Constructability Related to TQM, Value Engineering, and Cost/Benefits

By Jeffrey S. Russell,[1] Associate Member, ASCE, Kevin E. Swiggum,[2] Jeffrey M. Shapiro,[3] and Achmad F. Alaydrus[4]

Abstract: Recently, constructability has received considerable attention from researchers and practicing engineers. Constructability has been defined as the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives ("Constructability" 1986). This paper discusses the evolution of constructability and how programs have been developed to bring design and construction closer to the level of integration once achieved by the master builder. There is a great deal of discussion among industry professionals as to how constructability is related to total quality management and value engineering. This paper conceptually describes these interrelations. In addition, the paper presents a framework to measure costs and benefits related to constructability. By providing owners with this framework, the parameters will be visible and defined, thus removing skepticism as to the measurement process as well as enabling more consistent and uniform results to be obtained. Additionally, these standardized parameters may facilitate developing a means to measure company and industry performance.

INTRODUCTION

Constructability has been defined as the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives ("Constructability" 1986). More specifically, the Business Roundtable defined a constructability program as "the planned involvement of construction in the engineering process" ("Integrating" 1982). The Construction Management Committee of the Construction Division of ASCE ("Constructability" 1991) defines constructability programs more specifically as "the application of a disciplined, systematic optimization of the procurement, construction, test, and start-up phases by knowledgeable, experienced construction personnel who are part of a project team." As a result of constructability, the quality of a constructed facility can be improved by better communication among major project participants such as design engineers and construction professionals. Communication among these participants reduces the chance of project failure and other related performance problems.

There is considerable discussion among industry professionals as to how constructability is related to total quality management (TQM) and value engineering. This paper attempts to conceptually describe these interrelations. It also presents a framework to measure costs and benefits related to constructability.

---

[1]Asst. Prof., Dept. of Civ. and Envir. Engrg., Univ. of Wisconsin, 1415 Johnson Dr., Madison, WI 53706.

[2]Grad. Res. Asst., Dept. of Civ. and Envir. Engrg., Univ. of Wisconsin, 1415 Johnson Dr., Madison, WI.

[3]Design Engr., Barrientos & Associates, Inc., 3822 Mineral Point Rd., Madison, WI 53705.

[4]Constr. Engr., Maxus Southeast Sumata, Inc., Jakarta, Indonesia.

Note. Discussion open until July 1, 1994. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on January 28, 1993. This paper is part of the *Journal of Performance of Constructed Facilities*, Vol. 8, No. 1, February, 1994. ©ASCE, ISSN 0887-3828/94/0001-0031/$1.00 + $.15 per page. Paper No. 5516.

Considerable attention has been given to the topic of constructability ("Integrating" 1982; "Can" 1986; "Constructability" 1986; O'Connor et al. 1986; Tatum et al. 1986; O'Connor and Tucker 1986; "Evaluation" 1986; "Constructability" 1987; "Guidelines" 1987; Tatum 1987a, 1987b; O'Connor et al. 1987; O'Connor and Davis 1988; Vanegas 1988; Eldin 1988; Kirby et al. 1988; Tatum 1989; O'Connor and Hugo 1989; Tatum 1990; *Model* 1990; "Constructability" 1991; O'Connor et al. 1991; Rowings and Kaspar 1991; Fisher and O'Connor 1991; Turner 1992; Russell et al. 1992a, 1992b; Gugel 1992; "Constructability" 1993).

EVOLUTION OF CONSTRUCTABILITY

Since the formalization of constructability, constructability has been an evolving work process. Fig. 1 presents the evolution of methods used within the U.S. construction industry to obtain construction participation during project activities prior to the start of construction (Gugel 1992). Years ago, construction and design activities were integrated within the master builder's organization. Master builders were responsible for all project activities required to plan, design, and construct a facility. During the planning and design phases, the master builder focused on the entire project and considered the impact early decisions had on the construction process. In a sense, the level of design and construction integration achieved within these organizations serves today as the model for modern constructability programs.

Increasing levels of competition and the introduction of manufacturing concepts within the construction industry led to specialization. Such specialization led to the separation of design and construction activities. In many cases, as designers became further removed from the construction process, their designs reflected a lesser understanding of the construction process (i.e., construction methods and techniques used to assemble building components). This lack of understanding often resulted in higher construction costs, and in some cases, unbuildable designs.

