Achieving Industrial Facility Quality: Integration is the Key

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ABSTRACT

This paper demonstrates methods for measuring integration (information flow) in the facility development process, and for measuring the quality of completed facilities. Facility quality measurements serve as benchmarks of the performance of the facility development process. Integration parameters are the basis for adjusting the facility development process so that it produces increasingly higher quality facilities each time the process is repeated. We measured the flow of information in the facility development process: *vertically* (between functions such as operations and engineering), *horizontally* (between disciplines such as process piping and electrical design), and *longitudinally* (across time). We also measured the plant manager's satisfaction with the operational facility. A study of 17 industrial facilities shows that the three dimensions of information flow are good predictors of facility quality. The results suggest an increased emphasis on vertical and longitudinal information flow in the facility development process to achieve higher quality facilities.

BACKGROUND

Creating an industrial facility is a complex undertaking. An industrial facility costing $250 million might have 50 or more organizations participating in its engineering, financing, regulation and construction, making effective coordination difficult. Unanticipated cost and schedule overruns often occur. Facilities frequently do not meet the expectations of the owner.

Clearly, there is room to improve the facility development process. But where do we focus our efforts? What project characteristics will have the greatest effect on customer satisfaction? Despite a long history of building industrial facilities, we have a limited understanding of how the different ways projects are executed impact the quality of the facilities which result. This research explores the relationship between facility development *process* characteristics and the quality of the *product*, the completed facility.

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CONTINUOUS PROCESS IMPROVEMENT

Continuous process improvement is a quality management concept familiar to most people in the AEC (architecture, engineering, construction) / EPC (engineering, procurement, construction) industry. In this context, the main business process we are addressing is the facility development process *as a whole*. This main process, shown in Figure 1, is composed of many intertwined subprocesses such as strategic planning, engineering, regulation, procurement, equipment manufacture, construction, and startup. These subprocesses are themselves composed of subprocesses. Each process or subprocess has four steps: plan, do, check, and act. Plan the work to meet strategic business objectives, do the work, check the work to determine if the strategic objectives were achieved, then act by adjusting the process to achieve even better results from its next repetition.

