Constructability Concepts for Engineering and Procurement

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Abstract: Constructability is the optimum use of construction knowledge and experience in planning, engineering, procurement and field operations to achieve overall objectives. Seven concepts for improving constructability during the engineering/procurement phase of a project are presented and analyzed. A limited number of specific applications of each concept are also presented. The concepts promote construction-driven schedules, simplified design configurations, standardization of elements, and module/preassembly designs which facilitate fabrication, transport, and installation. Concepts also address the accessibility of manpower, materials, and equipment; design modifications to facilitate construction in adverse weather; and specification improvements.

Introduction

The Constructability Task Force of the Construction Industry Institute (CII) based at The University of Texas has defined constructability as follows: constructability is the optimum use of construction knowledge and experience in planning, engineering, procurement and field operations to achieve overall objectives.

The infusion of construction knowledge into activities preceding construction will result in efficient site operations. The reference to overall project objectives is also important. It is an acknowledgment that construction efficiency considerations often must yield to project operability, maintainability, or aesthetic goals. Most often, however, a balance of such objectives is both desirable and achievable. The effective use of construction knowledge and experience is the mechanism often missing for achieving that balance.

This paper addresses how construction knowledge and experience may be most effectively used during the engineering and procurement phases of projects. A primary purpose of this study has been to develop constructability-enhancement tools for project management and middle management. Specific research objectives and scope limitations include:

1. Identifying constructability improvement ideas related to engineering and procurement, focusing on electrical, instrumentation, piping, and structural work;
2. Identifying, from specific ideas, a limited number of significant concepts that project personnel may use to generate additional specific applications.

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3. Analyzing the constructability concepts, and exploring the details of execution, advantages and disadvantages, limitations and appropriate conditions, and organizational and timing aspects.

Constructability is an information-intensive pursuit. As such, a hierarchical structure of information has evolved from the deliberations of the Constructability Task Force of the Construction Industry Institute. The terms concept and application are used to convey this hierarchy. In this research these terms have taken on special meaning and their usage should be read as deliberate. The following definitions are offered.

Concept.—A significant, distinct, and executable objective for enhancing constructability. Concepts are not specific or unique with respect to project type or organization. Concepts are abstracted from analysis of ideas. Project managers should be keenly aware of constructability concepts.

Application.—An executable specific action that is tactical in nature and that may be viewed as an implementation of a concept. Applications represent the best ideas and may be numerous in number. Middle managers should be aware of constructability applications.

Corporate Constructability Programs: State of the Art

In August 1984, a survey questionnaire was sent to the then 34 member companies of CII. This questionnaire was designed to determine the current level of constructability practiced by the member companies. It was also used to determine candidates for further participation in the study and potential project sites to investigate. As of September 1984,

TABLE 1.—Corporate Constructability Programs

Question (1)	Breakdown of respondents (2)
Profile of respondents	
Project owner	14
Engineering contractor	4
Construction contractor	1
Engineer-constructor	4
Effort devoted to constructability	
Extensive, comprehensive	9
Above average	9
Average	2
No response	3
Printed material on constructability	
Companies having material	9
Companies with no material	14
Primary focus of constructability program	
Project planning	18
Detailed design/procurement	13
Construction field operations	11
Other	6

Note: 23 of 34 questionnaires returned.

J. Constr. Eng. Manage., 1987, 113(2): 235-248

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23 of the 34 companies had responded. The responses have been totaled and are presented in Table 1.

Most companies view their constructability programs as extensive and comprehensive or, at least, above average. While a limited number of printed materials were returned as requested, nine of the respondents have developed such materials. Also, the primary focus of constructability programs appears to cover a broad range. The project planning phase receives the most attention, but the average respondent indicated two project phases in which constructability is addressed.

It appears that constructability is not as neglected as once believed. Certainly many companies have been addressing constructability, but do not refer to it by that name. To these organizations, constructability is simply good project management. Still others safeguard the details of their programs as proprietary. They view program elements as their cutting edge, and are reluctant to share such information.

Research Method

A primary objective of this research was to identify and analyze engineering constructability concepts. As illustrated in Fig. 1, the research method and, in particular, data analysis activities were directly supportive of this objective.

