored. In addition, a sampling approach to achieve a more balanced number of respondents in each owner group is necessary.

One idea for collecting more accurate information on the exchange of information and knowledge over the course of a project is the use of an "info meter" that would record characteristics of integration events. I envision a small, hand-held data collection device like those commonly used by utilities maintenance workers. Upon completing each integration event, or upon a pager's cue, or once a day at the end of a day, a person could use a barcoded "scorecard" to enter attributes of the one or more integration "events" in which she or he participated. Attributes might include means of exchange (types of organizational or technical coordination), duration, recipients or participants in the event, importance, and subject matter.

This would be a quick, accurate, and relatively inexpensive form of data collection, and would remove several kinds of bias in data collection. The novelty and fun of the collection device could be an incentive for people to participate in such a study. In addition, it would enable the collection of a large volume of data with a relatively small investment in time by the researcher. A final advantage is that the data could be efficiently downloaded into a data analysis program without the heavy expense of time, labor and inaccuracies associated with traditional modes of data collection.

Returning to more traditional methods, I wish to expand the detail of measurement of high importance, low satisfaction facility characteristics. Since these characteristics are areas in which both owners and EPC firms can gain competitive advantage, studies should probe them in more depth by developing several measures for each characteristic, and should use open ended questions to gather rich verbal data.

The distinctions between groups within the owner organization need further exploration. Some ideas for this are suggested in Appendix B. Of particular interest to industry may be a determination of the function(s) of the people within an owner organization who typically have the most say in choosing the contractor. These are the most important people to satisfy directly from a competitive standpoint. But certainly diffusion of opinion within the owner organization will influence these people as well. Another interesting idea to test is whether the level of concurrence in attitudes among people in different groups in the owner organization is correlated with plant quality. In other words, does alignment of goals within the owner organization lead to higher overall quality?

Certainly the relative importance of the dimensions of integration (vertical, horizontal, and longitudinal) should be studied in more depth. In addition, how do the concepts of organizational and technical coordination relate to the three primary dimensions? Is it possible to quantify these relationships? Are certain modes always more influential than others, or do they vary by primary dimension? Does the form of contract influence the relative importance of these dimensions? Are there trade-offs between technical and organizational coordination, or are they complementary?

An in-depth longitudinal study of one or two plants, from the start of conceptual design through the first few months of operation could deepen our fundamental understanding of modes of coordination and integration variables in all three dimensions. In particular, more representational measures of both quality and integration could be explored in addition to the nonrepresentational measures emphasized in this study. However, studies which rely on representational measures of quality are advised to use a population of the same type of plants, since such measures can be expected to vary by plant type.

Once additional measures are identified, another longitudinal study, this time with a large sample of projects, could be undertaken. A key objective would be to measure integration while design and construction were underway, and then measure quality after the first several months of operation and again at one or more later times. This experiment design would ensure that participants' attitudes about the quality of an existing plant did not cause selective recall of knowledge and information flow characteristics during the facility development process.

This study has resulted in new insights regarding quality and integration. These findings raise important new research questions which deserve more in-depth exploration by future researchers. The development of sound, easy-to-use quality and integration measures will help owners as well as engineering and construction professionals to meet the competitive challenges of the 1990s and beyond.

# *Appendix A — Data Collection Instruments*

This appendix has three main sections. The first section is the Industrial Facility Quality Factors questionnaire which was used in this study to obtain plant quality data from people in the owner organization. This questionnaire is composed of 31 facility quality characteristics which were rated on importance and satisfaction scales by the respondents.

The second section of this appendix annotates these characteristics. Measurement problems experienced with two of the items are discussed, and one item is added to the list for a total of 32 facility characteristics that comprise the scope of industrial facility quality as defined in this study.

The final section of the appendix is the Industrial Plant Life Cycle Process Factors questionnaire that was used to capture integration data from four project participants: an owner representative, the engineering project manager, the construction project manager, and the plant manager.

## INDUSTRIAL FACILITY QUALITY FACTORS

**Instructions:**

People in the owner and operations organization(s) rate each item below on two scales. First, what is the importance of the item to the owner or operator in this case? Secondly, what is the owner or operator's satisfaction level with the item? Each scale runs from 1 (low) to 5 (high).

Case name: ______________________________
(See Life Cycle Process Factors Questionnaire for project information and description)

Circle your rating for each item below on the **Importance / Priority** scale and on the **Satisfaction** scale.

If the item is not applicable to your facility, circle N/A in the right-hand column.

1. Timeliness of start-up

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

2. Meeting production output specifications

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

3. Capital cost (including design, construction, and start-up)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

4. Profitability of plant

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

5. Cost of operating (excluding energy cost)

| | | |
|---|---|---|
| **Importance / Priority**: | **Satisfaction:** | |
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

6. Energy cost for operating

| | | |
|---|---|---|
| **Importance / Priority**: | **Satisfaction:** | |
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

7. Adaptability to changing owner/operator needs

| | | |
|---|---|---|
| **Importance / Priority**: | **Satisfaction:** | |
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

8. Control systems providing industrial process feedback

| | | |
|---|---|---|
| **Importance / Priority**: | **Satisfaction:** | |
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

9. Meeting emissions requirements (all waste types)

| | | |
|---|---|---|
| **Importance / Priority**: | **Satisfaction:** | |
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

10. Meeting emissions requirements under all operating conditions (e.g. varying loads)

| | | |
|---|---|---|
| **Importance / Priority**: | **Satisfaction:** | |
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

11. Flexibility to meet more stringent emissions requirements

| | | |
|---|---|---|
| **Importance / Priority**: | **Satisfaction:** | |
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

12. Flexibility to use alternative fuel types

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

13. Adequate warranty

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

14. Flexibility of major systems for expansion

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

15. Useful Operations and Maintenance Manual

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

16. Training of operators during start-up

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

17. Ease of operating (e.g. operation of machinery by less experienced workers)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

18. Healthfulness of worker environment

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

19. Comfort of worker environment

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Importance / Priority:** | | | | | **Satisfaction:** | | | | | |
| 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | N/A |
| (low) | | | | (high) | (low) | | | | (high) | |

20. Safety

| **Importance / Priority:** | **Satisfaction:** | |
|---|---|---|
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

21. Security (Proprietary processes, materials, assets, etc.)

| **Importance / Priority:** | **Satisfaction:** | |
|---|---|---|
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

22. Storage space

| **Importance / Priority:** | **Satisfaction:** | |
|---|---|---|
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

23. Reliability of major systems

| **Importance / Priority:** | **Satisfaction:** | |
|---|---|---|
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

24. Durability of major materials

| **Importance / Priority:** | **Satisfaction:** | |
|---|---|---|
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

25. Cost of maintenance

| **Importance / Priority:** | **Satisfaction:** | |
|---|---|---|
| 1 2 3 4 5 | 1 2 3 4 5 | N/A |
| (low) (high) | (low) (high) | |

26. Ease of maintenance (Accessibility of equipment, clearances around equipment)

| | |
|---|---|
| **Importance / Priority:** | **Satisfaction:** |
| 1 2 3 4 5 | 1 2 3 4 5 N/A |
| (low) (high) | (low) (high) |

27. Ability to predict failures of major components

| | |
|---|---|
| **Importance / Priority:** | **Satisfaction:** |
| 1 2 3 4 5 | 1 2 3 4 5 N/A |
| (low) (high) | (low) (high) |

28. Ability to avoid catastrophic failures of major components

| | |
|---|---|
| **Importance / Priority:** | **Satisfaction:** |
| 1 2 3 4 5 | 1 2 3 4 5 N/A |
| (low) (high) | (low) (high) |

29. Equipment replacement cost

| | |
|---|---|
| **Importance / Priority:** | **Satisfaction:** |
| 1 2 3 4 5 | 1 2 3 4 5 N/A |
| (low) (high) | (low) (high) |

30. Cost of cleaning

| | |
|---|---|
| **Importance / Priority:** | **Satisfaction:** |
| 1 2 3 4 5 | 1 2 3 4 5 N/A |
| (low) (high) | (low) (high) |

31. Ease of cleaning

| | |
|---|---|
| **Importance / Priority:** | **Satisfaction:** |
| 1 2 3 4 5 | 1 2 3 4 5 N/A |
| (low) (high) | (low) (high) |

**Additional Quality Factors:**

32. ______________________

| | |
|---|---|
| **Importance / Priority:** | **Satisfaction:** |
| 1 2 3 4 5 | 1 2 3 4 5 N/A |
| (low) (high) | (low) (high) |

33. ______________________

| | |
|---|---|
| **Importance / Priority:** | **Satisfaction:** |
| 1 2 3 4 5 | 1 2 3 4 5 N/A |
| (low) (high) | (low) (high) |

34. ______________________

| | |
|---|---|
| **Importance / Priority:** | **Satisfaction:** |
| 1 2 3 4 5 | 1 2 3 4 5 N/A |
| (low) (high) | (low) (high) |

35. ______________________

| | |
|---|---|
| **Importance / Priority:** | **Satisfaction:** |
| 1 2 3 4 5 | 1 2 3 4 5 N/A |
| (low) (high) | (low) (high) |

Please discuss the best features of the plant. (For example, features that enhance your capability to produce your product.) Who was responsible for identifying/specifying these features? **[QUA17]**

Please discuss any problems and/or failures with the operability or operations of the plant. **[QUA16]**

## ANNOTATIONS REGARDING FACILITY QUALITY CHARACTERISTICS

My intention of including this section is to give some background regarding the subconcepts of quality I strove to measure in this study. Many of the items cover more than one aspect of a subconcept, and could be developed into several related items in future studies. This is also an appropriate place to discuss issues with question wording and response difficulties.