With the problems associated with separated design and construction

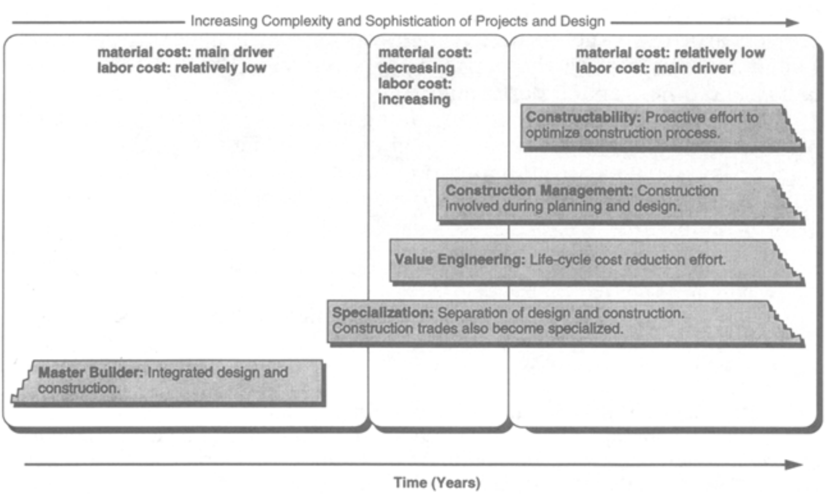

FIG. 1. Evolution of Events Leading to Formalized Constructability (Relative Timing Indicated in Figure Is Intended to Be Approximate)

continuing to grow, industry began implementing value engineering and construction management services. Value engineering (VE) provided a means to reduce project life-cycle cost while construction management services recognized the benefit of constructor involvement during planning and design phases.

Constructability programs have recently been developed in an attempt to bring design and construction closer to the level of integration once achieved by the master builder. Constructability may be implemented in varying degrees of formality. Radtke (1992) identified several approaches, varying by level of formality, in which industry participants are using constructability to integrate construction knowledge and experience into the planning and design phases of their projects. Informal constructability approaches, usually indistinguishable from other construction management activities, may include design reviews and construction coordinators. Formal programs, usually having a documented corporate philosophy and program supports, may involve tracking of lessons learned on past projects, team-building exercises, and construction personnel participating in project planning. Fig. 2 graphically shows how the resources of a formal constructability approach may yield greater benefits than informal approaches.

CONSTRUCTABILITY RELATED TO TQM AND VE

Fig. 3 presents a conceptual graphic relating constructability to TQM and VE. In this section, each topic is further discussed and its relationship to constructability highlighted.

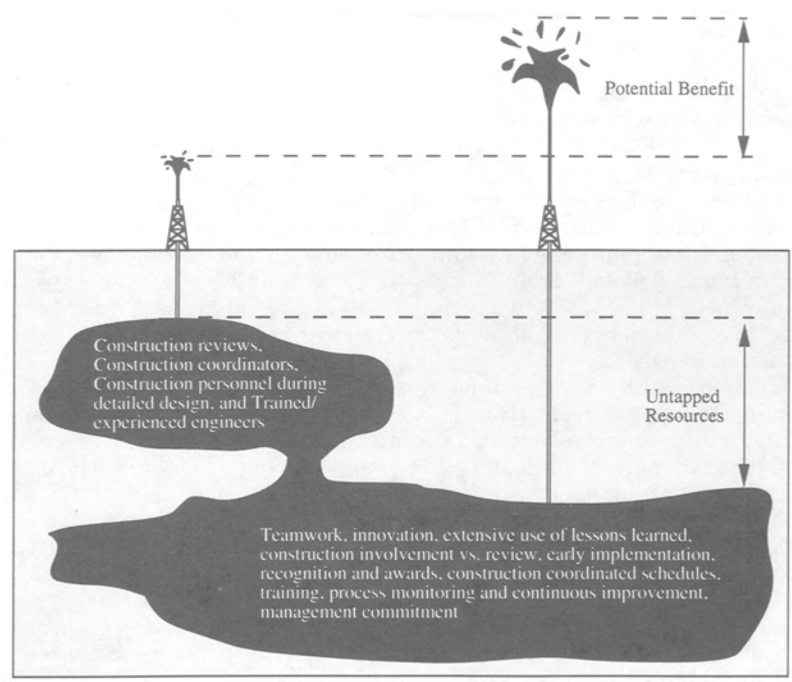

FIG. 2. Untapped Constructability Resources (Adapted from Steve Knisely)