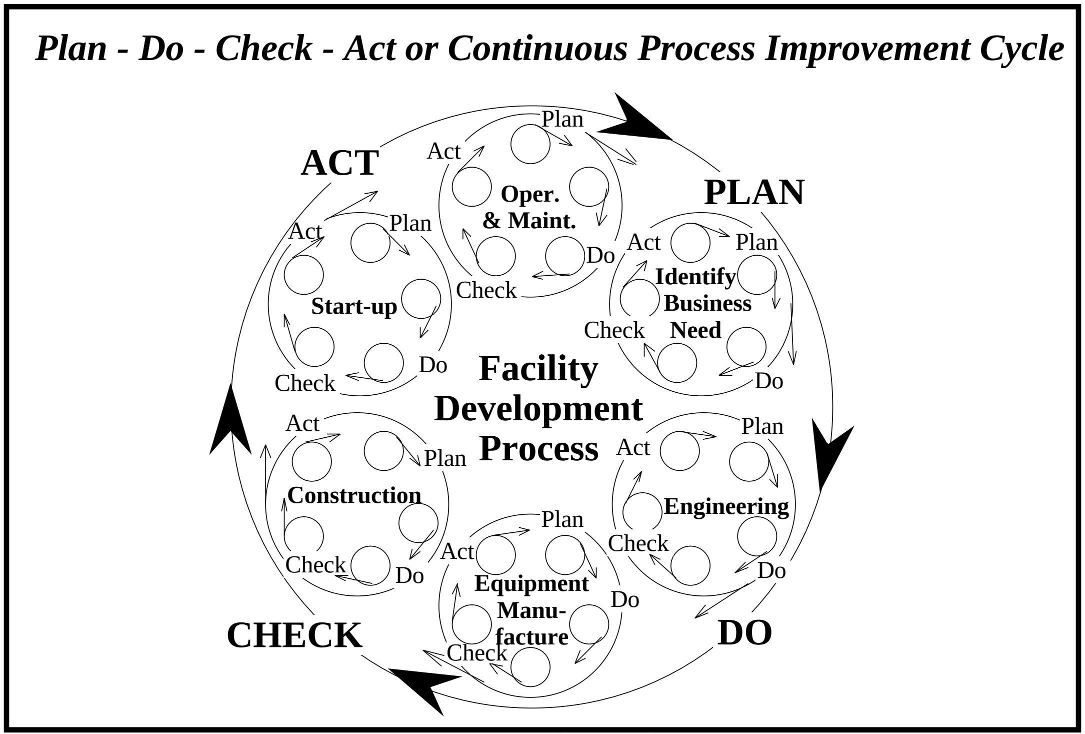


Figure 1. The Plan - Do - Check - Act Cycle for the facility development process.

The facility development process is different from business processes in most other industries because of its complexity and scope. Compared to main business processes in other industries, the facility development process crosses large numbers of organizational boundaries, and typically requires several years to produce an operational facility. Coordination of the process, that is, maintaining the flow of knowledge and information across organizational boundaries, is often poor. In this context of project complexity, fragmentation, and size, the implementation of quality management principles is very challenging indeed.

That no one organizational entity has control over the entire process has made it difficult in the past to manage this process as a *whole*. Rather, it has been a natural tendency for people to suboptimize the subprocess(es) over which they have control, but this has not led to optimization of the whole as judged by the quality of the product. We think there is a opportunity to make fundamental breakthroughs in plant quality if owners and contractors are willing to grapple with and understand optimization of the process as a whole, even though their direct participation concerns only certain subprocesses.

The approach presented below is directly applicable to the facility development process *Plan-Do-Check-Act* or continuous improvement cycle. Specifically, measurements are made at the *Check* stage, when we want to determine if we have accomplished our planned objectives, and changes are made at the *Act* stage, when we want to adjust the process to better achieve our planned objectives during the development of the next facility. For example, a *Check* analysis may indicate inadequate information flow between the engineering prime and the operations personnel, and a facility that fell short of customer expectations in certain areas. The *Act* step may include management action such as a decision, instruction, or policy change to increase operator input to the engineering design process when undertaking the next project, with the expectation of producing a better facility than the last.

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. Many authors have stressed the pivotal role of integration in successful facility development (Howard 1989, Nam 1992, Tatum 1990, Vanegas 1988). But these studies do not measure integration nor empirically link it to project outcomes. The concept of integration can be used to create a structured understanding of this extraordinarily complex process: it enables detailed process variables to be grouped into a robust framework based on ideas drawn from the literature of organizational theory, economics and law. The integration framework acts as a lens, or filter, through which to view and analyze the facility development process in a structured manner. The objectives of the research 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 integration in the industrial facility development process*. Based on integration themes in organizational theory and the literature of economics and law, we present a theoretical framework of the facility development process. We develop and implement measures of integration to show how knowledge and information flows can be measured.

The second objective is *to establish the meaning and measurement of industrial facility quality*. To accomplish this we develop a definition of industrial facility quality, and a quality measurement method that focuses on industrial facilities as the product of the facility development process. The most important aspects of quality are combined into a single quality index for each plant.

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. We determine the relative impact of different types of integration on industrial facility quality. We thus provide a rational basis for the improved management of the facility development process.

OVERVIEW OF STUDY DESIGN

We collected data from 17 industrial facilities (including power plants, chemical manufacturing plants, pulp and paper plants, water and waste water treatment plants, and a hardware manufacturing plant) in the United States and Canada. The plants had been in operation for at least six months. We defined and modeled integration in the facility development process as the flow of knowledge and information between project participants. We defined quality of as satisfaction of owner representatives with the operational facility. Using data collected from the 17 projects, we 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 2.