The first step was the scoping of study issues, followed by the development of interview guides. Interview guides enabled the researchers to conduct organized and uniform interviews. Data from previous studies by O'Connor and others (Glanville and O'Connor 1985; Larimore and Tucker 1983; O'Connor and Tucker 1983) formed the original data base of constructability ideas. Beyond this, three methods of data collection were utilized to acquire information from which constructability concepts could be derived:

1. Personal interviews with project personnel.
2. Topical discussions with panels of experts.
3. Frequent discussions with task force members.

Beginning in December 1984, research trips were taken to conduct interviews at home offices and plant sites. Interviews were conducted with owner project managers and engineers, engineering contractors, construction contractors, and subcontractors. In all, 16 different organiza-

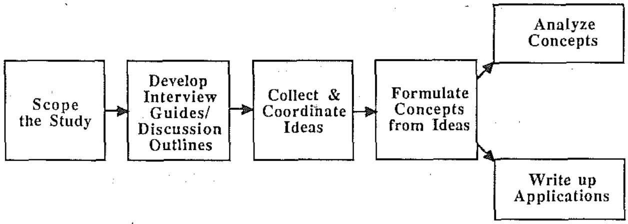

FIG. 1.—Research Method: Identification and Analysis of Constructability Concepts

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tions and 83 individuals were involved in approximately 200 hours of interviewing. Given the focus of this study on electrical, instrumentation, piping, and structural work, industrial projects were primarily studied.

During June and July 1985, three panel discussions on the topics of scheduling, procurement, and work packaging were conducted with project managers and engineering managers. Four to six experts were involved in each discussion, and participants were chosen on the basis of their knowledge in the particular area of discussion. Outlines covering a wide range of related issues thought to influence project constructability were used to direct each discussion. Participants were also encouraged to bring up points not addressed on the outlines.

The CII Constructability Task Force also served as a rich source of information. Through frequent meeting discussions, the experiences of member company personnel supplemented and tempered data from other sources.

Once ideas had been collected, the coordination of ideas was required. Duplicated ideas were eliminated, and contrasting ideas were combined in order to better present the trade-offs. Personal preferences and highly controversial ideas were eliminated.

The analytical step of formulating concepts from ideas followed. This was a discussion-intensive activity that passed through several iterations. Finally, the task force settled on the seven engineering and procurement constructability concepts discussed below. Non-concepts did not meet a significance threshold, were directly supportive of another concept, or decidedly fell outside the defined scope of constructability.

Following the identification of concepts, each was analyzed for basic details of execution, advantages, appropriate conditions for application, and barriers. The final step was the selection of concept applications. These applications represent the best ideas supportive of each concept.

Concepts, Analyses, and Applications

The presentation format for each concept is comprised of three parts: (1) Statement of the concept; (2) discussion of the concept; and (3) specific applications of the concept. The discussions of the concepts identify how constructability is enhanced and include analyses of concept execution, advantages, and conditions for application as appropriate.

Construction-Driven Schedule

Concept.—Constructability is enhanced when design and procurement schedules are construction-driven.

Analysis.—The schedules for design and procurement activities should be driven by the needs of construction. Thus, a construction schedule must be developed before design and procurement schedules are initiated. All schedules are then detailed and finalized in an iterative fashion.

The construction-driven approach to scheduling is a departure from the traditional method in which the sequence of design is dictated by design logic. It is particularly appropriate for projects with cost-reim-

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bursable contracts or for design-build (E-P-C) type contracts. The advantages of the construction-driven schedule are significant: (1) Project durations are reduced; (2) fewer delays are experienced in the field; (3) engineering and procurement activities are effectively prioritized; (4) work packaging is more effective; and (5) project personnel have an increased awareness of true schedule goals.

The schedule development process should involve an interdisciplinary team of experts with construction well-represented. The focus of planning should be placed on the field need dates for the issuance of drawings and specifications and the delivery of materials.

Work packaging is particularly critical for a fine-tuned construction-driven schedule, and it must be developed at a fairly detailed level to be effective. Poor work packaging can result in an excessive amount of interdependency among work packages, thus increasing the likelihood of delays.

Project owners should take an active role in assuring that design and procurement schedules are construction-driven.

