Constructability Improvement During Field Operations

James T. O'Connor,[1] Associate Member, ASCE, and Victoria S. Davis[2]

Abstract: Constructability issues still exist during field operations and once in the field, constructors can still reap constructability benefits from their actions alone. The objective of this paper is to explore the ways in which construction knowledge and experience can enhance constructability during field operations. While previous constructability research efforts have been primarily directed toward owners and designers, this research is primarily directed toward constructor organizations. The employed research method was an iterative process of issue identification, literature search, site interviews, and analysis. Ultimately, a single prime concept for field operations constructability was concluded: *Constructability is enhanced when innovative construction methods are utilized.* Innovative construction methods may involve innovations related to sequencing of field tasks, temporary construction materials/systems, hand tools, construction equipment, constructor-optional preassembly, temporary facilities directly supportive of field methods, or post-bid constructor preferences. Beyond addressing each of these in detail, in this document "innovative" construction is also analyzed in terms of related prompters or drivers. The linkage between field operations constructability and construction technology is also addressed.

Objective and Background

The objective of this paper is to explore the ways in which construction knowledge and experience can enhance constructability during field operations.

The Constructability Task Force of the Construction Industry Institute defines *constructability* as follows:

> Constructability is the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives. (*Constructability: A Primer* 1986)

As stated, constructability issues still exist during field operations; thus constructors can still reap constructability benefits from their actions alone. This belief is graphically depicted in Fig. 1 (*Constructability: A Primer* 1986), in which the ability to influence final project cost during field operations is still considered significant, albeit substantially less significant than during the prior phases of procurement, design, and conceptual planning. While decisions related to field operations constructability tend to be relatively low-leverage decisions, collectively they offer substantial benefits. A secondary purpose of this research, then, is to determine the nature of field operations constructability issues/decisions.

[1]Asst. Prof., Dept. of Civ. Engrg, ECJ 5.200, Univ. of Texas at Austin, Austin, TX 78712.

[2]Assoc. Development Dir., Trammell Crow, Maryland Residential Div., 2 Bethesda Metro Center, Suite 250, Bethesda, MD 20814.

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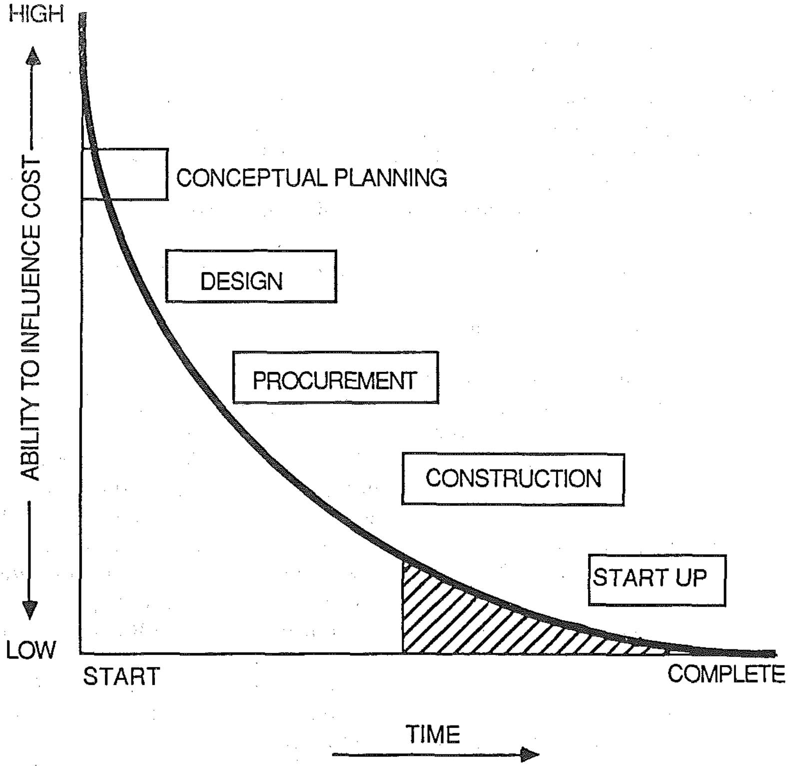

FIG. 1. Ability to Influence Final Cost Over Project Life

The scope of this research is strictly limited to field operations issues. Issues that are most beneficially addressed during conceptual planning, design, or procurement have been discussed in other publications (Tatum et al. 1986; O'Connor et al. 1986). Readers are encouraged to review these documents.