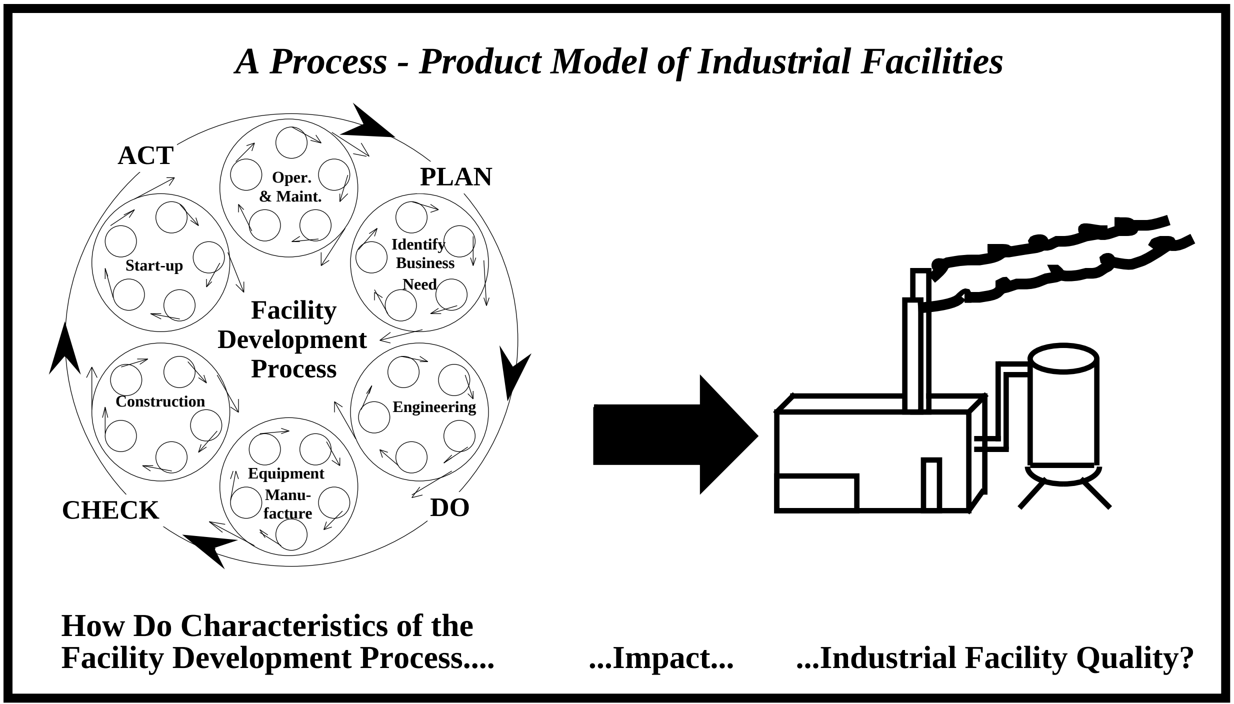


Figure 2. A process-product model of industrial facilities. On the left is he facility development process and on the right is he product of the process, the operational facility.

The left-hand part of the figure displays the facility development process composed of six subprocesses. The arrows symbolize the flow of knowledge and information within and between the subprocesses. The right-hand part of the figure depicts the operational facility itself as the output or product of the facility development process. Our intent in taking this overall process-product viewpoint is to analyze and optimize the facility development process *as a whole*, rather than suboptimizing part 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 constructability 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.

In summary, we measured characteristics of the processes that create facilities, and characteristics of the completed and operational facilities. We then determined the impact of the process characteristics on the quality of the resultant products, the facilities themselves. The conceptual framework of integration is used to create a structured understanding of the facility development process. Facility quality is defined as satisfaction of the plant manager with a combination of several important plant characteristics. This process-product model encourages a strategic, high level understanding of process optimization in order to maximize the quality of operational facilities.

DEFINITION AND MEASUREMENT OF INTEGRATION

Integration is a term often used in our industry, but rarely defined. 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.

In this study, 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), by organizational (humanware) and technical (software and hardware) modes of coordination. The vertical, horizontal, and longitudinal dimensions of integration are shown in Figure 3.