The Industrial Facility Quality Factors questionnaire shown above was distributed to people in the owner organization. It contained 31 items which respondents rated in terms of their importance and satisfaction dimensions. Two of the items, ability to use alternative fuel types and equipment replacement cost, demonstrated response problems and so were dropped from the analysis described in Chapter 5. Architectural image portrayed by the facility was added to the list because several respondents indicated it was an additional quality factor by writing it on the final page of the questionnaire. Therefore, the comprehensive list which comprises a definition of industrial facility quality contains a total of 32 items, though only 29 were used in the analysis of facility quality data. All 32 items are discussed below.

1. **Timeliness of start-up:** Start-up is the period of time between mechanical completion and sustainable commercial production. There are at least two aspects to start-up. First, how does the *duration* of the start-up compare to the industry norm for this particular type of plant? Secondly, did the *point in time* when the plant attained sustainable commercial production suit the business needs of the owner? (This may or may not be related to meeting the project schedule.) The "start-up curve" makes the issue more complex. Facilities such as pulp and paper plants gradually attain full production capacity over the course of the first two or three years after start-up. A concept related in language but not meaning is the quickness with which the plant can start back up and resume production after it has been down for planned or unplanned maintenance.

2. **Meeting production output specifications:** This item taps whether or not the facility conforms to specified requirements. It targets a similar concept to that of the actual production to planned capacity ratio that was discussed in the Validation section of Chapter 5. This item, however, is less confounded by additional concepts such as general

market demand for the plant's output and planned extra capacity. Better wording might be "ability to meet production output specifications."

3. **Capital cost (including design, construction, and start-up):** This item has two aspects. First, was the first cost of the facility comparable to the price which would have been charged by other service providers? Secondly, is the owner organization receiving value for its money or a return on investment from the facility consistent with what it expected? Garvin (1984) discusses this Value-based approach to quality.

4. **Profitability of plant:** Is the plant meeting the expectations of the owner organization with respect to its profitability? This item reflects both the quality of the facility development process as well as the wisdom of the decision to develop the facility in the first place. Scope, capacity, location, capital cost, and market are factors which influence profitability.

5. **Cost of operating (excluding energy cost):** Is the cost of operating the plant reasonable considering industry norms? Does the cost of operating the plant conform to that which was anticipated in the planning stages of the project?

6. **Energy cost for operating:** Is the plant efficient in its use and conversion of energy compared to the industry norm for this type of plant?

7. **Adaptability to changing owner/operator needs:** There are both short term and long term components to this item. On a day-to-day or week-to-week basis, does the plant provide enough flexibility to produce output according to fluctuations in short term demand? On a month-to-month and year-to-year basis, can the base process be modified, diversified, refined, or expanded to adapt to changing markets? Can volume of production be adapted?

8. **Control systems providing industrial process feedback (DCS):** The distributed control system (DCS) is the electronic monitoring and control network which the operators use to run the plant remotely from a central control room. It allows them, for example, to monitor fluid levels, pressure levels, chemical composition of materials, and to operate valves, pumps, and other equipment. The design and implementation of this system is frequently a trouble spot in facility development. The system is often subject to modifications, and it uses technology which is evolving rather than stable.

**9. Meeting emissions requirements (all waste types):** Is the plant capable of controlling its emissions for all different types of waste, including waste released into waterways and groundwater as well as air emissions and solid waste. The focus of this item is diversity of wastes and whether current standards are being met. The issue of emissions is highly sensitive, and may be prone to response error.

**10. Meeting emissions requirements under all operating conditions (e.g. varying loads):** Similar to the previous item, this item taps whether the plant meets emissions requirements under varying conditions such as certain weather conditions, extended periods of maximum production, and planned and unplanned maintenance events.

**11. Flexibility to meet more stringent emissions requirements:** Environmental regulations are gradually evolving to more stringent levels. Did the engineering firm, equipment vendors, and owner organization anticipate these changes adequately, and ensure the plant can be simply and effectively upgraded? Or will a costly retrofit be required in the future?

**12. Flexibility to use alternative fuel types:** There were many "not applicable" responses to this item. This appears to be a poorly worded item. Better wording may have included the words "alternative energy source" or "alternative power source." The intention of this item was to determine owner attitudes and senses of risk associated with their reliance on their power supply, whether it be foreign oil, electricity provided by a local utility, or kinetic energy embodied in impounded water. Because of the large number of "not applicable" responses, this item was not included in the analysis described in Chapter 5.

**13. Adequate warranty:** Was the warranty associated with the equipment or plant sufficient? Did the equipment vendors and the facility developers provide the support to their client that was expected? Did the equipment and the plant perform and endure as expected? This idea includes both written and implied warranties. It may be measured using multiple items in future studies.

**14. Flexibility of major systems for expansion:** Can the plant be expanded, or was the plant and equipment sized in a rigid manner? Is the site capable of accommodating expansion? This item tests the facility developers' foresight.

**15. Useful operations and maintenance manual:** The operations and maintenance manual should communicate operating instructions and design intent for the process as a whole as well as individual pieces of equipment or systems. The manual should provide operators with a better understanding of how to achieve peak operating performance. It should also guide the maintenance schedule and provide troubleshooting assistance.

**16. Training of operators during start-up:** Well trained operators are both safer and better able to run the plant in a profitable manner. Training makes operators feel appreciated and valuable, and improves their competence. It serves to reduce their anxiety regarding their responsibility for operating extremely expensive and potentially delicate and dangerous equipment. Training also contributes to timeliness of start-up by familiarizing the operators with new procedures in advance. Better wording would be achieved by replacing the phrase "during start-up" with "associated with start-up." Also, different aspects of training could be probed such as emergency response training, equipment training, process control training, safety training, etc.

**17. Ease of operating (e.g. operation of machinery by less experienced workers):** If equipment is easy to operate, less training of operators may be required. The equipment will be less likely to require repair due to ill-use. In some types of plants, skilled operators may be in short supply. In such cases, the sophistication of the equipment might be enhanced to compensate for lack of skilled personnel. In wording this item, replace "machinery" with the more general term "equipment."

**18. Healthfulness of worker environment:** This and the next two items might be termed "operator well-being" variables. Operators should have confidence that their environment is safe and free from overt and perceived health threats. The perceived threat of exposure, as well as actual risk of exposure to harmful substances should be addressed in plant design as well as operating procedures. Protections to workers' health should be embodied in the physical form of the plant.

**19. Comfort of worker environment:** Plants are not just elaborate machines that manufacture goods; they are work environments for human beings. As such, they should be designed with ergonomics in mind. Operators in some types of plants are required to work long shifts outside of normal working hours. Operators of certain types of plants may be subject to higher-than-usual levels of stress. Amenities which address both the physical and psychological needs of operators are a characteristic of a higher quality plant.

**20. Safety:** There are several aspects to plant safety. The physical form of the plant should protect the operator from injury. The plant should not present operators with hazards such as low-hanging pipes on which they might hit their heads. There should be adequate catwalks, platforms, and railings. In case of catastrophic failure, the operator should be able to escape to a safe haven. The DCS should be intelligent enough to warn operators of dangerous conditions. In answering this item, it is assumed that respondents interpreted it to mean safety of the operational plant rather than safety during engineering and construction because of its context among all the other facility characteristics. However, to ensure that this is indeed the case, the words "plant safety" rather than just "safety" should be used.

**21. Security (proprietary processes, materials, assets, etc.):** Proprietary processes should be protected from theft by competitors. The site of the facility should be secure against theft of materials (both internal and external) and vandalism.

**22. Storage space:** Storage space should be adequate for tools, parts, and other operations, maintenance and cleaning equipment. Otherwise these items could pose hazards by being left in positions where they could cause operator injury. Adequate storage should be provided so that housekeeping standards can be easily maintained. Easily accessible storage should also be provided for schematics and drawings.

**23. Reliability of major systems:** Reliability is a facility characteristic of extreme importance, and should be probed with several questions. The plant should be operational when it needs to be operational. Plant output is dependable and has low variance in its conformance to specifications. Customer orders can be met in a timely fashion. Unplanned downtime is rare. Equipment operates as expected, both on a piece-by-piece basis as well as together with other equipment. When operations problems do occur, they can be fixed quickly. The operation of the plant should be trouble free. Operators have confidence in equipment stability and dependability. Vibration of equipment is low and appropriately damped.

**24. Durability of major materials:** Materials which make up the plant are long lasting. Except where planned and where easily and cost effectively replaceable, they should not chip, break, fade, crack, become loose, or otherwise deteriorate.