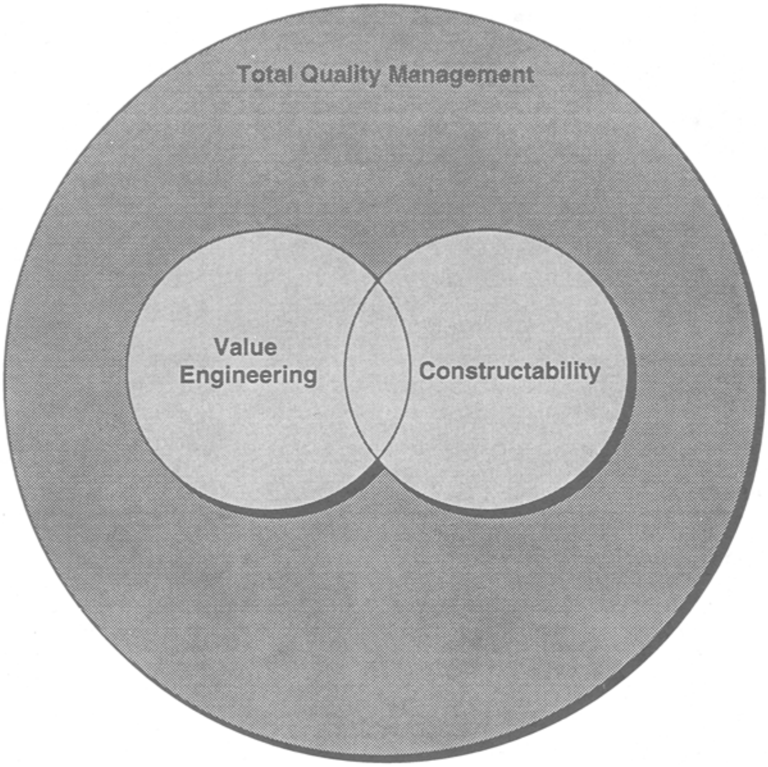

FIG. 3. Constructability Related to Total Quality Management and Value Engineering [Adapted from Hugo et al. (1990)]

Total Quality Management

During recent years, the use of TQM has spread beyond the manufacturing industry to construction. Organizations embracing TQM are adopting a management philosophy that makes quality a strategic objective for the organization ("Total" 1990). Successful application of TQM to constructor and owner organizations in Japan, as well as several in the United States, have increased its recognition as an effective method to improve quality and productivity.

TQM has two principal objectives: (1) Customer satisfaction; and (2) continuous improvement (Burati et al. 1992). Within the construction industry, each party involved on a project, including the owner, constructor, and designer, plays the role of customer and supplier of services. The owner supplies the requirements to the designer, the designer supplies the plans and specifications to the constructor, and the constructor supplies the built facility to the owner (Juran 1988). A principal focus of TQM is for each supplier of services to identify and satisfy or exceed their customer's needs in terms of cost, quality, and time.

Continuous improvement not only involves problem solving on projects but also a proactive search for methods of completing a task more efficiently. The first step of the process is problem avoidance. That is, looking and accounting for areas that may later cause problems. In the construction industry, this means making a formal effort to recognize problems during the planning and design phases instead of discovering problems during construction. The second step in continuous improvement is identifying methods that increase productivity including technological innovations.

Both steps toward continuous improvement create progress toward more productive and higher-quality construction. However, these steps must be accompanied by a method of measuring the progress and cost-effectiveness of the TQM program. This assures that quality and productivity are not only increased but also maintained. Measurement of cost-effectiveness may also be used to increase corporate awareness and commitment by showing the financial benefits accrued as a result of the TQM process. Table 1

TABLE 1. Measures for Tangible Effects of TQM Activities [Source: Kano and Koura (1991)]

Project objective (1)	Measure (2)
	(*a*) Cost
Cost reduction	Cost reduction amount
	Rate of defect cost
	Degree of achieving target cost
	(*b*) Schedule
Delivery date	Delivery date achievement rate
	Late delivery
	Delivery troubles
	(*c*) Quality
Finished product inspection	Acceptance rate of inspection by QA Department
	Acceptance rate of outgoing inspection
User demerit	Customer complaints (cost, rate, number)
	Defective rate of incoming inspections of products delivered to customers
	Compensation work cost
	Rate of complaints at customer's line
	Complaints from market (cost, rate, number)
	Annual failure rate
User merit	Comparison of market quality evaluation
	User satisfaction
	Comparison with international level
	Change in contents of quality problems
	Customer cost reduction
	Extension of guarantee period
	(*d*) Safety/Human Resources
Safety	Number of accidents
	Accident rates
	Severity rates
Human resource development	Number of completed QC circle themes
	Number of suggestions
	Number of qualification obtained
	Absenteeism
	Number of employees receiving QC education

presents some of the quantitative, tangible effects of a quality program that may be measured (Kano and Koura 1991). Each category presented in Table 1 is related to the primary objectives of a construction project and thus, a constructability program: cost, schedule, quality, and safety.

The goals of TQM and constructability are similar if not the same. Table 2 shows a comparison of the philosophical characteristics for both quality improvement and constructability programs. The similarities show that constructability is one aspect necessary to achieve quality in a constructed facility. A constructability program can enhance customer satisfaction by facilitating teamwork among owner, designer, and constructor representatives as early as the planning phase of a project. By so doing, it provides more resources, including construction knowledge and experience, for planning and designing a quality project that maximizes construction productivity.

Constructability is a means of continuous improvement in several respects. Maintaining a lessons-learned database allows communication of positive and negative activities and experiences from one project to future projects. Thus, improvements and innovations can be implemented in future designs. Also, construction personnel may be more aware of innovations in equipment or construction techniques that may play a key role in improving designs.

Measurement of program effectiveness is also a key aspect of both a TQM and constructability program. This includes tabulating quantitative costs and benefits stemming from constructability and TQM such as dollar and schedule savings, as well as recognizing qualitative effects such as higher quality and increased customer satisfaction.