As they serve as an important point of departure, the previously determined concepts related to constructability during conceptual planning, design, and procurement are presented here:

Conceptual Planning

1. Constructability programs are made an integral part of project execution plans.
2. Project planning actively involves construction knowledge and experience.
3. The source and qualifications of personnel with construction knowledge and experience varies with different contracting strategies.
4. Overall project schedules are construction-sensitive.
5. Basic design approaches consider major construction methods.

Design and Procurement

1. Site layouts promote efficient construction.

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2. Design and procurement schedules are construction-sensitive.
3. Designs are configured to enable efficient construction.
4. Design elements are standardized.
5. Project constructability is enhanced when construction efficiency is considered in specification development.
6. Module/preassembly designs are prepared to facilitate fabrication, transportation, and installation.
7. Designs promote construction accessibility of personnel, material, and equipment.
8. Designs facilitate construction under adverse weather conditions.

Sequence of Research Activities

The overall sequence of research activities began with a listing of issues potentially related to field operations constructability that was brainstormed by researchers and liaison subcommittee members. An interview guide reflective of these issues was developed for data collection purposes and a number of on-going construction projects were targeted for study. Data collection activities followed, with personal interviews at job sites being the prime means of information collection. Relevant published literature also was reviewed periodically. With a sizable amount of information in hand, researchers analyzed the data and formalized trial constructability issues or concepts. Liaison subcommittee review of the trial issues followed and the listing was refined. The process of refining issues, collecting additional information, and analyzing information was iterated several times until research findings offered a complete perspective on the opportunities for constructability improvement during field operations.

The bulk of the data analyzed was solicited through site interviews. Table

TABLE 1. Projects Visited for Study

Type/purpose (1)	Location (2)	Contract amount (3)	Construction duration (4)	Percent completion (5)	Union/ non (6)	Maximum work force (7)
Industrial/Alky Unit	S.E. Texas	100 MM+	17 Mo.	85%	Non	500
Industrial/Cogeneration	S.E. Texas	100 MM+	14 Mo.	97%	Non	1,000
Residential/Apartments and Homes	Central Texas	35 MM	15 Mo.	60%	Non	500
Commercial/Office Building	Central Texas	8 MM	10 Mo.	70%	Non	150
Industrial/Cogeneration	S.E. Texas	192 MM	30 Mo.	100%	Union	800
Industrial/Flexi-coker	S.E. Texas	1 Bil.	30 Mo.	9%	Union	4,000
Industrial/Cogeneration	W. Pennsylvania	100 MM	24 Mo.	1%	Union	600
Utility/Coal Power Plant	S.E. Texas	1.3 Bil.	60 Mo.	97%	Non	2,500
Commercial/Research Center	S.E. Texas	50 MM	18 Mo.	15%	Non	300
Industrial/Pulp Mill	N. Michigan	600 MM	42 Mo.	100%	Union	1,900
Industrial/Coal Gasification	S.E. Texas	75 MM	18 Mo.	50%	Non	1,100
Industrial/Auto Plant	Kentucky	800 MM	18 Mo.	5%	Non	4,500
Industrial/Plastic Factory	Alabama	310 MM	24 Mo.	80%	Non	2,010
Utility/Steam Generation	Kentucky	200 MM	32 Mo.	20%	Union	600
		348 MM AVG.	26 Mo. AVG.	56% AVG.	36% U 64% N	1,442 AVG.

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TABLE 2. Personnel Interviewed at Construction Sites

Position (1)		Number (2)
Project Directors, Project Managers, and Construction Managers		14
Project Field Engineers		15
Project Controls Personnel		16
General	3	
Cost	5	
Schedule	6	
Materials	2	
Superintendents		9
Foremen		5
Total		59

1 briefly describes the 14 projects visited, with a limited number of project characteristics. Eleven of the 14 projects were either industrial or utility projects, with nine of the 14 being located in Texas. The average project cost was $348,000,000; construction durations averaged 26 months; and, on average, construction was 56% complete at the time of interviewing. Nearly two-thirds of the projects were nonunion and the average maximum construction work force was 1,442.

Table 2 lists the types of personnel interviewed at the construction sites. In all, a total of 59 individuals was interviewed. They represented managers, field engineers, controls personnel, superintendents, and foremen.