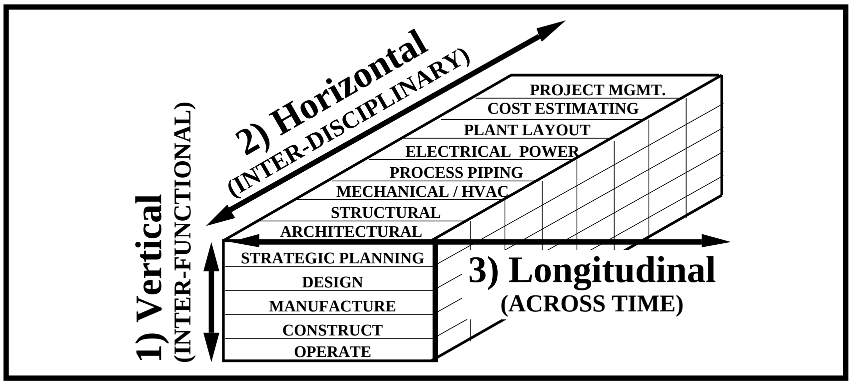


Figure 3. Three dimensions of integration in facility development: vertical, horizontal, and longitudinal. Vertical and horizontal integration adapted from Thomas (1993).

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. Keidel (1985, p. 45) states that vertical integration, "... starts with the discovery/ identification of a raw material and ends with a completed sale — or even service after the sale." Ownership of functions within a single company or government agency is not a prerequisite for successful vertical integration (Blair and Kaserman 1983). Companies and agencies use contracts for the duration of a project to create temporary organizations with all necessary functions. Like a single company owning all functions, temporary organizations can create benefits of vertical integration (Williamson 1979, Stinchcombe 1985). Thus, in this study, *information flow* rather than *ownership* was used as a basis for measuring vertical integration.

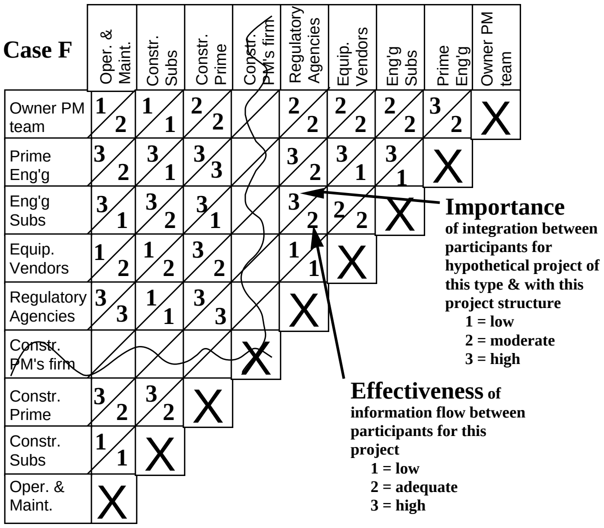
Thomas (1993) portrays horizontal integration between the facility development disciplines of architectural, structural/civil, mechanical/HVAC, plumbing/piping, electrical power, lighting, cost estimating, and project management. In addition to information flow within the engineering function, a similar breakdown can be seen within the manufacture and construction functions. Within the manufacture 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.

Longitudinal 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 the operational life 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. Reducing cycle times improves the flow of information and knowledge by requiring the identification and reduction of time wasted waiting for information and 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.

A questionnaire and in-person interviews were used to gather data related to integration in the facility development process from the members of the prior project organization, including owner representatives as well as the engineering and construction project managers. Vertical, horizontal, and longitudinal integration were each measured in several ways using different types of questions. Only one measure per dimension is presented in this article.

Vertical Integration Measurement

Vertical integration was measured using a matrix listing eight functional participants in the facility development process. This measurement instrument is shown in Figure 4, which includes the data for Case F. The main functional participants listed were 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 respondent first eliminates participants from the matrix that are not applicable to the structure of the project. For Case F, the respondent indicates that no Construction Project Management (CPM) firm participated in this project, so all relationships involving the CPM firm are eliminated from the matrix. Next, the respondent rates the *importance* of the flow of knowledge and information between each pair of participants in a *hypothetical* project of this type with this project structure. Finally, the respondent rates the *effectiveness* of the flow of knowledge and information on this *particular* project.