TQM and constructability both stress commitment from all personnel. This commitment must be established from the executive level to the construction craftsmen on the site. This is a proactive process requiring teamwork, recognition of the need for education regarding the program, and a self-assessment regarding capabilities and resources available to achieve the desired goals.

Value Engineering

VE has been defined as "the systematic effort directed at analyzing the functional requirements of systems, equipment, facilities, procedures, and supplies for the purpose of achieving the essential function at the lowest total (life-cycle) cost, consistent with meeting needed performance, reliability, quality, maintainability, aesthetics, safety, and fire resistance" (Kavanagh et al. 1978). Implementation of VE involves six steps: (1) Infor-

TABLE 2. Comparative Analysis of TQM and Constructability

Philosophical characteristics (1)	Quality improvement (2)	Constructability (3)
Performance-driver	customer	design's customer—construction
Principle	"do it right the first time"	problem avoidance, optimize construction process
Growth	continuous improvement (measurement, corrective action)	document lessons learned (program progress measurement, corrective action)

mation; (2) functional analysis; (3) speculation; (4) evaluation; (5) planning/proposal; and (6) implementation/follow-up (Snodgrass and Kasi 1986). The creative step involves a brainstorming session where life-cycle cost alternatives for design components are considered.

VE may be performed in two ways: proactively or reactively. A proactive approach uses VE to collect ideas starting at the beginning of design. Thus, multiple design alternatives are considered and the most cost-effective is selected on a continual basis throughout the design phase. A reactive approach gathers cost-effective alternatives through design reviews by other project personnel such as constructors and other designer engineers. This is performed after the entire design or specific component of design is complete. Thus, suggestions for improvement require design rework. Experience gained by the first two writers during research related to constructability suggests the reactive method of implementation is most common within industry. In the building sector, the term VE is often synonymous with "the project is over budget and we need to cut X dollars from the project's scope." Some designers view VE as an attack on their design.

Table 3 presents a comparison of VE and constructability in regard to focus, implementation, and timing. The primary objective of VE is to reduce the total life-cycle cost of a facility, whereas constructability focuses upon optimization of the entire construction process. In most cases of industry implementation, VE is normally performed during the design phase of the facility delivery process. An effective formal constructability program ideally begins during the conceptual planning phase and continues through construction.

Constructability and VE differ in terms of the criteria discussed previously. However, this does not mean that they are mutually exclusive. Rather, activities within the two work processes may complement each other in achieving their goals. This may result in construction optimization while, at the same time, achieving lowest life-cycle cost. For example, VE recognizes the increased benefit from early implementation (O'Brien 1976). However, information available during planning and design is typically limited. Constructability implementation can act as a precursor to VE, providing information through constructor input and lessons learned from past projects so that VE may be more effective.

TABLE 3. Comparison of Value Engineering and Constructability

Criteria (1)	Value engineering (2)	Constructability (3)
Focus	Overall reduction of life-cycle cost.	Optimize construction process in terms of construction cost, schedule, safety, and quality.
Implementation	A brainstorming session where life-cycle cost alternatives are considered for systems components while maintaining design function.	An integral part of project management and scheduling allowing construction knowledge and experience to be integrated into project planning and design.
Timing	Usually performed during design phase. In many cases, performed as a reactive process to reduce cost after design has been completed.	On-going from conceptual planning through construction and start-up.

DESCRIPTION OF COST/BENEFIT FRAMEWORK

As with TQM, improvements of a constructability program depend upon accurate and consistent measurements of its effectiveness. Inconsistent means of cost/benefit measurement may incorrectly reflect the effectiveness of constructability on a project in comparison to other projects or programs in industry. Thus, a need exists for standardized cost/benefit measurement parameters so that constructability performance may be documented and compared among projects and organizations. This section describes a simplified framework for identifying and quantifying the costs and benefits stemming from implementing constructability at the project level.

Cost Parameters

To quantify the costs of implementing constructability at the project level, a cost estimation framework is necessary. Cost parameters primarily consist of personnel and miscellaneous cost items. Project constructability costs can be determined by (1)

$$TC = \sum_{i=1}^{n} \left[(PS_i)\left(\frac{p_i}{100\%}\right) \times t_i \right] + \sum_{j=1}^{m} M_j \qquad (1)$$

where TC = the total cost of the constructability effort for a given project measured in dollars; n = the number of personnel involved; PS = the monthly salary of personnel i involved in implementing constructability where $i = 1, 2, 3 \ldots n$; p = the portion of the person's salary related to constructability measured as a percent (e.g., 20%); t = the time determined in months that each personnel is required; m = the number of miscellaneous cost items; M = the miscellaneous cost item j where $j = 1, 2, 3 \ldots m$.

Personnel (PS_i) can include project constructability coordinator, project constructability team (i.e., construction project management, owner's representatives, project engineers, discipline engineers, construction superintendents, construction engineers, procurement specialists, vendors, subcontractors, quality-control personnel, and ad hoc specialists). Ad hoc specialists include rigging, heating, ventilating, an air conditioning (HVAC), piping, concrete, instrumentation, electrical, structural, welding, transportation, and equipment, among others. Personnel may be involved over multiple phases of the facility delivery process. Miscellaneous (M_j) items can include telephone calls, travel, and office expenses required to support the personnel.