The initial scoping was broad, covering a variety of issues such as management of resources, planning, organizations, communications, temporary facilities, rework, and field delays. As site interviews progressed, with more information available, researchers and the liaison committee became better equipped to define major thrusts or concepts that drive enhanced constructability during field operations. Some issues were deleted, a few issues were de-emphasized, and others were emphasized. Researchers envisioned a hierarchical structure of constructability concerns in which a limited number of major concepts were to be further delineated with analysis and applications. Ultimately, a single concept encompassing innovative construction methods was developed.

Constructability Concept

A single concept for enhancing constructability during field operations emerged from the extensive research activities previously described:

Constructability is enhanced when innovative construction methods are utilized.

The term "construction methods" is admittedly broad in scope and generally refers to the *technical manner* in which the various construction resources are deployed. *Innovative* construction methods refer to methods that are not generally considered common practice across the industry and which are often creative solutions responsive to field challenges. The attribute of being *in-*

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novative in the context of construction is discussed further in the latter part of this chapter.

Innovative construction methods may involve:

1. Innovative definitive sequencing of field tasks.
2. Innovative uses of temporary construction materials/systems.
3. Innovative uses of hand tools.
4. Innovative uses of construction equipment.
5. Constructor-optional preassembly.
6. Innovative temporary facilities directly supportive of field methods.
7. Post-bid constructor preferences related to the layout, design, and selection of permanent materials.

Innovative, Definitive Sequencing of Field Tasks

Innovative field sequencing can enhance constructability in a number of ways:

1. A repetitive operation with learning-curve benefits can be promoted with a deliberate serial approach to sequencing. The benefits are particularly significant for skill-intensive work, such as mechanical equipment installation, instrumentation installation, architectural concrete, fine wood mill work, etc.
2. Mock-ups may be useful in fine-tuning a sequence. Example application: repetitive and congested plumbing/mechanical equipment installation in hotel construction.
3. Effective definitive sequencing can serve to minimize congestion and keep access routes open.
4. Construction equipment/systems that are shared by several subcontractors such as scaffolding, hoisting equipment, and small cranes are important sequencing considerations. Of course, with a construction-sensitive schedule, planning for large crane usage should occur as early as possible, perhaps during definitive design.
5. Stairs and platforms may be erected early to reduce scaffolding needs, and lighting systems may be installed early to reduce temporary lighting requirements.
6. Early sequencing of pavement activities can minimize mud problems and facilitate the use of rolling scaffolding.
7. Late sequencing of finishing activities in heavily traveled corridors and stairwells can minimize related damage and rework.
8. A checkerboard approach to sequencing of slab/pavement construction can minimize formwork and speed construction.

Innovative Uses of Temporary Construction Materials/Systems

Innovations with temporary construction materials also can enhance constructability:

1. While not new, the use of seal slabs or polyethylene sheet beneath foundation rebar or underground concrete is effective in protecting the excavation and supporting reinforcing steel.
2. Innovations in formwork and scaffolding have led to systems that are modular, easily transportable, and easily erectable. Example applications: Golden Gate Bridge Restoration scaffolding system (Madewell 1986), flying formwork systems, and slipforming systems.

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3. Advances in (consumable) temporary construction materials include such developments as tunneling foams which serve as fluidizing agents in soft-ground tunneling (*Engineering News-Record* Aug. 14, 1986), foamed polyurethane grouts for stabilizing fissured rock (*Civil Engineering* Sept. 1985), and advanced cable-pulling lubricants with low coefficients of friction (Zaist 1986).

4. Some advances in temporary construction systems involve new construction procedures or processes. Examples include high-speed steam curing (*Engineering News-Record* Mar. 14, 1985), and ground freezing, in which a coolant is used to freeze in-situ pore water to temporarily stabilize soil (*Civil Engineering* Jan. 1985).

5. Other advances in temporary construction systems include fire blankets in lieu of standard spark boxes for the containment of welding spark, eliminating the need for scaffolding, and tents used to shield underwater concrete placement from fast currents (*Construction Specifier* June 1986).

Innovative Uses of Hand Tools

Constructability is enhanced with the use of tools that reduce labor-intensity, increase mobility, increase accessibility, increase safety, or increase reliability. Of course, such tools range from simple to complex. They may also be available "off the shelf," require some modification of an available tool, or be entirely locally originated. Some examples include the following:

1. Labor-reducing power hand tools such as the automatic nailing gun and the pneumatic caulking gun. These may not be considered new, but surprisingly remain untried in many organizations.
2. Cordless power hand tools that enhance mobility. These also appear to be underutilized.
3. Craftsman stilts that enhance accessibility for elevated work.
4. An extended hand drill devised for the at-grade installation of hanging wire for suspended ceilings, eliminating the need for a ladder or scaffolding.
5. Pulling wheels developed to facilitate cable installation (see Fig. 2).
6. Pipe carriers developed to facilitate short-distance transport of spools (see Fig. 3).
7. The devisement of a P-shooter out of small bore pipe with an inserted rebar for the purpose of driving nails through several layers of obstructing rebar. In responding to the challenge, nailing was accomplished easily, quickly, and safely.