Specific Applications.—Some applications of this concept are listed:

1. The design schedule for engineered equipment should be driven by the procurement schedule, which is construction-driven.
2. One mechanism for facilitating team scheduling is to make standardized skeletal sequence networks available to engineering, procurement, construction, and start-up personnel for review and markup.
3. Plans and specifications should arrive at the field in advance of construction to allow adequate time for job site preplanning.
4. Design changes initiated without full appreciation of the schedule implications are to be avoided. The design "freeze" should be adhered to.
5. The timing of issue of purchase orders should depend on the required sequence of delivery and required lead times.
6. Effective sequencing of the delivery of equipment and material should be given high priority. Schedule-effectiveness should be considered as a performance criterion for vendor selection.
7. Appropriate use of blanket purchase orders enhances sequence of delivery.
8. The sequence of material delivery should be based on constructor input. An erectable sequence should be defined and supported by the issue of drawings. For large purchase orders and multiple deliveries, the specific sequence of material delivery and delivery dates should be specified in the purchase order, e.g., the delivery sequence of columns and beams from a single fabricator.

See Hout (1979) for additional discussion.

Simplified Designs

Concept.—Constructability is enhanced when designs are configured to enable efficient construction.

Discussion.—Safety, operability, maintainability, and aesthetics are project objectives which frequently supersede constructability. However, both design layouts and design details may often be modified to

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enhance constructability without sacrificing these other objectives. Illustrative principles for simplifying designs include:

1. Using a minimum number of components, elements, or parts for assembly.
2. Using readily available materials in common sizes and configurations.
3. Using simple, easy to execute connections with minimum requirements for highly skilled labor and special environmental controls.
4. Employing designs which allow for field capability for dimensional adjustment.
5. Employing designs which minimize construction task interdependencies.

The choice of materials and required connecting arrangements such as welding, bolting, and splicing/terminating should also recognize handling, inspection, and testing requirements. Complex connections not only slow construction, but may make it difficult to verify the integrity of the connection.

An emphasis on simplified designs, however, should not result in the issue of construction drawings which do not present all the necessary information. The goal should still be effective communication, not drawing simplification.

How may overly complex designs be identified? Designs should be reviewed by qualified construction personnel. Project organization and execution plans should provide for the availability of experienced construction people on a continuing, or timely, basis so that they can help the design team. The ultimate implementation of this concept would result in the people involved in the design effort routinely considering how to apply these and similar principles to their work.

Specific Applications.—Some applications of this concept are listed:

1. Electrical grounds should be a stub-up cable of 18 inches which can be tied (clamped) to a bus bar, in lieu of ground plates embedded in concrete slabs. Ground plates are difficult to place correctly during a slab pour and require a special attachment from the cable to the bus bar.
2. Expansion joints for rack piping runs should be nested together in a common location. This allows several joints to be supported at a common point, and reduces the likelihood of physical interferences in the pipe racks.
3. Underground piping and electrical conduit should each be run at consistent elevations in zones whenever possible. Elevation changes should be minimized.
4. Piping or conduit wall penetrations should occur at a uniform height to simplify support needs.
5. Concrete block-outs should be combined where possible.
6. Conduit runs should be grouped where possible.
7. Cable trays should be used in lieu of conduits to improve sequencing.
8. Instruments that are precalibrated or self-calibrating can reduce testing and turn over time.

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9. Conduit connections to equipment should be flexible as opposed to rigid. Rigid conduit is difficult to align prior to equipment installation and requires more labor and material than flexible conduit to make connections after the equipment is installed.

10. Elevated cable junctions should be located in as few places as possible to minimize scaffolding needs.

See (Blunck 1985; *Engineering News Record* 1985; Holesapple 1982) for additional discussion.

Standardization

Concept.—Constructability is enhanced when design elements are standardized and repetition is taken advantage of.

Analysis.—The standardization of components is based on a recognition that savings can be realized when the number of variations of components is kept to a minimum. Many construction project elements have potential for standardization. Building systems, material types, construction details, dimensions, and elevations may all be standardized for increased field efficiency.

The advantages of standardization include the following: (1) Benefits of the learning curve from repetitive field operations and increased productivity; (2) volume purchase discounts from more of the same material; and (3) simplified material procurement and materials management from fewer differing materials.

Standardization, however, may require an additional step in the design process. Following the detailed design of unique elements, designers should analyze designs and identify elements with standardization potential. Standardized elements may require additional design effort to accommodate all uses, or vendor standards may be employed with the selection of off-the-shelf materials. Of course, the extent of standardization should be based on economic analysis including consideration of downstream construction benefits. Project management should encourage standardization analyses, and construction expertise should be drawn upon in identifying items for standardization.