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

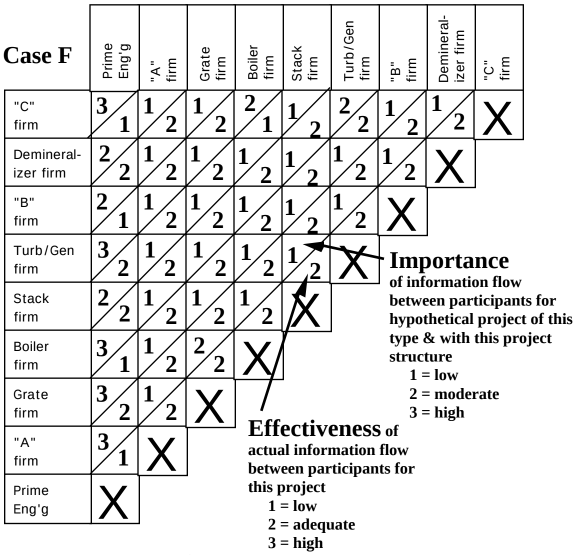
Figure 4. Measurement instrument for vertical integration and responses for Case F.

To create a summary measure of vertical integration (V), a ratio comparing the number of "unfavorable" relationships to the number "important" relationships. "Important" relationships were those rated *moderate* or *high* in importance. "Unfavorable" relationships were those rated *moderate* or *high* in importance, and *low* in effectiveness, as well as relationships rated *high* in importance but only *adequate* in effectiveness. This ratio was subtracted from 1 to create a summary measure that ranged from 0 to 1. Thus, this summary measure approaches 1 as vertical integration increases, and approaches 0 as integration decreases. Case F has 21 "important" relationships and of these, 13 are "unfavorable," and V = 1 - 13/21 = 0.38, where V is vertical integration.

This index was useful in demonstrating that effective information flow between particular pairs of participants discriminates between high-quality and low-quality plants, thus suggesting that these relationships should be the focus of attempts to improve vertical information flow in project organizations. For a discussion of these relationships, see Fergusson (1993).

Horizontal Integration Measurement

Similarly, horizontal integration was measured using a matrix listing the organizations which had performed significant engineering work. The engineering project manager rated these participants from different disciplines in terms of the importance and effectiveness of information flow between each pair in the matrix. This is shown in Figure 5, which includes the data from Case F. The engineering project manager first is asked to identify a list of firms that have some element of engineering design work. The interviewer builds a matrix based on this list. For Case F, eight firms contributed significant engineering work to this project, in addition to the prime engineering design firm. Next, like the previous measure, the engineering project manager gives the *importance* and *effectiveness* ratings for each pair of participants. Note that the matrix measurement instruments for both vertical and horizontal integration accomodate variations in project structure from case to case.



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 5. Measurement instrument for horizontal integration and responses for Case F.

A similar method to that used for vertical integration was used to create a summary measure of horizontal integration (H). Again, a ratio was calculated comparing the number of "unfavorable" (7) relationships to the number "important" (11) relationships. To reduce the influence of measurement error, relationships that were rated "low" in importance were not included in the calculation of either V or H. For Case F, H = 1- 7/11 = 0.36, where H is horizontal integration.

To validate the horizontal integration index, it was correlated with another measure of horizontal integration, the number of firms doing engineering work. The expected inverse relationship was found ($p<.05$, $r^2 = .28$); that is, the greater the number of engineering firms, the greater the burden of coordination, and the less effective the overall flow of knowledge and information between them. p is the probability of predicting a relationship between the variables when none, in fact exists. An r^2 of .28 means that 28% of the variation in each variable is explained by the other variable; loosely speaking, the two related concepts of horizontal integration overlap by 28%.

Longitudinal Integration Measurement

The measure for longitudinal integration tapped the owner organization's capacity for formalized learning and knowledge perpetuation given its experience with relevant tools. The number of years of experience with several quality management tools was measured. These included statistical process control (SPC), quality assurance (QA), total quality management (TQM) (or control, TQC), continuous process improvement (CPI) (or plan-do-check-act cycle, PDCA), quality function deployment (QFD), and the Construction Industry Institute's quality performance tracking system (QPTS). The measurement instrument for longitudinal integration (L) and the data for Case H is shown in Figure 6. The capacity of the owner organization for longitudinal integration, given its experience with relevant organizational learning 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?" For Case H, the respondent indicated the owner organization had experience with four of the quality management programs listed. Respondents 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. To provide a consistent viewpoint across all cases, the respondents to this question were the operations managers in the owner organization.