**25. Cost of maintenance:** The cost of maintenance should not be excessive. It should not be inflated by inaccessibility of equipment, or equipment failure. The maintenance budget should be adequate to maintain the equipment and other facility components at a level sufficient to ensure the items' design life cycle.

**26. Ease of maintenance (accessibility of equipment, clearances around equipment):** All other things being equal, equipment that is easy to maintain is more likely actually to be maintained. Equipment that is easy to maintain is less likely to be the source of worker injury. Equipment should be accessible and should have sufficient clearances for maintenance purposes.

**27. Ability to predict failures of major components:** Automated and manual monitoring of equipment can uncover irregular equipment behavior which might lead to failure of critical components of the plant.

**28. Ability to avoid catastrophic failures of major components:** This item includes both the ability to prevent catastrophic failure in response to a warning signal, as well as the inherent safety of the plant in this regard. Are there sufficient monitoring and warning devices in place? Are there sufficient relief valves and back up systems?

**29. Equipment replacement cost:** Respondents found the wording of this item to be ambiguous, so it was dropped from the analysis. The difficulty arises from the fact that the item addresses two different ideas, cost of *equipment* and cost of *replacing*. The intention of the item was to measure attitudes regarding *replacing*. In other words, when equipment needs to be replaced, is it accessible and removable at a reasonable cost? Some respondents interpreted this item as probing whether the equipment lasted long enough considering its initial capital cost.

**30. Cost of cleaning:** Keeping the facility clean in accordance with housekeeping standards should not be an expensive, time consuming activity. The cost of cleaning can be addressed in the physical form of the facility by minimizing the operator time required to perform cleaning tasks. For example, materials which can be cleaned quickly are preferable in this regard. Spatial layout of the facility also is a determining factor of cleaning cost.

**31. Ease of cleaning:** Whether a plant is kept clean and tidy is sometimes a matter not of cost but of ease. If cleaning equipment is accessible and systems are appropriately designed, cleaning can be a less arduous, and therefore less undesirable task. For example, hosing down a floor with water from easily accessible hoses into floor drains is much easier than cleaning a floor from a bucket and mop.

**32. Architectural image portrayed by facility:** Although this item appeared on early test versions of the questionnaire, it was dropped from the final version because it did not fit with the researchers' conceptions of facility quality components. However, the comments of several respondents prompted the researchers to reconsider. The architectural image portrayed by the facility is an essential part of its public image. Workers take pride in an attractive facility.

The above discussion of facility quality characteristics reveals the diversity and depth of the dimensions of facility quality. The subconcepts of quality addressed by the items in the list are general in nature. More specific items could be developed for more specific types of plants. However, as a whole, the list probes all the essential areas of industrial facility performance.

The next section presents the questionnaire that was used to gather project integration data from four key members of the facility development effort.

## INDUSTRIAL PLANT LIFE CYCLE PROCESS FACTORS

**Instructions: Follow steps 1 through 3 below.**

1. You are one of four people that will be interviewed about this project. Each person will respond to the set of questions regarding his or her area of involvement with the project.

2. You will answer questions using a "guided interview" approach. The researcher is with you to clarify the survey questions if needed and to discuss "open ended" survey questions.

3. All responses will be confidential and anonymous. No project, company, or person's name will be released.

## General Project Characteristics:

Name of Project:

Contact information - Owner Project Manager:
Name, title, address, phone

Contact information - Engineering Project Manager:
Name, title, address, phone

Contact information - Construction Project Manager:
Name, title, address, phone

Contact information - Plant Engineer / Operating Manager:
Name, title, address, phone

## Participants

1. List all **design/engineering** and **construction** organizations that participated in the project in addition to the prime design/engineering firm and the construction project management firms. (Use either specific company names or general description, e.g. Electrical Engineering Firm or Steel Erection Sub.) Continue list in margins if necessary. **[ORG2,3]**

Design/Engineering Participants (including major equipment vendors)

1.
2.
3.
4.
5.
6.
7.
8.
9.
10.

Construction Participants (Don't list prime if same as construction project manager's firm)

1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.
15.

## OWNER PROJECT MANAGER SECTION

### Project Time Line Information

Please provide approximate dates in the following table: **[QUA13] [INF15]**

| Project Phase: | Start (month / year) | Completion (month /year) |
|---|---|---|
| Planning | | |
| Engineering/Design | | |
| Construction | | |
| Start-up | | |
| First date of full production | | |

### Project Man Hours Information

How many man hours were spent by whom at each stage of the project? **[INF15] [INF6]**

| | Owner/ Operator | All Engineering /Design | All Construction | Total |
|---|---|---|---|---|
| Planning | ____ | ____ | ____ | ____ |
| Eng'g/Design | ____ | ____ | ____ | ____ |
| Construction | ____ | ____ | ____ | ____ |
| Start-up | ____ | ____ | ____ | ____ |

What percentage of engineering/design was complete when construction began? ____% **[INF12]**

### Project Cost Information

What was the capital cost of the facility? ________ **[QUA1]**
(Capital cost, e.g. cost that will be depreciated)

### Past Experience with Other Project Participants:

On how many prior projects in the 10 year period prior to this project had the owner worked with each of the prime engineering/design firm, the construction project manager's firm, and the prime construction contractor? **[ORG2]**

Indicate the number of prior projects (or "N/A") in the blanks:

| | Owner |
|---|---|
| Prime Engineering/Design firm | |
| Construction Project Manager's firm | |
| Prime Construction Contractor | |

## Preliminary Design

How many major alternative facility configurations were considered before the final design concept was decided upon?_____ [TEC3]

Was CAD/CAE used to generate the alternatives? Circle one: Yes No [TEC3]

## Design Effectiveness

Indicate the number of changes by the project phase and type in the chart below. Also estimate the percentage of final capital cost encompassed by the changes in each box. **[QUA12]**

| | Project Phase: | | | |
|---|---|---|---|---|
| Type: | Planning and Preliminary design | Engineering (Design Change) | Construction (Physical Change) | Start-up (design or physical) |
| Owner enhancements | | | | |
| Omissions | | | | |
| Errors | | | | |
| Other changes | | | | |

Please discuss the cost and time impacts associated with the design and construction changes, errors, omissions and resulting rework. **[QUA12]**

Did the design, in all respects, meet the specified needs of the owner?
**[INF14] [QUA15]** Check one: ___Yes ___No

If no, what systems, components, or other items did not meet the specified requirements? **[QUA15]**

Were the specified requirements an accurate reflection of the owner's current needs? **[INF14] [QUA15]**
Check one: ___Yes ___No

If no, what systems, components, or other items do not meet the owner's current needs? **[QUA15,16]**

## Formal Review Processes

Which of the following formal review processes were used? Check all that apply. [ORG5] **[INF2,3,4,7,8]**

___ Design review — How many meetings? _________
On what time basis?____________________

___ Constructibility review — How many meetings? _________
On what time basis?____________________

___ Start-up review — How many meetings? _________
On what time basis?____________________

___ Operations & Maintenance review — How many meetings? _________
On what time basis?____________________

___ Post start-up evaluation — How many meetings? _________
On what time basis?____________________

___ Other: ________________________________________

___ Other: ________________________________________

## Project Team Continuity

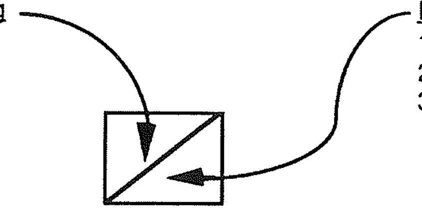
**[ORG4]**

| Year | Number of people on owner's project management team | % turnover |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |

## Information Exchange

How important and how effective was the integration (i.e. the sharing of knowledge and information by technical and organizational means) among the **main project participants** shown in the matrix below: **[MAIN]**

Importance Rating
1 = low
2 = moderate
3 = high



Effectiveness Rating
1 = low
2 = adequate
3 = high

Indicate an **Importance** and **Effectiveness** rating for each intersection below:

| | Operations & Maint. | Construction Subs | Construction Prime | Construction PM | Regul. Agencies | Equip& Material Vendor | Eng'g / Design Subs | Prime Eng'g / Design | Owner PM Team |
|---|---|---|---|---|---|---|---|---|---|
| Owner PM Team | | | | | | | | | XX |
| Prime Eng'g / Design | | | | | | | | XX | |
| Eng'g/ Design Subs | | | | | | | XX | | |
| Equip. & Material Vendors | | | | | | XX | | | |
| Regulatory Agencies | | | | | XX | | | | |
| Construction PM's firm | | | | XX | | | | | |
| Construction Prime | | | XX | | | | | | |
| Construction Subs | | XX | | | | | | | |
| Operation & Maintenance | XX | | | | | | | | |

What methods were used for the exchange of project data between the participants? Check each box that applies. **[TEC1] [INF1,2,3]**

| | Owner PM <==> Eng'g/Design (Prime) | Owner PM <==> Construction PM's firm | Owner PM <==> Prime Constr'n Contractor | Owner PM <==> Operator |
|---|---|---|---|---|
| Face-to-face | | | | |
| Electronic mail | | | | |
| Telephone | | | | |
| Video Conferencing | | | | |
| Hand carry documents | | | | |
| Fax | | | | |
| Batch Files | | | | |
| On-line 2D model | | | | |
| On-line 3D model | | | | |
| Letters | | | | |
| Systematic method (describe) | | | | |
| Other: _______ ___________ | | | | |
| Other: _______ ___________ | | | | |