While construction templates or "jigs" may be considered temporary material as much as tool innovations, they collectively represent a common type of field innovation that often significantly enhances constructability and reduces construction cost. For example, on one project a template was devised to enable workers to install four pile uplift connectors (chucks) with a single jacking (see Fig. 4). In making the operation more efficient, costs were cut in excess of $50,000.

Although tool devisement and effective utilization can significantly enhance constructability and productivity, such innovations are not as common as expected. There appears to be a lack of enthusiasm in promoting new tool development and utilization, as well as a lack of communication in sharing the successes.

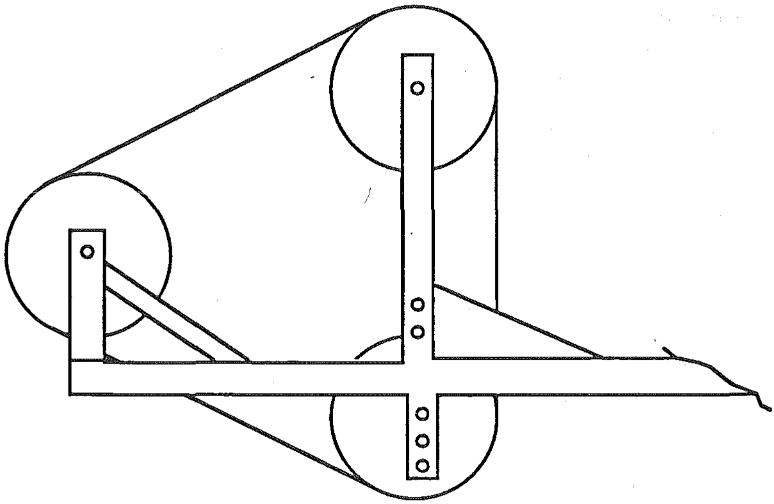

FIG. 2. Cable-Pulling Wheel

Construction Equipment Innovations

Recent construction equipment innovations incorporate microprocessor controls and diagnostics, modular machine components, versatile attachments, quieter engines, and economic, lightweight materials. (*Constructor* Nov. 1985) Such developments will extend the life of new machinery, render better fuel economy and less maintenance, and increase productivity. Some specific developments are listed:

1. Laser-equipped surveying equipment.
2. Microtunneling systems (*Civil Engineering* Aug. 1986) and horizontal drilling systems.