At the organization level, the total cost of constructability can be measured by (2)

$$TCC_k = \sum_{j=1}^{n} TC_j + CCP \qquad (2)$$

where TCC_k = the total cost of corporate constructability program measured in dollars; n = the number of projects; TC_j = the total dollar cost to implement a constructability program on project j where $j = 1, 2, 3 \ldots n$; and CCP = the total cost of the corporate constructability program measured in dollars. CCP includes the costs to start-up and maintain a corporate constructability program. Cost elements include written program procedures, computer hardware and software that contains the lessons-learned database, constructability analysis tools, and a corporate constructability coordinator (Russell and Gugel 1993). Example values of the cost of a constructability program including both the project and organization level can be found in Russell and Gugel (1993).

Benefit Parameters

A common concern among parties that procure construction input is the difficulty of accurately estimating its value or benefit. Benefits accrued through implementing constructability are often difficult to quantify. They are typically measured through documented benefits from constructability ideas implemented. It is relatively simple to track the cost of design, construction labor, and materials used to complete a given design alternative. Constructability, however, involves generating ideas that optimize the construction process. Hence, the question, how do you estimate the value of such ideas? Fig. 4 presents a framework for determining benefits stemming from implementation of constructability. Benefits can be either quantitative or qualitative.

Quantitative

Quantitative benefits stem from one of two means: (1) Strategic or key execution decisions; and (2) functional analysis. This concept is presented

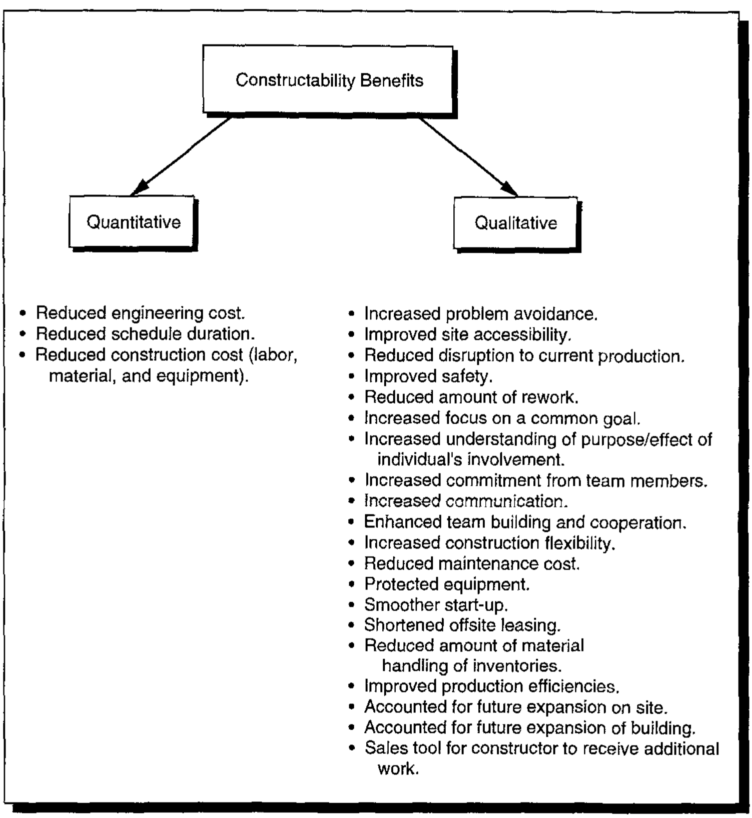

FIG. 4. Framework For Determining Constructability Benefits

in Fig. 5. Both of these quantitative benefit categories lead to a reduction in engineering, construction cost, and schedule duration. The magnitude of the benefits measured in dollars saved, however, does vary; strategic decisions have the largest impact on design and construction costs and on the project schedule. Reduction in engineering can occur through the use of standardized building components and design details. Construction costs can be reduced by using labor more efficiently through prefabrication, preassembly, and modular techniques, and efficient use of construction materials, mechanized equipment, and hand tools.

Several key factors must be considered in order to impact design and construction costs, and scheduled duration. Such factors include contract strategy (fixed price or reimbursable), construction methods and techniques, and construction sequencing. Measurement of the effect of these factors can be obtained by determining the impact of the change from that of standard practice. Fig. 6 illustrates how up-front consideration of these factors affects measurable cost and schedule savings.