## Degree of Integration of Control Systems

Was the same work breakdown structure used for more than one project control system?
Circle one: Yes No If yes, which systems used the same work breakdown structure?
[CON3]

Assume you had a change in the project of the type indicated in the top row of the chart below. Indicate which of the project control systems in the left column would have been updated as a consequence of the change. Write one of the following symbols in each box: [CON3]

NU = Not Updated
UM = Updated Manually
UA = Updated Automatically
N/A = Not Applicable

| | Scope Change | Design Change | Procurement Change | Schedule Change |
|---|---|---|---|---|
| Schedule | | | | |
| Budget | | | | |
| Forecast Cost | | | | |
| Committed Cost | | | | |
| Procurement Documents | | | | |
| Design Document Revision Control | | | | |

## Experience with Quality Management Programs:

For how many years has the **owner** organization used each of the following quality programs? Also state during what years each program was used. [ORG1]

| | Number of years | Which years (e.g. 1980 to 82) |
|---|---|---|
| Statistical Process Control (SPC) | ____ | ________ |
| Quality Assurance (QA) | ____ | ________ |
| Total Quality Control (TQC) | ____ | ________ |
| Total Quality Management (TQM) | ____ | ________ |
| Plan, Do, Check, Act (PDCA) Cycle | ____ | ________ |
| Continuous Process Improvement (CPI) | ____ | ________ |
| Quality Performance Tracking System (QPTS) | ____ | ________ |
| Quality Function Deployment (QFD) | ____ | ________ |
| Other: ________________ | ____ | ________ |

## Process Improvement

Please discuss what methods were used to examine or improve the process (or sub-processes) of planning, engineering, constructing and operating this facility or the next to be built? What lessons were learned?
**[ORG5]** **[INF2,3,4,7,8]**

## ENGINEERING / DESIGN PROJECT MANAGER SECTION

### Past Experience with Other Project Participants:

On how many prior projects in the 10 year period prior to this project had the prime engineering/design firm worked with the owner, the construction project manager's firm, the prime construction contractor, and each of the engineering/design "subcontractors" listed on page one? **[ORG2]**

Indicate the number of prior projects in the blanks:

| | Prime Engineering/ Design firm |
|---|---|
| Owner | |
| Construction project manager's firm | |
| Prime construction contractor | |
| Engineering / Design Sub 1 | |
| Engineering / Design Sub 2 | |
| Engineering / Design Sub 3 | |
| Engineering / Design Sub 4 | |
| Engineering / Design Sub 5 | |
| Engineering / Design Sub 6 | |
| Engineering / Design Sub 7 | |
| Engineering/ Design Sub 8 | |
| Engineering / Design Sub 9 | |
| Engineering / Design Sub 10 | |
| Engineering / Design Sub 11 | |
| Engineering / Design Sub 12 | |

## Design Specifications

What daily production rate was specified for the principal output of the plant? [QUA3] ______

Were any of the following items addressed in the output (production) specifications for the design? **[QUA14]**

___ Limits of variation in quantity of output
___ Limits of variation in quality of output
___ Flexibility to operate at different levels of output
___ Other output goals: __________

For each item checked above, what wording was used in the specifications? [QUA14]

Please discuss the processes that were used to determine the owner's requirements. [INF5]

Compared to other similar facilities in your experience, is the design of this facility (check one): **[QUA6]**

___ less complex ___ about equally complex ___ more complex

Approximately what percentage of the engineering effort was expended on previously untried technology or systems that had never been built before? **[QUA6]** _____%

Compared to other similar projects in your experience, was the owner's involvement with the design of this facility (check one): **[INF6]**

___ lesser ___ about equal ___ greater

## Preliminary Design

How many major alternative facility configurations were considered before the final design concept was decided upon?_____ **[TEC3]**

Was CAD/CAE used to generate the alternatives? Circle one: Yes No **[TEC3]**

## Use of CAD/CAE in Engineering / Design

How was each discipline's design efforts distributed among the following methods/tools? Use percentages; each row should total 100%. [TEC2]

| | Manual | 2D CAD | 3D CAD | 3D with database links |
|---|---|---|---|---|
| Civil/foundation | ____ | ____ | ____ | _____ |
| Structural | ____ | ____ | ____ | _____ |
| Mechanical (HVAC) | ____ | ____ | ____ | _____ |
| Mechanical (Process & Piping) | ____ | ____ | ____ | _____ |
| P & ID | ____ | ____ | ____ | _____ |
| Electrical | ____ | ____ | ____ | _____ |
| Lighting | ____ | ____ | ____ | _____ |
| Communications (Tel, etc...) | ____ | ____ | ____ | _____ |
| Layout | ____ | ____ | ____ | _____ |

Check which on-line CAD/CAE information in the top row was available through data links (batch or on-line) to the engineering discipline in the left column. In the far right column, write which CAD/CAE system (if any) was used by each discipline in the left column. [INF1] [TEC2]

| | Civil/ Fdn | Structural | Mech HVAC | Mech Pipe/ Proc. | P & ID | Electrical | Lighting | Com. (tel, etc..) | Equip/ Plant Lyout | CAD/CAE system used |
|---|---|---|---|---|---|---|---|---|---|---|
| Civil/ Foundation | XX<br>XX | | | | | | | | | |
| Structural | | XX<br>XX | | | | | | | | |
| Mechanical HVAC | | | XX<br>XX | | | | | | | |
| Mechanical Piping/Process | | | | XX<br>XX | | | | | | |
| P & ID | | | | | XX<br>XX | | | | | |
| Electrical | | | | | | XX<br>XX | | | | |
| Lighting | | | | | | | XX<br>XX | | | |
| Communication Tel, netwrk, etc | | | | | | | | XX<br>XX | | |
| Equipment/ Plant Layout | | | | | | | | | XX<br>XX | |

Was automated interference checking performed? Circle one: Yes No [TEC6]
If yes, for which disciplines &/or facility systems was interference checking performed?

To what extent and how was the P&ID used to check the accuracy and consistency of the plant design? Circle one or more: **[TEC2A]**

a) ) manually
b) automated links between systems, explain: ______________________________
c) other, explain: ______________________________________________________

## Formal Review Processes

Which of the following formal review processes were used? Check all that apply. [ORG5] [INF2,3,4,7,8]

___ Design review How many meetings? ________
On what time basis?____________________
___ Constructibility review How many meetings? ________
On what time basis?____________________
___ Start-up review How many meetings? ________
On what time basis?____________________
___ Operations & Maintenance review How many meetings? ________
On what time basis?____________________
___ Post start-up evaluation How many meetings? ________
___ Other: ________________________________________
___ Other: ________________________________________

## Expertise of Other Participants

What other methods were used to incorporate into the facility design the expertise of: [INF2,3,13] [ORG5]

1) Design Subcontractors

2) Equipment and Material Vendors

3) Construction Project Manager

4) Prime construction contractor and subcontractors

5) Plant Operators

## Project Team Continuity

[ORG4]

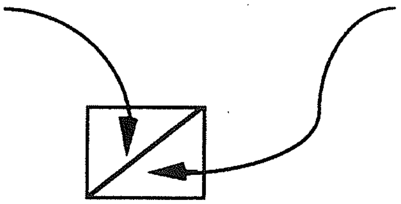
| Year | Number of people on engineering project management team | % turnover |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |

## Information Exchange

How important and how effective was the integration (i.e. the sharing of knowledge and information by technical and organizational means) among the **main project participants** shown in the matrix below: **[MAIN]**

Importance Rating
1 = low
2 = moderate
3 = high

Effectiveness Rating
1 = low
2 = adequate
3 = high

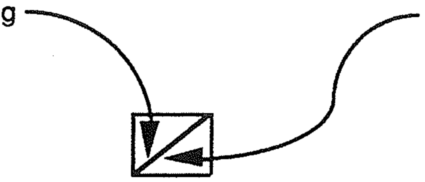


Indicate an **Importance** and **Effectiveness** rating for each intersection below:

| | Operations & Maint. | Construction Subs | Construction Prime | Construction PM | Regul. Agencies | Equip& Material Vendor | Eng'g / Design Subs | Prime Eng'g / Design | Owner PM Team |
|---|---|---|---|---|---|---|---|---|---|
| Owner PM Team | / | / | / | / | / | / | / | / | XX |
| Prime Eng'g / Design | / | / | / | / | / | / | / | XX | |
| Eng'g/ Design Subs | / | / | / | / | / | / | XX | | |
| Equip. & Material Vendors | / | / | / | / | / | XX | | | |
| Regulatory Agencies | / | / | / | / | XX | | | | |
| Construction PM's firm | / | / | / | XX | | | | | |
| Construction Prime | / | / | XX | | | | | | |
| Construction Subs | / | XX | | | | | | | |
| Operation & Maintenance | XX | | | | | | | | |