	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 6. Measurement instrument for longitudinal integration and responses for Case H.

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 with TQC, and likewise PDCA with CPI, only the maximum of the two responses for each was used. The following equation shows the calculation for the summary index of longitudinal integration, after the raw data were corrected:

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

where L is longitudinal integration. For Case H, if the duration between start-up and the interview date was one year, the value of L would be 8.0. This index has a Cronbach's alpha statistic of 0.80 indicating that this is a highly reliable index with low error and high inter-item correlations.

This index was found to correlate significantly ($p<.01$; $r^2 = .54$) with another measure of longitudinal integration based on the number of prior projects worked on together by the main participants. This positive correlation lent validity to the concept of longitudinal integration and the measurement instruments used.

DEFINITION AND MEASUREMENT OF QUALITY

Traditionally, the industrial facility engineering and construction industry has operated in accordance with a *conformance to requirements* definition of quality (Matthews and Burati 1989). However, owner dissatisfaction with cost-effectiveness of engineering and construction services (Business Roundtable 1983) and the losses of AEC and EPC firms in international competitiveness (Wiggins 1988, Yates 1992) have prompted many of these companies to advance to a *satisfies the customer* definition of quality. Adopting this definition of quality — satisfaction of the client with the facility itself — suggests the measurement of owner satisfaction as an important strategic business device. Satisfaction-based metrics provide valuable feedback to consumers as well as providers of industrial facilities regarding the strengths and weaknesses of both facility and project performance.

To measure quality, we developed a list of 32 facility characteristics represented by phrases used to analyze and discuss facility quality. These phrases were culled from literature and from discussions with industry professionals, and included items such as profitability of plant, meeting production output specifications, reliability, etc. By means of a questionnaire, people in the owner organization of the 17 plants were asked to rate the *importance* of each facility characteristic, as well as their *satisfaction* with it, on five-point semantic differential scales. Figure 7 shows these two scales for the facility characteristic of reliability.

Profitability of Plant

Importance Scale
1 2 3 4 5
(low) (high)

Satisfaction Scale
1 2 3 4 5
(low) (high)

Figure 7. Importance and satisfaction rating scales for reliability facility characteristic.

The data gathered from the 53 respondents from the owner organizations is analyzed in Fergusson (1994). That study segments the respondents into three groups: strategic business perspective, project management, and operations. In the present paper, we focus on the responses of the 17 plant managers of the 17 facilities included in this study, although results from all 53 respondents were taken into account in developing the summary quality index presented below.

SUMMARY QUALITY INDEX

The data from the 53 respondents was analyzed in two ways, first *within* owner groups, and secondly *between* owner groups. First, *within* each group, items with high importance rankings but low satisfaction rankings were identified as having implications for competitiveness, i.e. important needs are not being fulfilled by service providers, creating a market niche. Secondly, importance and satisfaction values were compared *between* owner groups to determine whether they were significantly different. A more complete interpretation of both *within* and *between* group differences appears in Fergusson (1994).

The identification of *within* and *between* group differences suggested several facility quality components which could be combined into a single coherent measure describing overall plant quality. A summary quality measure allows the comparison of varied, complex facilities on a simple straightforward basis. We developed such a summary measure, or index, by combining the standardized values[3] of six items representing a broad spectrum of facility quality issues, and representing 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*, maintain key differences in opinions *between* the three owner groups. Four of the six items are high importance, low satisfaction items *within* owner groups, indicating that these facility characteristics have important competitive implications. Thus, the quality 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. The quality index combines the standardized values of the selected items:

$$\mathbf{Q} = \mathbf{S}_{\text{Safety}} + \mathbf{S}_{\text{Reliability}} + \mathbf{S}_{\substack{\text{Ability to avoid}\\ \text{catastrophic failure}}} + \mathbf{S}_{\text{DCS}} + \mathbf{S}_{\substack{\text{Operator}\\ \text{training}}} + \mathbf{S}_{\substack{\text{Meeting prod-}\\ \text{uction output}\\ \text{specifications}}}$$

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

Because of the differences in quality perspectives in owner organizations, it is important to select a consistent viewpoint when using the quality 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 in the ensuing analysis.