Quantitative benefits may be estimated by assessing the cost savings, in comparison to standard practice, for each idea generated through con-

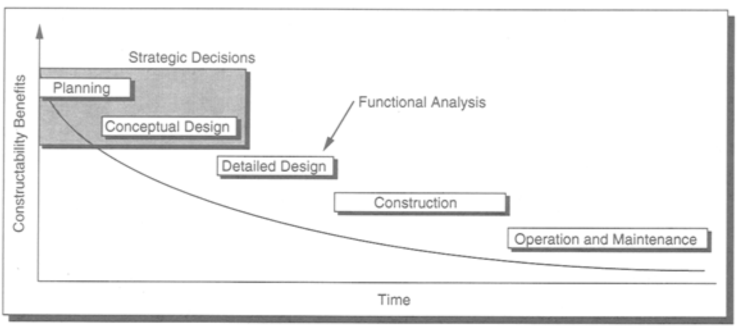

FIG. 5. Categories of Quantitative Benefits for Phases in Facility Delivery Process

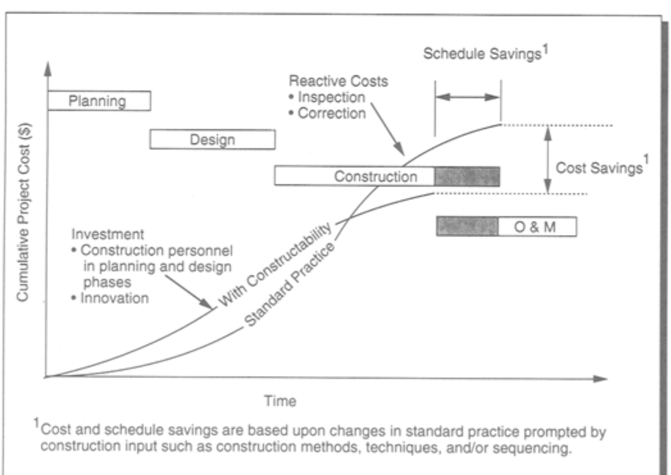

FIG. 6. Realization of Cost and Schedule Savings From Early Investment

structability. Direct savings can stem from less material, fewer number of workers (i.e., reduced labor effort-hours), and a reduced amount of fixed equipment used in construction. Constructability implementation often results in decreased schedule duration. The reduced schedule, in comparison with standard practice, can be translated into cost savings. Cost benefits realized through reduced schedule include: (1) Decreased labor hours; (2) decreased equipment rental and/or operation; (3) decreased overhead expenses; and (4) achieving contract incentives if available.

A constructability idea may result in more expensive materials or other up-front investment. However, the cost savings through reduced schedule must be taken into account when assessing the total benefit of the idea.

The quantitative benefits estimated for each major constructability idea may be totaled for each project and compared to the costs of constructability. This cost/benefit ratio can be a measure of the effectiveness and/or maturity of the constructability program. Case studies of past projects involving petrochemical, general building, and manufacturing construction have shown cost/benefit ratios exceeding 1:10 (Russell et al. 1992a).

Reduction in construction costs can occur through the use of off-site fabrication techniques such that the direct and indirect field labor is minimized. For example, the use of traditional direct field labor construction techniques as comapred to prefabrication, preassembly, or module techniques. On a petrochemical industrial project, one significant constructability idea that resulted in a cost savings of $10,000 (0.50% of the total project cost), included the design of a module to enable the evaporative cooler to be supported by a skid housing pumps with all associated piping, valves, fittings, and instrumentation (Russell et al. 1992a). Historically, this owner field-assembled all components of the evaporative cooler. Thus, the savings could be calculated by comparing the costs of this project with projects using traditional methods.

Other quantitative benefits can be generated through functional analysis. As the scope of the design is refined during the design phase, it is easier to capture a quantitative estimate of the benefits resulting from constructability. The cost estimation technique to quantify the benefit used frequently in industry is an order-of-magnitude estimate. Fig. 7 presents ideas generated from a constructability team involved in a consumer-products industrial project. Many of these ideas are related to improving existing design. Many of these ideas are traditionally considered to be part of a VE effort.

Qualitative

Accurately quantifying benefits attributable to constructability may not be possible, particularly when considering the qualitative benefits listed in Fig. 4. Significant qualitative benefits include problem avoidance through increased communication, cooperation and respect among participants, and teamwork. Problem avoidance is difficult to measure due to many interrelated factors that contribute to avoiding problems. It is difficult to identify and separate the impact of each factor. Example factors include project-management capabilities, skill level of craftsmen, equipment utilization, and weather conditions. Thus, the economic value of problem avoidance is difficult to quantify.