How important and how effective (i.e.in both directions in a rapid and accurate manner) was the flow of information (i.e. specs, plans, budget and schedule data) between the **design/engineering participants** shown in the matrix below: **[INF1,2,3]**

Importance Rating
1 = low
2 = moderate
3 = high



Effectiveness Rating
1 = low
2 = adequate
3 = high

Indicate an **Importance** and **Effectiveness** rating for each intersection below:

| | Prime E/D | Sub 1 | Sub 2 | Sub 3 | Sub 4 | Sub 5 | Sub 6 | Sub 7 | Sub 8 | Sub 9 | Sub 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sub10 | / | / | / | / | / | / | / | / | / | / | XX<br>XX |
| Sub9 | / | / | / | / | / | / | / | / | / | XX<br>XX | |
| Sub8 | / | / | / | / | / | / | / | / | XX<br>XX | | |
| Sub7 | / | / | / | / | / | / | / | XX<br>XX | | | |
| Sub6 | / | / | / | / | / | / | XX<br>XX | | | | |
| Sub5 | / | / | / | / | / | XX<br>XX | | | | | |
| Sub4 | / | / | / | / | XX<br>XX | | | | | | |
| Sub3 | / | / | / | XX<br>XX | | | | | | | |
| Sub2 | / | / | XX<br>XX | | | | | | | | |
| Sub1 | / | XX<br>XX | | | | | | | | | |
| Prime E/D | XX<br>XX | | | | | | | | | | |

What methods were used for the exchange of project data between the participants? Check each box that applies. **[TEC1] [INF1,2,3]**

| | Eng'g/Design (Prime) <==> Owner PM | Eng'g/Design (Prime) <==> Construction PM's firm | Eng'g/Design (Prime) <==> Prime Constr. Contractor | Eng'g/Design (Prime) <==> Operator | Eng'g/Design (Prime) <==> Eng'g/Design (Subs) |
|---|---|---|---|---|---|
| Face-to-face | | | | | |
| Electronic mail | | | | | |
| Telephone | | | | | |
| Video Conferencing | | | | | |
| Hand carry documents | | | | | |
| Fax | | | | | |
| Batch Files | | | | | |
| On-line 2D model | | | | | |
| On-line 3D model | | | | | |
| Systematic method (describe) | | | | | |
| Other: _______ | | | | | |
| Other: _______ | | | | | |

## Experience with Quality Management Programs:

For how many years has the **prime engineering / design** organization used each of the following quality programs? Also state during what years each program was used. [ORG1]

| | Number of years | Which years (e.g. 1980 to 82) |
|---|---|---|
| Statistical Process Control (SPC) | ____ | ________ |
| Quality Assurance (QA) | ____ | ________ |
| Total Quality Control (TQC) | ____ | ________ |
| Total Quality Management (TQM) | ____ | ________ |
| Plan, Do, Check, Act (PDCA) Cycle | ____ | ________ |
| Continuous Process Improvement (CPI) | ____ | ________ |
| Quality Performance Tracking System (QPTS) | ____ | ________ |
| Quality Function Deployment (QFD) | ____ | ________ |
| Other: ________________ | ____ | ________ |

## Process Improvement

Please discuss what methods were used to examine or improve the process (or sub-processes) of planning, engineering, constructing and operating this facility or the next to be built? **[ORG5]** **[INF2,3,4,7,8]**

# CONSTRUCTION PROJECT MANAGER SECTION

## Past Experience with Other Project Participants:

On how many prior projects in the 10 year period prior to this project had the construction project manager 's firm worked with the owner, the prime engineering/design firm, and the construction participants listed on page one? **[ORG2]**

Indicate the number of prior projects in the blanks:

| | Construction Project Manager's firm |
|---|---|
| Owner | |
| Prime Engineering / Design | |
| Construction (Prime or Sub) 1 | |
| Construction Sub 2 | |
| Construction Sub 3 | |
| Construction Sub 4 | |
| Construction Sub 5 | |
| Construction Sub 6 | |
| Construction Sub 7 | |
| Construction Sub 8 | |
| Construction Sub 9 | |
| Construction Sub 10 | |
| Construction Sub 11 | |
| Construction Sub 12 | |
| Construction Sub 13 | |
| Construction Sub 14 | |
| Construction Sub 15 | |

## Design Effectiveness

Compared to other projects in your experience, please rate the following items on a five-point scale. Each scale runs from 1 (low) to 5 (high). **[QUA15]**

Completeness of the design.
1 2 3 4 5
(low) (high)

Timeliness of the design.
1 2 3 4 5
(low) (high)

Clarity of the design.
1 2 3 4 5
(low) (high)

Constructibility of the design.
1 2 3 4 5
(low) (high)

## Constructibility / Expertise of Participants

Describe the prime constructor's contribution to the design in terms of content and timing. Use the following questions as guidelines, but include any relevant additional information. **[INF2] [QUA15]**

At what stage in the project did the construction project manager first have design input?
___Early Planning ___Late Planning ___Early Design ___Late Design ___Beginning of Construction
___ Other: _______________

Were formal constructibility reviews held? Circle one: Yes No
If yes, how many constructibility reviews were held? _____
What time basis (frequency)? _______________________________________

What other methods were used to incorporate into the facility design or construction the expertise of: **[INF2,13]**

1) Construction Project Manager

2) Construction Prime- and Sub-contractors

3) Equipment and Material Vendors (if applicable)

Additional comments on constructibility:

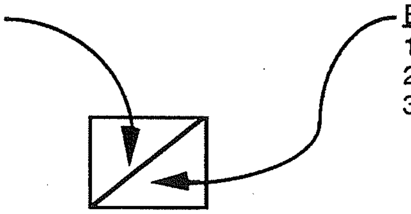
**Project Team Continuity** [ORG4]

| Year | Number of people on construction project management team | % turnover |
|---|---|---|
| | | |
| | | |
| | | |
| | | |

**Information Exchange**

How important and how effective was the integration (i.e. the sharing of knowledge and information by technical and organizational means) among the **main project participants** shown in the matrix below: **[MAIN]**

Importance Rating
1 = low
2 = moderate
3 = high



Effectiveness Rating
1 = low
2 = adequate
3 = high

Indicate an **Importance** and **Effectiveness** rating for each intersection below:

| | Opera-tions & Maint. | Constr-uction Subs | Constr-uction Prime | Constr-uction PM | Regul. Agen-cies | Equip& Material Vendor | Eng'g / Design Subs | Prime Eng'g / Design | Owner PM Team |
|---|---|---|---|---|---|---|---|---|---|
| Owner PM Team | | | | | | | | | XX |
| Prime Eng'g / Design | | | | | | | | XX | |
| Eng'g/ Design Subs | | | | | | | XX | | |
| Equip. & Material Vendors | | | | | | XX | | | |
| Regu-latory Agencies | | | | | XX | | | | |
| Constr-uction PM's firm | | | | XX | | | | | |
| Constr-uction Prime | | | XX | | | | | | |
| Constr-uction Subs | | XX | | | | | | | |
| Operation & Maint-enance | XX | | | | | | | | |

What methods were used for the exchange of project data between the participants? Check each box that applies. **[TEC1] [INF1,2,3]**

| | Construction PM <==> Owner PM | Construction PM <==> Eng'g/ Design (Prime) | Construction PM<==> Operator | Construction PM<=>Prime Construction Contractor | Construction PM==> Construction Subs |
|---|---|---|---|---|---|
| Face-to-face | | | | | |
| Electronic mail | | | | | |
| Telephone | | | | | |
| Video Conferencing | | | | | |
| Hand carry documents | | | | | |
| Fax | | | | | |
| Batch Files | | | | | |
| On-line 2D model | | | | | |
| On-line 3D model | | | | | |
| Systematic method (describe) | | | | | |
| Letters | | | | | |
| Other: _______ | | | | | |

## Experience with Quality Management Programs:

For how many years has the **prime construction** organization used each of the following quality programs? Also state during what years each program was used. **[ORG1]**

| | Number of years | Which years (e.g. 1980 to 82) |
|---|---|---|
| Statistical Process Control (SPC) | ____ | ________ |
| Quality Assurance (QA) | ____ | ________ |
| Total Quality Control (TQC) | ____ | ________ |
| Total Quality Management (TQM) | ____ | ________ |
| Plan, Do, Check, Act (PDCA) Cycle | ____ | ________ |
| Continuous Process Improvement (CPI) | ____ | ________ |
| Quality Performance Tracking System (QPTS) | ____ | ________ |
| Quality Function Deployment (QFD) | ____ | ________ |
| Other: ________________ | ____ | ________ |

## Conformance Quality

What quality difficulties were experienced by the subcontractors? How did you address them? **[ORG6]**

## Process Improvement

Please discuss what methods were used to examine or improve the process (or sub-processes) of planning, engineering, constructing and operating this facility or the next to be built? **[ORG5]** **[INF2,3,4,7,8]**

# PLANT OPERATOR SECTION

## Operations Information

**Note: Unless you note otherwise, we will assume the numbers below are figures for the past year.

How many hours did the plant operate? ___ [QUA2]

How many hours was the plant inoperative due to unscheduled down time? ___ [QUA2]
[want to get "% availability"]

What was the actual average daily production of the plant? _______ [QUA3]

What was the annual operations cost (including energy cost)? ________ [QUA1]
[could use % of initial capital cost]

What was the annual maintenance cost? ________ [QUA1]

What measures do you use to track the efficiency of the plant? [QUA18]

## Facility Start-Up

Who started-up the plant? Indicate number of people from each group of participants:

____ Engineering / Design
____ Constructors
____ Operator
____ Equipment Vendors
____ Other ____________________________

## Operability

Describe the operator's contribution to the design in terms of content and timing. Use the following questions as guidelines, but include any relevant additional information. Note: "operator" refers to the operator function, not necessarily the same person who is currently operating the plant. [INF3]

Did operator contribute to scope definition? Circle one: Yes No
If yes, describe:

Did operator contribute to design specifications? Circle one: Yes No
If yes, describe:

Did operator have input into the design process? Circle one: Yes No
If yes, at what stage in the project did the operator first have design input?
___Early Planning ___Late Planning ___Early Design ___Late Design ___Beginning of Construction
___ Other: _______________

Did operator have representation in the engineering/design office? Circle one: Yes No
If yes, with what level of authority?