The six-item quality index was validated by correlating it with an objective though weaker measure, the ratio of actual production to planned capacity. Although the ratio represents a much narrower concept of quality than the six-item index, the two measures do correlate significantly ($p<.05$, $r^2 = .23$). Loosely speaking, the two related concepts of quality overlap by 23%.

ASSESSING THE IMPACT OF INTEGRATION ON FACILITY QUALITY

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[3] To obtain standardized values for a variable, subtract the mean from each data point and divide by the standard deviaiton. A set of standardized values has a mean of zero, and a standard deviation of 1.0.

The thesis of this study 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 adjustment of these levels in ensuing projects could lead to higher quality facilities.

A regression model was used to determine whether the three-dimensional integration framework presented earlier could be used to predict facility quality. The dependent, or predicted, variable is the plant manager's satisfaction index of plant quality. The independent, or explanatory, variables are the standardized values (denoted by substript s) of the summary measures of the three dimensions of integration, vertical (V), horizontal (H), and longitudinal (L). The three dimensions of integration were found to be independent of each other, yet each correlated positively with facility quality. No interaction effects were discerned.

The regression analysis produces a very strong model (F = 21.9; p<.001; adjusted R^2 = .82), which is shown in Figure 8. The standardized regression equation is:

$$\hat{Q}_s = .54V_s + .32\,H_s + .52L_s$$

In addition to the statistical significance of the equation as a whole, 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. Each dimension of integration (i.e. knowledge and information flow) in the facility development process is a useful predictor of the quality of the resultant facility.

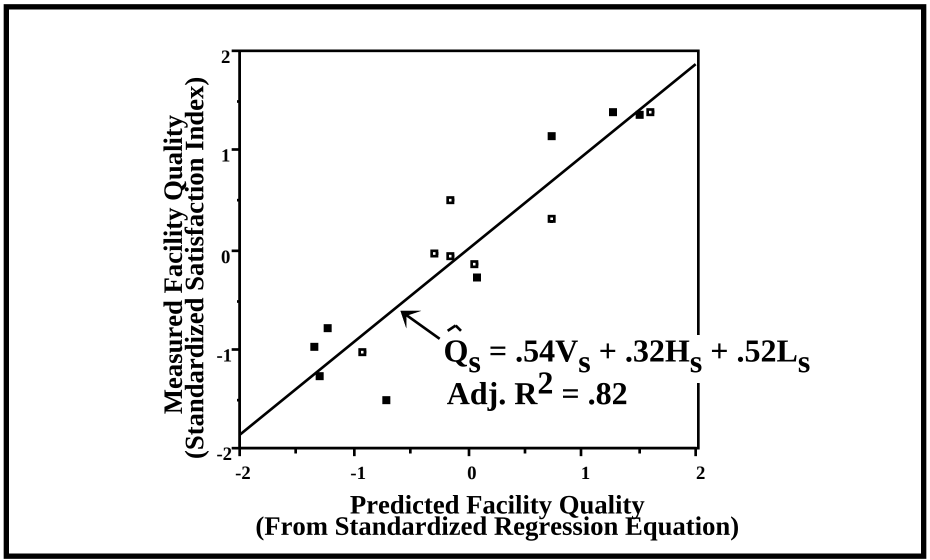

Figure 8. The regression of vertical, horizontal, and longitudinal integration with facility quality.

The standardized beta coefficients suggest the relative importance of integration in these three dimensions for developing a high quality plant. 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 AEC/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.

The possible project structure changes to increase integration are limited only by the innovativeness and resolve of the project execution team. Process changes to increase vertical integration might include increasing operator and construction knowledge input into the engineering design; requiring design engineers to present on-site during construction; and mandating extended training sessions for operators by equipment vendors and manufacturers. Changes to increase longitudinal integration might include incorporation of process technology performance data from prior plants or pilots into the engineering design of the new facility; contracting with firms with which the owner has prior experience; or accessing design elements from a data base library of components whose performance has been proven on prior projects.