An example of problem avoidance was related to welding procedures for an owner-designed and -managed gas production facility (Russell et al. 1992a). Welding procedures are normally submitted during the construction phase and often delay pipe installation due to the time-consuming approval

		Estimated Savings ($)
1.	Elevated Pipe Bridge at Alcohol Tanks	4,575.00
2.	Reduction in Cut (Soil) North Road	975.00
3.	Delete Paving Around Existing R/R, Scale Pit, and New Alcohol Unload Area 7,600 SF	19,000.00
4.	Leave Dam and Delete Rip-Rap Ditch 50 Ft.	2,032.00
5.	Delete Demo of Existing Concrete, Work New Asphalt to Concrete	10,000.00
6.	Re-Route Storm drain System for Tie-In by North Road	1,000.00
7.	Delete Installation of New R/R Spur, Concrete Spill Protection and U.G. Drainage System	79,300.00
8.	Re-Route Sanitary Sewer Liner and Delete Lift Station	26,000.00
9.	Reduce Excavated Sedimentation Area from 3,000 CY to 800 CY	2,500.00
10.	Changes to Guard House at West Gate	11,000.00
11.	Changed Wire Sizes for Building Receptacles	23,000.00
	TOTAL SAVINGS	180,000.00

FIG. 7. Example of Constructability Ideas Generated from Functional Analysis

process. As a result of discussing this with the constructability team, welding procedures were provided months before the start of construction thereby eliminating potential for construction delays. On a manufacturing facility, the largest door designed in a building did not appear large enough to accommodate a late arriving tank. The tank, larger than the designed door opening, was scheduled to arrive after the completion of the building enclosure. The constructability team requested that a door large enough to permit the tank to gain entry into the building be installed. This idea prevented cutting a hole and patching the building enclosure.

A qualitative consideration of constructability is site logistics. There were considerable site logistics associated with erecting a 15-story stainless steel building cap on the 57th story of an office tower (Russell et al. 1992a). The construction management firm assigned additional in-house personnel that had recently completed a high-rise office building with a similar cap. Mechanical equipment deliveries were coordinated with the progress of each subsequent level of the cap. The construction management firm developed nine schematic drawings to communicate the nine phases necessary to construct the cap. Every detail, including materials storage, was carefully planned to avoid interference difficulties. The level of planning and coordination, however, required the direct involvement of the organizations responsible for its fabrication, shipment, and erection.

Related to project objectives, safety and quality (through a reduction in the amount of rework) can be improved. Constructability implementation can enhance safety performance on a project through, for example, rigging and erection studies. Also, use of preassembly, prefabrication, and modularization techniques can reduce the amount of work performed on scaffolding. As an example, on an industrial petrochemical project, the constructability effort resulted in a high use of prefabrication that contributed to increased productivity as well as to a safety record of zero lost-time accidents in 4.0 million direct and indirect field effort-hours including owner's, design engineer's, constructor's, and subcontractor's field staffs. The program provided construction input regarding erection sequencing, off-site shop fabrication of various major vessels, and off-site field dressing of vessels to significantly reduce the need for scaffolding (Russell et al. 1992a).

Other benefits are accrued through smoother facility start-up and turnover, reduced maintenance, and easier expansion of the site or facility. When one accounts for qualitative benefits such as those described previously, it is believed that any quantitative measure of benefits will always be underestimated.

CONCLUSION

There has been considerable discussion among industry professionals as to how constructability is related to total quality management and value engineering. This paper conceptually described the interrelationships between these subjects as well as how they have contributed toward the integration of design and construction similar to that once achieved by the master builder. Total quality management, value engineering, and constructability are not mutually exclusive. Instead, value engineering and constructability are complementary work processes that may be used as key elements in achieving total quality.

This paper also presented a framework to measure costs and benefits stemming from implementing constructability. Beyond the documented quantitative benefits from constructability, the qualitative benefits in and of themselves are substantial. Thus, the documented benefits, not reflecting these qualitative benefits, will usually be underestimated. Using the framework, a cost/benefit ratio may be calculated reflecting the effectiveness and/or maturity of a constructability program. Providing owners with visible and defined measurement parameters may facilitate consistent and uniform estimates of constructability savings. Thus, such a framework may remove owner skepticism as to the savings measurement process. By having standardized parameters, a constructability index to measure company performance versus an industry standard may be also developed.

ACKNOWLEDGMENTS

The first writer sincerely thanks the Construction Industry Institute and the National Science Foundation grant No. MSM-9058092, Presidential Young Investigator Award, for financial support of the research described herein.

APPENDIX. REFERENCES

Burati, J. L., Matthews, M. F., and Kalidindi, S. N. (1992). "Quality management organizations and techniques." *J. Constr. Engrg. Mgmt.*, ASCE, 118(1), 112–128.

"Can your design be built?" (1986). *Civ. Engrg.*, ASCE, 56(1), 49–51.