Were formal operability reviews held? Circle one: Yes No
If yes, how many operability reviews were held? _____
When, or on what time basis? ________________________________________

Were post start-up reviews held? Circle one: Yes No
If yes, how many post start-up reviews were held? _____
If yes, when, or on what time basis? ________________________________________

What data was available from past projects of similar types? Please describe:

Additional operability comments:

## Use of CAD/CAE Data for Operations

Was as-built data provided to the owner in an automated format usable by the owner's plant operations or maintenance functions? Circle one: Yes No
If yes, how has it added value to the facility? **[TEC5]**

## Operations Training

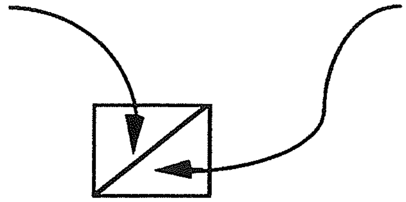
Did Engineering/Design firm provide training to facility operators? **[INF4]**
Circle One: Yes No
If yes, how many engineering hours? ____ How many operator hours? ____

Did vendors provide training to facility operators? **[INF4]**
Circle One: Yes No
If yes, how many vendor hours? ____ How many operator hours? ____

## Information Exchange

How important and how effective was the integration (i.e. the sharing of knowledge and information by technical and organizational means) among the **main project participants** shown in the matrix below: **[MAIN]**

Importance Rating
1 = low
2 = moderate
3 = high



Effectiveness Rating
1 = low
2 = adequate
3 = high

Indicate an **Importance** and **Effectiveness** rating for each intersection below:

| | Operations & Maint. | Construction Subs | Construction Prime | Construction PM | Regul. Agencies | Equip& Material Vendor | Eng'g / Design Subs | Prime Eng'g / Design | Owner PM Team |
|---|---|---|---|---|---|---|---|---|---|
| Owner PM Team | / | / | / | / | / | / | / | / | XX |
| Prime Eng'g / Design | / | / | / | / | / | / | / | XX | |
| Eng'g/ Design Subs | / | / | / | / | / | / | XX | | |
| Equip. & Material Vendors | / | / | / | / | / | XX | | | |
| Regulatory Agencies | / | / | / | / | XX | | | | |
| Construction PM's firm | / | / | / | XX | | | | | |
| Construction Prime | / | / | XX | | | | | | |
| Construction Subs | / | XX | | | | | | | |
| Operation & Maintenance | XX | | | | | | | | |

What methods were used for the exchange of project data between the participants? Check each box that applies. **[TEC1] [INF1,2,3]**

| | Operator<==> Owner PM | Operator<==> Eng'g/Design (Prime) | Operator<==> Construction PM | Operator<==> Prime Constr. Contractor | Operator<==> Constr. Sub Contractors |
|---|---|---|---|---|---|
| Face-to-face | | | | | |
| Electronic mail | | | | | |
| Telephone | | | | | |
| Video Conferencing | | | | | |
| Hand carry documents | | | | | |
| Fax | | | | | |
| Batch Files | | | | | |
| On-line 2D model | | | | | |
| On-line 3D model | | | | | |
| Systematic method-describe | | | | | |
| Letters | | | | | |
| Other: _______ | | | | | |

## Experience with Quality Management Programs:

(Answer the following question if information is different than corresponding question in Owner Project Manager Section.)

For how many years has the **owner/operator** organization used each of the following quality programs? Also state during what years each program was used. **[ORG1]**

| | Number of years | Which years (e.g. 1980 to 82) |
|---|---|---|
| Statistical Process Control (SPC) | ____ | ________ |
| Quality Assurance (QA) | ____ | ________ |
| Total Quality Control (TQC) | ____ | ________ |
| Total Quality Management (TQM) | ____ | ________ |
| Plan, Do, Check, Act (PDCA) Cycle | ____ | ________ |
| Continuous Process Improvement (CPI) | ____ | ________ |
| Quality Performance Tracking System (QPTS) | ____ | ________ |
| Quality Function Deployment (QFD) | ____ | ________ |
| Other: _______________ | ____ | ________ |

## Process Improvement

Please discuss what methods were used to examine or improve the process (or sub-processes) of planning, engineering, constructing and operating this facility or the next to be built? **[ORG5]** **[INF2,3,4,7,8]**

## Quality and Performance Measures

What quantitative or qualitative measures do you use as indicators of plant performance or quality?
**[QUA+]**

# *Appendix B — Questionnaire Enhancements*

These recommendations and ideas are presented for the benefit of industry professionals who wish to implement a measurement program such as the one discussed in this dissertation, as well as academic researchers who wish to probe in greater depth the ideas developed in this study.

My intention in this section is not to create a new questionnaire, but rather to share briefly with the reader my thoughts regarding the general ways I might change the measurement instruments in future work.

## DISTINCTIONS BETWEEN OWNER GROUPS

In the study described in this dissertation, I defined the owner groups (see page 73), and classified the respondents into these groups. A more scientific approach would be to ask the respondents to answer questions regarding their job responsibilities, then group them accordingly. Below are examples of items which can be used to classify respondents into the owner groups.

What is your job title? ________________________________

Briefly describe your day-to-day responsibilities. ________________________________

What percentage of the facility development (planning, engineering, and construction) *cost* did you authorize (circle one):

0% 1-10% 11-20% 21-30% 31-40% 41-50% 51-60% 61-70% 71-80% 81-90% 91-100%

What percentage of the facility development *budget* did you manage (circle one):

0% 1-10% 11-20% 21-30% 31-40% 41-50% 51-60% 61-70% 71-80% 81-90% 91-100%

What percentage of the plant's operating budget (including maintenance) do you have responsibility for (circle one)?

0% 1-10% 11-20% 21-30% 31-40% 41-50% 51-60% 61-70% 71-80% 81-90% 91-100%

Do you currently hold job responsibilities for more than one operational plant?
__ Yes or __ No.
If yes, how many plants? ___

What is your interest in this (these) plants (check as many as apply)?
__ Corporate officer
__ Financial specialist
__ Research and development
__ Process specialist
__ Plant Manager
__ Engineering Project Manager
__ Owner Project Representative
__ Operations supervisor
__ Board of Directors member
__ Equipment specialist
__ Operations specialist
__ Quality of plant's output or product
__ Senior Operations Manager
__ Construction Project Manager
__ Maintenance supervisor
__ Other ____________________

My main job responsibilities include (check as many as apply):
__ Setting strategic direction for the company
__ Deciding which major capital projects (>$5,000,000 in size) to implement
__ Managing the implementation of capital projects.
__ Selecting engineering contractors
__ Selecting construction contractors
__ Selecting equipment vendors
__ Managing schedules and budgets for capital projects
__ Plant manager
__ Managing operations budget
__ Managing maintenance budget
__ Supervising maintenance personnel
__ Supervising operating personnel
__ Maintaining equipment
__ Operating equipment
__ Using a distributed control system to monitor plant operations
__ Working with external customers
__ Working with external suppliers
__ Other ______________________

Check true statements:

__ After a plant begins commercial production, I start working on another capital facility project.
__ I work for my company's (or other organization's) project management division.
__ Being involved in the development of this facility was a departure from my normal month-to-month or year-to-year job responsibilities.

How many major facility development projects (<$5,000,000 in size) have you been involved in during your career (at least 50% time on a day-to-day basis for some segment of the planning, engineering, and construction process)?