Standardization also may lead to conservative designs involving additional material or increased weight. While construction efficiencies will most often offset these disadvantages, economic analyses are encouraged for cases in which net benefits appear marginal. Reiterating, construction expertise should be used when needed.

Why is the full potential of standardization seldom realized? The misconception that all projects are unique often prevails and stifles standardization efforts. Standardization should be accorded the status of a project sub-objective.

Specific Applications.—Some applications of this concept are listed:

1. Designers should maximize the use of manufacturers' standards in the selection of piping system components, thus minimizing the number of variations used in such items as valves and pipe supports.

2. Designers should avoid the use of unique connections in the design of structural steel in attempts to save a slight amount of structural steel. Beam and bolt sizes are particularly well suited to standardization.

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3. Electrical/instrumentation accessory items such as hangers/supports and instrument stands should be standardized.

4. Location standardization, either through consistent elevation heights or the use of designated zones, and dropouts should reduce the number of interference problems.

5. The number of different foundation sizes should be minimized to permit the maximum reuse of form work. The number of types and lengths of anchor bolts should also be minimized.

6. Instrumentation line installation requirements related to connections, details, supports, and testing are quite variable for different line types (electrical, steam, pneumatic, etc.). The standardization of elements such as instrument stands, and DP cell manifolds would greatly simplify field operations.

7. The detailed design of pipe hangers often introduces more problems with coordination than it saves in material. Thus, pipe hanger length is often best field-fitted. The design should specify standard rod hangers, and field personnel should adjust the length to fit existing conditions.

See George (1971) for additional discussion.

Module Engineering/Preassembly Scoping

Concept.—Constructability is enhanced when preassembly work is scoped in advance and module/preassembly designs are prepared to facilitate fabrication, transport, and installation.

Analysis.—Modularization is a major project strategy and should be addressed during the conceptual planning phase. Preassembly efforts resemble modularization, but the products are smaller in scale. The scoping of preassembly work should also occur early, preferably during the engineering phase.

The scoping of preassembly work is the identification of project components that may be beneficially constructed or fabricated away from the final workface. Scoping studies involve an analysis of costs and benefits. The benefits of preassembly typically include improved task productivity, parallel sequencing of activity, increased safety, improved quality control, and a reduced need for scaffolding. Disadvantages include additional management challenges, the need for preassembly support facilities, and an increased likelihood for misalignment or damage. The extent of preassembly (i.e., the amount of work away from the workface) should also be defined early.

Once modularization and preassembly efforts have been scoped, engineering should also provide design support. Module/assembly designs should be configured to facilitate their fabrication, transport, and installation. Both engineering and construction should work jointly to achieve this objective.

Module/assembly fabrication concerns might include the following: (1) temporary structural supports; (2) dimensional accuracy; (3) minimization of scaffolding needs; (4) sequence of operations; and (5) design standardization wherever possible.

For design to facilitate module/assembly transport, the basic methods and details of transportation should be known. Lifting limitations and

J. Constr. Eng. Manage., 1987, 113(2): 235-248

delivery route restrictions are often significant design determinants. Designs should facilitate lifting, jacking, and rolling needs. Transport accelerations should be accommodated with additional structural bracing, and methods should be devised for minimizing the potential for damage.

Module installation issues to be addressed during design should focus on the ease of module-to-module connections. The proper type of connection and the accessibility to the connection may significantly ease field operations. Again, it is desirable to minimize scaffolding requirements and standardize connections. Particular attention should be given to the coordination of connected units which are fabricated by different contractors.

Specific Applications.—Some applications of this concept are listed:

1. Pipe spools received from vendors are generally limited in size due to shipping constraints. Spools should be site-preassembled into the largest size, depending upon job site access requirements and handling/transportation.
2. Precast concrete elements for preassembly include manholes, catch basins, dry boxes, sump pumps, small pedestal foundations, and structural frames.
3. Repetitive, standardized assemblies should be preassembled. Examples include control valve stations, utility stations, steam trap assemblies, instrument assemblies, vent and drain assemblies, junction boxes, and cable tray turns and drop-outs.
4. Prefabricated buildings should be considered for all substations/switch gear buildings.
5. It is generally desirable to maximize vendor preassembly efforts or shop fabrication in order to ship equipment and material in as few pieces as possible. However, some vendor installations waste time and money when they must be repeated in the field for one reason or another. These situations should be identified and avoided.
6. Module interface connection adaptability may be enhanced with the use of flexible conduit, leveling devices, or slotted holes.
7. Trades working in the latter part of the construction schedule, such as electrical and instrumentation, may find preassembly to be a particularly attractive option. Junction boxes, control panels, and pull points are appropriate elements for preassembly.