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 lens or filter through which to interpret it.

CONCLUSION

This study has demonstrated a method for measuring integration, measuring facility quality, and modeling the impact of integration on quality. If viewed in the context of continuous process improvement, this approach can be used to incrementally upgrade the facility development process. As shown in Figure 9, evaluation of facility quality with respect to process characteristics such as integration should occur at the "Check" stage of the facility development business process. Based on the results of the analysis, adjustments to the process are made at the "Act" stage with the goal of creating an even better quality facility with the next iteration of the cycle, i.e. the next time a project is executed. Interestingly, the engineering and construction companies which participated in this study had no formal method of measuring the quality of its products. However, several "post-mortem" reviews were held to discuss the projects' problems and successes among the owner, engineering, and construction participants. These meetings focus on the *project*, not the *product*, and typically involve only the owners' project management personnel, not the operations personnel using the completed facilities. The feedback information generated from these meetings generally lacks content useful for improving the facility development process. This paper suggests a methodology to address this critical stage of the facility development process.

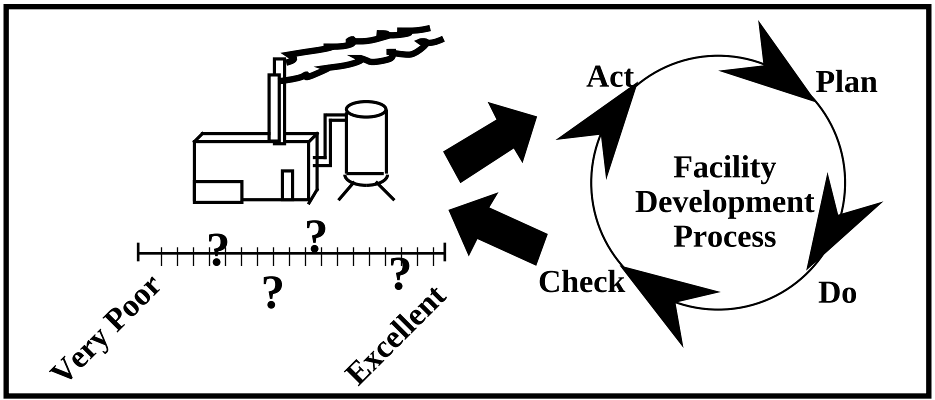

Figure 9. Owners and AEC/EPC firms can apply the product and process evaluation method developed in this study at the "Check" and "Act" stages of the facility development process.

This study found that vertical, horizontal and longitudinal integration were strong predictors of resultant facility quality. Future studies may reveal other good predictors. Guided by such predictors, we can adjust the structure of our project organizations, contract incentives and work processes to create better quality facilities. And that, after all, is our ultimate goal.

ONGOING WORK

Because this was the first study of its kind, we have numerous suggestions and insights on how it might be complemented by ensuing studies that explore these issues in an empirical, quantitative manner. The interested reader should consult Fergusson (1993).

The work described in this paper is being continued in conjunction with the development of the General Performance Model (GPM) (Alarcón-Cárdenas and Ashley 1992), a joint effort between researchers at Stanford and University of California at Berkeley to model the impact of facility development strategic decisions and process characteristics on a suite of project outcome measures, including facility quality. The continuation effort is being funded by the National Science Foundation.

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NOTATION

The following symbols are used in this paper:

ε	regression residual
F	F-statistic
H	horizontal integration index
L	longitudinal integration index
n	sample size
p	probability of Type I error
$\mathbf{Q}$	measured quality index score
r	correlation coefficient
r^2	explained variance
R^2	explained variance (regression)
$\mathbf{S}$	standardized satisfaction rating for the indicated item
subscript s	standardized value for the indicated variable
V	vertical integration index
^	predicted value of the indicated variable

KEY WORDS

Quality measurement, engineering, construction, quality definition, integration definition, project management, process plants, industrial facilities.