Number of projects: ___
How many years have you been working in this career: ___

Which one of the following phrases best describes your job responsibilities:

__ engineering or construction project management
__ strategic business initiatives of organization
__ day-to-day operations and management of a single plant

## OVERALL PROJECT AND FACILITY SATISFACTION

My level of involvement *per week* with each function of the facility development project was (circle one):

| | | | | | | |
|---|---|---|---|---|---|---|
| Planning: | 0 hrs. | 1-10 hrs. | 11-20 hrs. | 21-30 hrs. | 31-40 hrs. | 40+ hrs. |
| Financing: | 0 hrs. | 1-10 hrs. | 11-20 hrs. | 21-30 hrs. | 31-40 hrs. | 40+ hrs. |
| Process Engineering: | 0 hrs. | 1-10 hrs. | 11-20 hrs. | 21-30 hrs. | 31-40 hrs. | 40+ hrs. |
| Procurement: | 0 hrs. | 1-10 hrs. | 11-20 hrs. | 21-30 hrs. | 31-40 hrs. | 40+ hrs. |
| Detailed Engineering: | 0 hrs. | 1-10 hrs. | 11-20 hrs. | 21-30 hrs. | 31-40 hrs. | 40+ hrs. |
| Construction: | 0 hrs. | 1-10 hrs. | 11-20 hrs. | 21-30 hrs. | 31-40 hrs. | 40+ hrs. |
| Start-up: | 0 hrs. | 1-10 hrs. | 11-20 hrs. | 21-30 hrs. | 31-40 hrs. | 40+ hrs. |
| Operations: | 0 hrs. | 1-10 hrs. | 11-20 hrs. | 21-30 hrs. | 31-40 hrs. | 40+ hrs. |

My overall satisfaction with the *operational facility* is (circle one):

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| very<br>low | | | | | | | | very<br>high |

My overall satisfaction with the facility development *project* (from planning through start-up) was (circle one):

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| very<br>low | | | | | | | | very<br>high |

## FACILITY QUALITY CHARACTERISTICS

In a new study, I would again measure importance and satisfaction attitudes regarding facility characteristics. However, I would use a 9-point scale rather than the 5-point scale used in this study. This is because I wish to obtain more variance on the importance scale. For several items in the current study such as safety and meeting emissions requirements, the mean importance value was 5 or nearly 5. This is clearly evident of a non-normal distribution. By placing the word "neutral" to coincide with 4 on the scale, I hope to "stretch out" respondents' importance ratings. In terms of positioning on the page, I would again place all importance scales in the right column and the satisfaction items on the left. Although it is perhaps not necessary to use a 9-point satisfaction scale (the existing variance was sufficient), it is desirable for the satisfaction scale to match the importance scale in appearance.

I would use the items listed in Table 2.A (page 12) and described in Appendix A (page 181) as a starting point to develop the semantic objects for rating by respondents. In particular, I want to probe in more depth characteristics highlighted by this study as critical areas. For example, to measure the subconcept of reliability, the following items could be used.

**Overall reliability of the plant**

IMPORTANCE SCALE

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| very<br>low | | | neutral | | | | | very<br>high |

SATISFACTION SCALE

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| very<br>low | | | | | | | | very<br>high |

**Reliability of major equipment**

IMPORTANCE SCALE

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| very<br>low | | | neutral | | | | | very<br>high |

SATISFACTION SCALE

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| very<br>low | | | | | | | | very<br>high |

**Reliability of auxiliary equipment**

IMPORTANCE SCALE

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| very<br>low | | | neutral | | | | | very<br>high |

SATISFACTION SCALE

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| very<br>low | | | | | | | | very<br>high |

**Avoidance of unscheduled downtime**

IMPORTANCE SCALE

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| very<br>low | | | neutral | | | | | very<br>high |

SATISFACTION SCALE

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| very<br>low | | | | | | | | very<br>high |

**Reliability of the Distributed Control System (DCS)**

IMPORTANCE SCALE

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| very<br>low | | | neutral | | | | | very<br>high |

SATISFACTION SCALE

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| very<br>low | | | | | | | | very<br>high |

## INTEGRATION ITEMS

In a new study, we would seek to measure each of the three dimensions in ten to twenty different ways. About one third of the instruments should tap organizational modes of coordination, another third, technical modes of coordination, and the final third, a naturally occurring mix of the coordination modes. Items should be derived from a combination of common sense, the theoretical background (described in pages 23-40) regarding the dimensions and coordination modes, original thought, additional literature review, and discussions with industry professionals.

Measures for each dimension and mode of integration should tap the flow of knowledge and information both *between* firms and *within* firms in the project organization.

## SAMPLING DISTRIBUTION

To sample projects, I would approach McGraw-Hill, Inc.'s F. W. Dodge division Construction Information Group to request a list of all industrial facilities between $10 and $500 million in construction cost that started commercial production between 1 year and 18 months previously. I would need the project name, location, type or brief description, company, contact name, telephone number. I would create a sample of approximately 100 plants randomly selected from this list . The next step would be to telephone or write the contact or company president to attempt to gain access to the owner organization. A rough estimate is that about half of the organizations would agree to participate.

If the owner organization did agree to participate, I would attempt to obtain the names of three to five respondents in each of the three owner groups (strategic, operations, project management). One of the strategic people should be the CEO. One operations person should be the plant manger. In addition, I would obtain names and contact information for the engineering and construction project managers outside the owner organization.

The research budget would determine the overall data collection strategy. Although a better response rate would be obtained by interviewing respondents in person, it might be possible to use the mail and telephone to obtain questionnaire responses.

## DATA ENTRY METHOD AND COMPUTER PLATFORM

Even though a traditional paper questionnaire would probably be used in an ensuing study, a portable computer is a necessity for in-person interviews to record verbal responses and elaborations to open-ended questions. After the interview, the written responses would be entered into a previously prepared data base application which could be easily be exported to a statistical package.

The computer platform used throughout this study was the Macintosh computer. The software tools included Word, MacDraw Pro, 4th Dimension (data base), Excel, Statview, and SPSS. Working on a single, portable, and easily networked platform enables very straightforward transfer of information between the applications.

# *Appendix C — Permutation Test to Assess Group Homogeneity*

In addition to testing the differences between means as was shown in Figure 5.2, the correlation between the 29 satisfaction means for each group was explored using a permutation test. The purpose of the test was to discover whether the homogeneity of attitudes within each group is greater than within the sample as a whole. In other words, do people's attitudes differ distinctively by groups, or are attitudes just different in general? To answer this question, an SPSS program was written to see if the correlation within groups was greater than the correlation between groups. The null hypothesis is that the groups' attitudes are the same. The program first calculated the correlation coefficient between the three pairs of groups: project management vs. strategic; project management vs. operations; and strategic vs. operations. Next, three simulated groups were created by randomly sampling subjects (without replacement) from the total sample. Again, correlation coefficients of the satisfaction means were computed for each of the three pairs of groups. One thousand sets of simulated coefficients were calculated, and these simulated coefficients were compared to the actual coefficients. When the actual coefficient was less than the simulated coefficient, the groups' attitudes were deemed different. The p value is the number of times divided by 1000 that the actual value exceeded the simulated value.

Although the results of the test did not reach significance, this technique could be used with a larger balanced sample, in which the roles of the respondents in the owner organization were measured and defined in more detail than in this study.