See (Glaser and Kramer 1983; Kliewer 1983; O'Connor and Tucker 1983) for additional discussion.

Accessibility

Concept.—Constructability is enhanced when designs promote accessibility of manpower, material and equipment.

Discussion.—The accessibility needs of workmen, material, and equipment should be reflected in plant layouts and detailed designs. The effects of poor accessibility may be quite serious. Delays in progress, slowed productivity, and increased damage to completed work often result from accessibility problems.

Accessibility can be a problem for:

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1. Projects on tight sites, or where road capacity is limited.
2. Additions or modifications to existing plants, where material is threaded into congested areas or work is restricted due to operations.
3. Work at high elevations.
4. Late placement of major equipment.
5. Sites with steep grade changes.
6. Sites located contiguous to other projects under construction.
7. Sites with extreme environmental conditions, such as weather, soils, or vegetation.
8. Above-ground work when nearby underground work remains incomplete.
9. Restricted sites where heavy lifts are underway or are planned.
10. Projects involving multiple prime contractors.

Recommendations for increasing accessibility include: (1) Establish guidelines for minimum spacing of project elements; (2) specify well-defined access lanes; (3) dedicate clear spaces for pieces of equipment and linear runs; and (4) communicate accessibility-related information to project designers and planners regarding methods of transport and erection, construction equipment sizes and needed clearances, and congested construction activities that are sequenced in parallel and that are in close proximity to each other.

An accessibility checklist for assessing a project's specific opportunities and problems may be worth developing. Manual or CAD overlay techniques also have proven useful for visually studying accessibility problems. For serious and costly problems, computerized simulation models have been employed to plan work flow and logistics. Perhaps the most effective mechanism for assuring accessibility is the timely review of project plans by construction personnel.

Specific Applications.—Some applications of this concept are listed:

1. Particular attention should be given to the location of underground elements to minimize accessibility problems. Electrical pull boxes often are designed and located such that they inhibit other construction operations. Access to the pull box from the surface may be limited or the pull box may be located in such a way that an area required by other crafts is sterilized. Access for cable pulling operations should be reflected in the design of the manholes, which should be located away from construction roadways and heavy construction equipment access areas.
2. Designers should be aware of the maximum cable reel sizes that can be handled and minimum working space needs around pull boxes. This is of value in the layout of pull points and reduces splicing problems. Working space requirements vary depending on equipment needs, size of cable and reels, and turns involved.
3. Accessibility problems are often encountered when new pipe is added to an existing pipe rack. The adding of an additional tier above the existing rack is a suggested alternative.
4. Bolted structural connections should be designed to allow for bolt torquing. When torquing is not possible, inspectors cannot verify a connection strength. Access is not generally a problem for orthogonal structures, but may be a problem for structures with unique designs.

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5. The location of prefabrication and lay-down areas should be established early to minimize any effect on construction access.
6. Utility stations, junction boxes, and stub-ups are often located near columns, resulting in very congested areas. Increased coordination between design disciplines and extensive design reviews of typically congested areas may eliminate costly construction problems.

See Rad (1980) for additional discussion.

Adverse Weather

Concept.—Constructability is enhanced when designs facilitate construction under adverse weather conditions when they exist.

Discussion.—Projects constructed in localities where weather conditions are adverse present a greater challenge to both the designer and the constructor. Designers should investigate ways in which the exposure to temperature extremes and the effects of rain (particularly mud) may be minimized. In addition, the amount of quality-sensitive work conducted outdoors may also be minimized.

Of course, projects constructed in cold regions such as Alaska must be carefully planned and engineered from their inception. In these cases limited schedule windows, site access limitations, and quality control concerns are some of the constructability challenges posed. In-depth investigations employing state-of-the-art techniques must be conducted.