"Constructability concepts file." (1987). *Publication 3-3*, Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.
"Constructability and constructability programs: White paper." (1991). *J. Constr. Engrg. Mgmt.*, ASCE, 117(1), 67–89.
"Constructability implementation guide." (1993). *Publication 34-1*, Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.
"Constructability: A primer." (1986). *Publication 3-1*, Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.
Eldin, N. N. (1988). "Constructability improvement of project designs." *J. Constr. Engrg. Mgmt.*, ASCE, 114(4), 631–640.
"Evaluation of design effectiveness." (1986). *Publication 8-1*, Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.
Fisher, D. J., and O'Connor, J. T. (1991). "Constructability for piping automation: Field operations." *J. Constr. Engrg. Mgmt.*, ASCE, 117(3), 468–485.
Gugel, J. G. (1992). "Models for constructability approach selection and input-source evaluation," MS thesis, Univ. of Wisconsin, Madison, Wisc.
"Guidelines for implementing a constructability program." (1987). *Publication 3-2*, Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.
Hugo, F., O'Connor, J. T., and Ward, W. V. (1990). "Highway constructability guide." *Research Project 3-6-88-1149*, The Ctr. for Transp. Res., Univ. of Texas at Austin, Austin, Tex.
"Integrating construction resources and technology into engineering." (1982). *Report B-1*, The Business Rondtable, New York, N.Y.
Juran, J. M. (1988). *Juran of planning for quality*. The Free Press, New York, N.Y.,
Kano, N., and Koura, K. (1991). "Development of quality control seen through companies awarded the Deming Prize." *Reports of Statistical Application Research, JUSE*, 37(1–2), 79–105.
Kavanagh, T. C., Muller, F., and O'Brien, J. J. (1978). *Construction management—A professional approach*. McGraw Hill Book Co., New York, N.Y.
Kirby, J. G., Furry, D. A., and Hicks, D. K. (1988). "Improvements in design review management." *J. Constr. Engrg. Mgmt.*, ASCE, 114(1), 69–82.
Knisely, S. (1992). "Improving project constructability." Paper presented at CII Products for Project Management, Construction Industry Institute, University of Texas, Austin, Tex.
"Manual for special project management." (1991). *Special Publication*, Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.
Model plan for constructability. (1990). Houston Business Roundtable, Houston, Tex.
O'Brien, J. J. (1976). *Value analysis in design and construction*. McGraw Hill, Inc., New York, N.Y.
O'Connor, J. T., and Davis, V. S. (1988). "Constructability improvement during field operations." *J. Constr. Engrg. Mgmt.*, ASCE, 114(4), 548–564.
O'Connor, J. T., and Hugo, F. (1989). "Highway project constructability." *Proc., Constructed Project Excellence*, ASCE, New York, N.Y., 66–71.
O'Connor, J. T., Hugo, F., and Stamm, E. M. (1991). "Improving highway specifications for constructability." *J. Constr. Engrg. Mgmt.*, ASCE, 117(2), 242–258.
O'Connor, J. T., Larimore, M. A., and Tucker, R. L. (1986). "Collecting constructability improvement ideas." *J. Constr. Engrg. Mgmt.*, ASCE, 112(4), 463–475.
O'Connor, J. T., Rusch, S. E., and Schulz, M. J. (1987). "Constructability concepts for engineering and procurement." *J. Constr. Engrg. Mgmt.*, ASCE, 113(2), 235–247.
O'Connor, J. T., and Tucker, R. L. (1986). "Industrial project constructability improvement." *J. Constr. Engrg. Mgmt.*, ASCE, 112(1), 69–82.
Radtke, M. W. (1992). "Model constructability implementation procedures." MS thesis, Univ. of Wisconsin, Madison, Wisc.
Rowings, J. E., and Kaspar, S. L. (1991). "Constructability of cable-stayed bridges." *J. Constr. Engrg. Mgmt.*, ASCE, 117(2), 259–278.

Russell, J. S., and Gugel, J. G. (1992). "A comparison of two corporate constructability programs." *J. Constr. Engrg. Mgmt.*, ASCE, 119(4), 769–784.
Russell, J. S., Gugel, J. G., and Radtke, M. W. (1992a). "Benefits and costs of constructability: Four case studies." *Source Document 83*, Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.
Russell, J. S., Radtke, M. W., and Gugel, J. G. (1992b). "Project-level model and approaches to implement constructability." *Source Document 82*, Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.
Snodgrass, T. J., and Kasi, M. (1986). *Function analysis: The stepping stones to good value.* Univ. of Wisconsin, Madison, Wisc., 1–3.
Tatum, C. B. (1987a). "Improving constructability during conceptual planning." *J. Constr. Engrg. Mgmt.*, ASCE, 113(2), 191–207.
Tatum, C. B. (1987b). "The project manager's role in integrating design and construction." *Project Mgmt. J.*, 18(2), 96–107.
Tatum, C. B. (1989). "Management challenges of integrating construction methods and design approaches." *J. Mgmt. Engrg.*, ASCE, 5(2), 139–154.
Tatum, C. B. (1990). "Integrating design and construction to improve project performance." *Project Mgmt. J.*, 21(2), 35–42.
Tatum, C. B., Vanegas, J. A., and Williams, J. M. (1986). "Constructability improvement using prefabrication, preassembly, and modularization." *Tech. Report No. 297*, Stanford Univ., Stanford, Calif.
"Total quality management: The competitive edge." (1990). *Publication 10-4*, Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.
Turner, J. P. (1992). "Constructability for drilled shafts." *J. Constr. Engrg. Mgmt.*, ASCE, 118(1), 77–93.
Vanegas, J. A. (1988). "A model for design/construction integration during the initial phases of design for building construction projects," PhD thesis, Stanford Univ., Stanford, Calif.