# PROGRAM LISTING

```
/* This SPSS input program performs a permutation test using a
/* simulation method. The purpose is to determine whether the people
/* within each sub-group (Project management,Strategic, Operations)
/* have attitudes that are more homogenous within the group than within
/* the sample as a whole. In other words, do people's attitudes differ
/* distinctively by groups, or are attitudes just different in general?

/* First, calculate three correlation
/* coefficients for the covariance between the sub groups' satisfaction
/* attitude means. (PM vs. ST,PM vs. OP, and ST vs. OP). Next, randomly
/* assign each subject to one of the three sub-group, and calculate the
/* correlation coefficients between the sub-groups as above. Do this
/* simulation 1000 times. Finally, compare the simulated coefficients
/* to the actuals. For each of the three comparisons, when the actual
/* coefficient is less than the simulated it means that there is a
/* real distinction between the two subgroups.
/* The p value for each set of comparisons is the
/* number of times divided by 1000 that the actual value exceeds the
/* simulated value.

/* Ho: The groups' attitudes are the same. Operationalize this by
/* testing whether the correlations of satisfaction means of two
/* randomly composed groups are consistently greater than the correlations
/* of satisfaction means of two actual groups. If so, then we reject the
/* the null hypothesis because the differences between the actual groups are
/* greater than the differences in the sample as a whole.



/* This macro caculates the 1000*3 simulated correlation coefficients.
/* Actually need to run this 4 times with 250 iterations each time
/* because of storage constraints.

DEFINE PERMUTES ().
        !VAR=0.                    /*Instead of this, do set seed, and set max iter 1001.
        !DO !VAR = 1 !TO 1000.
                /* ALL53 is the raw satisfaction data
                GET FILE=ALL53.

                /* Randomly order the integers 1-53.
                COMPUTE RANDOM=UNIFORM(1).
                SORT CASES BY RANDOM.
                COMPUTE RANDOM=$CASENUM.

                /*Randomly assign cases to sub-groups
                RECODE RANDOM (1 THRU 12=1)(13 THRU 20=2)(21 THRU 53=3).
```

```
                /*Calculate means for each sub-group.
                AGGREGATE  OUTFILE=*
                      /BREAK=RANDOM
                   /AADAPT AALLWAST  ACAPCOST ACATASTR ACLNCOST
                           ACLNEASE ACOMFORT ADCS ADURAB AENCOST AFLEXEXP
                           AFLEXWAS AHEALTH ALOADWAS AMANUAL AMNTCOST
                           AMNTEASE AOPCOST AOPEASE APREDICT APRODUCT APROFIT
                           ARELIAB ASAFETY ASECURE ASTORAGE ASUTIME ATRAININ
                           AWARR =
                 MEAN(SADAPT SALLWAST  SCAPCOST SCATASTR SCLNCOST
                           SCLNEASE SCOMFORT SDCS SDURAB SENCOST SFLEXEXP
                           SFLEXWAS SHEALTH SLOADWAS SMANUAL SMNTCOST
                           SMNTEASE SOPCOST SOPEASE SPREDICT SPRODUCT SPROFIT
                           SRELIAB SSAFETY SSECURE SSTORAGE SSUTIME STRAININ
                           SWARR).

                /* Transpose the results
                FLIP /VARIABLES=AADAPT AALLWAST  ACAPCOST ACATASTR ACLNCOST
                      ACLNEASE ACOMFORT ADCS ADURAB AENCOST AFLEXEXP
                      AFLEXWAS AHEALTH ALOADWAS AMANUAL AMNTCOST
                      AMNTEASE AOPCOST AOPEASE APREDICT APRODUCT APROFIT
                      ARELIAB ASAFETY ASECURE ASTORAGE ASUTIME ATRAININ
                      AWARR.
                RENAME VARIABLES (VAR001=PM) (VAR002=ST) (VAR003=OP).

                /* In order to calculate the r, need these preliminary calcs.
                COMPUTE PMST = PM*ST.
                COMPUTE PMOP = PM*OP.
                COMPUTE STOP = ST*OP.
                COMPUTE DUMBREAK = 1.

                /* More prelim cals: sums and standard deviations of prior steps.
                AGGREGATE OUTFILE=*
                      /BREAK=DUMBREAK
                      /SUMPM SUMST SUMOP SUMPMST SUMPMOP SUMSTOP
                            = SUM(PM ST OP PMST PMOP STOP)
                      /SDPM SDST SDOP = SD(PM ST OP).

                /* Calculate the correlation coefficients
                COMPUTE RPMST= (SUMPMST - (SUMPM*SUMST)/29)/(SDPM*SDST*28).
                COMPUTE RPMOP= (SUMPMOP - (SUMPM*SUMOP)/29)/(SDPM*SDOP*28).
                COMPUTE RSTOP= (SUMSTOP - (SUMST*SUMOP)/29)/(SDST*SDOP*28).

                /* Write the three values to the ALL1000 file which grows to contain
                /* 3*1000 simulated coefficients.
                !IF (!VAR = 1)
                   !THEN
                        SAVE OUTFILE=ALL1000
                            /KEEP = RPMST RPMOP RSTOP.
                   !ELSE
                        SAVE OUTFILE=TEMPRS
                           /KEEP = RPMST RPMOP RSTOP.
                        GET FILE=ALL1000.
                        ADD FILES FILE=TEMPRS/FILE=*.
                        SAVE OUTFILE=ALL1000.
                 !IFEND.
        !DOEND.
!ENDDEFINE.
```

```
/*** MAIN PROGRAM ****
GET TRANSLATE /FILE "KJ lovers RC:Pilot Analysis:SPSS files:All 53 Q for SPSS" /TYPE TAB
      /FIELDNAMES. /* The raw data
MISSING VALUES  IADAPT IALLWAST IARCHIMA ICAPCOST ICATASTR ICLNCOST
      ICLNEASE ICOMFORT IDCS IDURAB IENCOST IEQCOST IFLEXEXP IFLEXFUE
      IFLEXWAS IHEALTH ILOADWAS IMANUAL IMNTCOST IMNTEASE INEXINDE IOPCOST
      IOPEASE IPREDICT IPRODUCT IPROFIT IRELIAB ISAFETY ISECURE ISTORAGE
      ISUTIME ITRAININ IWARR SADAPT SALLWAST SARCHIMA SCAPCOST SCATASTR
      SCLNCOST SCLNEASE SCOMFORT SDCS SDURAB SENCOST SEQCOST SFLEXEXP
      SFLEXFUE SFLEXWAS SHEALTH SLOADWAS SMANUAL SMNTCOST SMNTEASE
      SOPCOST SOPEASE SPREDICT SPRODUCT SPROFIT SRELIAB SSAFETY SSECURE
      SSTORAGE SSUTIME STRAININ SWARR (0).
RECODE VIEWPOIN ('ProjMgmt'=1) ('Strategic'=2) ('Operations'=3) INTO VPTCODE.
SAVE OUTFILE=ALL53.  /*The raw data in SPSS format.

/*  Calculate the means by subgroup
AGGREGATE  OUTFILE=*
      /BREAK=VPTCODE
      /AADAPT AALLWAST  ACAPCOST ACATASTR ACLNCOST
      ACLNEASE ACOMFORT ADCS ADURAB AENCOST AFLEXEXP
      AFLEXWAS AHEALTH ALOADWAS AMANUAL AMNTCOST
      AMNTEASE AOPCOST AOPEASE APREDICT APRODUCT APROFIT
      ARELIAB ASAFETY ASECURE ASTORAGE ASUTIME ATRAININ
      AWARR =
      MEAN(SADAPT SALLWAST  SCAPCOST SCATASTR SCLNCOST
      SCLNEASE SCOMFORT SDCS SDURAB SENCOST SFLEXEXP
      SFLEXWAS SHEALTH SLOADWAS SMANUAL SMNTCOST
      SMNTEASE SOPCOST
      SOPEASE SPREDICT SPRODUCT SPROFIT SRELIAB SSAFETY
      SSECURE SSTORAGE SSUTIME STRAININ SWARR).

/* Transpose the results
FLIP /VARIABLES=AADAPT AALLWAST  ACAPCOST ACATASTR
      ACLNCOST ACLNEASE ACOMFORT ADCS ADURAB AENCOST
      AFLEXEXP AFLEXWAS AHEALTH ALOADWAS AMANUAL
      AMNTCOST AMNTEASE AOPCOST AOPEASE APREDICT
      APRODUCT APROFIT ARELIAB ASAFETY ASECURE ASTORAGE
      ASUTIME ATRAININ AWARR.
RENAME VARIABLES (VAR001=PM) (VAR002=ST) (VAR003=OP).
COMPUTE PMST = PM*ST.                          /* Prepare to compute the
COMPUTE PMOP = PM*OP.                          /* correlation coefficient
COMPUTE STOP = ST*OP.
COMPUTE DUMBREAK = 1.                          /* Dummy variable for
CORRELATIONS   /* Just checking!               /* aggregate to collapse on
      VARIABLES=PM ST OP.
AGGREGATE OUTFILE=*
      /BREAK=DUMBREAK
      /SUMPM SUMST SUMOP SUMPMST SUMPMOP SUMSTOP
      = SUM(PM ST OP PMST PMOP STOP)
      /SDPM SDST SDOP = SD(PM ST OP).
COMPUTE RPMST= (SUMPMST - (SUMPM*SUMST)/29)/(SDPM*SDST*28).      /* Compute the
COMPUTE RPMOP= (SUMPMOP - (SUMPM*SUMOP)/29)/(SDPM*SDOP*28).      /* correlation
COMPUTE RSTOP= (SUMSTOP - (SUMST*SUMOP)/29)/(SDST*SDOP*28).      /* coefficient
COMPUTE MATCHER = 1.

SAVE OUTFILE=ACTUALRS                                      /*  Save the file with the
      /KEEP = RPMST RPMOP RSTOP MATCHER.                   /*  actual r's
```

```
GET FILE = ACTUALRS.
LIST VARIABLES=ALL.
/* Call the macro
PERMUTES.
GET FILE = ALL1000.
COMPUTE MATCHER = 1.
RENAME VARIABLES (RPMST=SIMRPMST) (RPMOP=SIMRPMOP) (RSTOP=SIMRSTOP).
SAVE OUTFILE = NEW1000.
GET FILE = ACTUALRS.
MATCH FILES FILE=NEW1000 /TABLE=* /BY MATCHER.
COMPUTE PMSTCNT = 0.
COMPUTE PMOPCNT = 0.
COMPUTE STOPCNT = 0.
IF (RPMST>SIMRPMST) PMSTCNT = 1.
IF (RPMOP>SIMRPMOP) PMOPCNT = 1.
IF (RSTOP>SIMRSTOP) STOPCNT = 1.
LIST VARIABLES=ALL.
COMPUTE DUMMY = 1.
AGGREGATE OUTFILE=*
        /BREAK=DUMMY
        /SUMPMST SUMPMOP SUMSTOP = SUM(PMSTCNT PMOPCNT STOPCNT).

LIST VARIABLES = ALL.

COMPUTE PPMST= SUMPMST/1000.
COMPUTE PPMOP= SUMPMOP/1000.
COMPUTE PSTOP= SUMSTOP/1000.

SAVE OUTFILE=PVALUES
        /KEEP= PPMST PPMOP PSTOP.
GET FILE=PVALUES.
LIST VARIABLES=ALL.
```

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