Specific Applications.—Some applications of this concept are listed:

1. Incorporate designs that enable early enclosure to permit construction to proceed as the weather becomes inclement.
2. Allow large enclosed spaces to double as fabricating shops and equipment storage during construction.
3. Allow for early paving of the site to eliminate muddy operations.
4. Specify concrete admixtures and curing techniques to overcome the effects of extreme heat, cold, or high winds.
5. Maximize offsite work. Require factory quality assurance checks prior to shipment of systems so that only final field-verification of connections is necessary. Have subassemblies prefinished or factory-coated to minimize field finishes.

Specifications

Concept.—Constructability is enhanced when specifications are reviewed in detail by owner, designer, and constructor personnel. It also serves to simplify the field construction process.

Discussion.—Extra effort should be given to the tailoring of specifications for individual projects. This should entail in-depth reviews by owner, designer, and constructor representatives. Both efficient field practices and a shortened specification familiarization process should be facilitated. The appropriate use of design basis specifications and the avoidance of misapplied material specifications are particularly worthy of attention.

Design basis or job specifications should communicate preferred design details while not overly constraining design configuration or the selection of equipment or material. Constructor input should be sought

J. Constr. Eng. Manage., 1987, 113(2): 235-248

in the identifications of preferred materials and methods. In those instances in which constructor preferences vary, specifications should allow for and encourage cost-effective alternatives. Of course, the usage of material that is difficult to obtain should be avoided.

Another specification problem is the misapplication of material specifications. The use of improper standards or code-excessive specifications can be costly and discourages cost-effectiveness when perceived as gold-plating. Examples of misapplied specifications include designing for service conditions which do not exist such as high temperature/high pressure, and requiring machine-like tolerances where unnecessary. The establishment of tolerances should be based on economic analysis. It is easy to double machining costs in order to meet tighter tolerances, and the same tolerances on larger nominal dimensions increase fabricating costs. The most beneficial tolerance relaxations permit the use of less sophisticated equipment and procedures (Marguglio 1977).

Specific Applications.—Some applications of this concept are listed:

1. For electrical conduit, PVC is often preferred to rigid conduit for several reasons. PVC is easier to install since it is lighter, can be worked with simple hand tools, and can be prefabricated in sections. PVC also allows for flexibility in settlement, and the likelihood of wire damage from pulling is reduced.
2. The use of splice boots on motor terminations and line splices may result in a substantial reduction in installation manhours, and provides improved protection of the lines compared to tape wrapping.
3. For steam tracing of instrument tubing, the woven stone type often is preferred to the slip-on type due to easier installation.
4. For existing pipe rack extensions, bolted connections are often preferred to welded connections. This reduces the amount of required permitting activity for welding in an operating area.
5. There is a trend toward using higher speed rotating equipment. It should be remembered that the higher speeds require tighter tolerances for alignment and vibration. The ability and incurred costs to obtain these tolerances needs to be considered.
6. Increasing the vertical tolerance of pipe rack sleepers from 1/16 to 3/8 in. eases construction, yet maintains adequate structural support.
7. All pipe systems do not require hydrotesting. Service testing should be conducted for such noncritical lines.
8. One practice for ensuring high quality specifications for commercial projects is to require that all drawings be complete one month prior to completion of specifications. This provides adequate time to ensure compatibility, appropriateness, and completeness of specifications.
9. Lightweight fireproofing for structural steel often is preferred by the field to concrete fireproofing.

See (Abdallah 1982; Fisk 1978, 1980) for additional discussion.

Conclusion

These concepts identify ways in which construction knowledge and experience may be most effectively used during the engineering and

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procurement phases of projects—ways in which engineers and designers may facilitate a more efficient field operation. The sequencing of design and procurement, the scoping of design, and the detailed execution of design may all be modified to enhance constructability.

These concepts are also characterized by some common themes. These themes stress good project management practices:

1. Project personnel should always be mindful of an important objective: capital cost reduction. Accurate measures of project success should be understood and used. Examples are quality/capital cost, operability/capital cost, plant output/capital cost.
2. Past practices should be challenged, innovations should be rewarded, good ideas should be developed, and successes should be documented.
3. Interorganizational communication should be encouraged and planned for, particularly between designers and constructors.
4. Decision-making should involve the "doers." A bottom-up approach results in a more informed decision.
5. Engineering problems are often addressed in parts, but solutions need to be holistic. An extra step involving the integration of parts is needed.
6. Some early expenditures of effort have significant payoffs later. Additional engineering efforts often reduce field efforts. Special studies may be appropriate for "big ticket" items.

Aggressive adoption of these concepts should significantly improve the chances of project success.

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