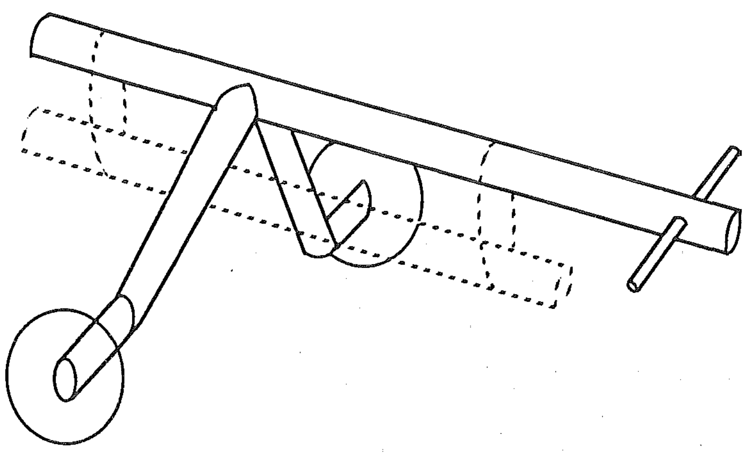

FIG. 3. Pipe Carrier

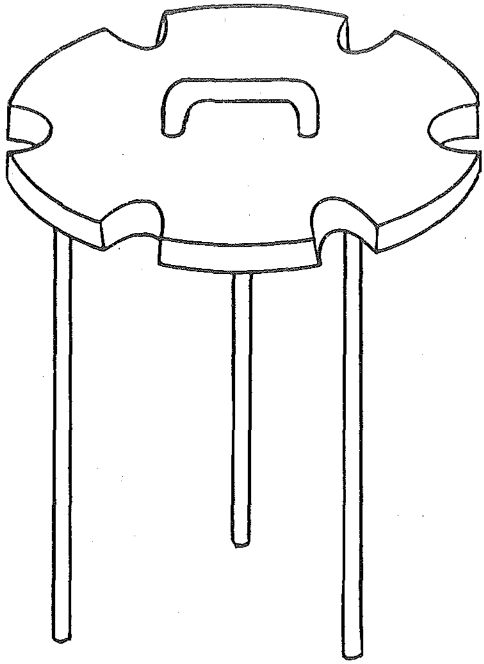

FIG. 4. Uplift Template

3. Mobile, hydraulic man-lift in lieu of spot scaffolding.

4. Hydraulic pipe bending machines and induction pipe bending machines (Hipley and Murphy 1983).

5. Pipe manipulator (Glass 1984).

6. Welding system advances such as the plate-crawler welder (Madewell 1986) and shielded active gas forge welding.

7. Pavement system advances such as the sloped pavement system (Guy 1985) and the narrow, single-lane paver (*Engineering News-Record* Aug. 7, 1985).

8. Remote, non-destructive sensing and inspection systems such as the nuclear soil density meter, infrared thermography, ground penetration radar (*Civil Engineering* Sept. 1984), and the cable-stay bridge inspection trolley (*Engineering News-Record* May 15, 1986)

In some cases, constructability has been served with the customization or upgrading of existing equipment by contractors themselves. On one project, steel rods were attached to the ends of a dozer blade to facilitate fine grading relative to a stringline. A more advanced solution to the same problem was devised by a contractor who attached a laser sensor to a grader, which then operated relative to a laser datum. In an altogether different example, constructors responded to the challenge of achieving a smooth slab underside which would receive a ceiling finish. The resulting elevated rubbing operation made use of a pivoting grinder mounted on a rolling tripod (see Fig. 5).

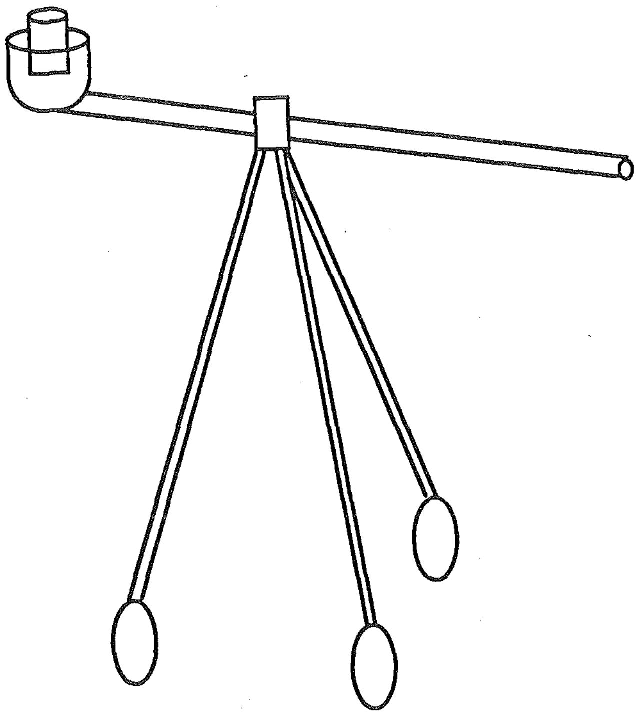

FIG. 5. Elevated Pivoting Grinder

Increased attention is being directed toward the development of automated construction equipment. Accordingly, constructability concerns will tend to become more machine-driven than worker-driven, as they have been. Constructability for automation poses a serious challenge to successful construction automation, and will undoubtedly keep researchers occupied for years to come.

While most construction automation developments will require extensive planning, design, and procurement consideration prior to field operations, many developments will not, and these devices will offer constructability enhancement opportunities optional to the field constructor. Constructors may enhance constructability with the utilization of these devices.

Examples of construction equipment with automated machine guidance or control, thereby eliminating an operator function or removing an operator to a more desirable location, include the following:

1. Fully-automated concrete batch plant.
2. Automated welding machine and remote-controlled welding system (Guy 1985).
3. Automated concrete floor finisher (*Constructor* Sept., 1986).
4. Spray robot for structural steel fireproofing (Ueno 1983).
5. Shotcrete robot (Guy 1985).
6. Automated rebar machine (Guy 1985).

7. Remotely operated equipment for underwater construction activities, such as trenching (*Engineering News-Record* July 21, 1983) and rubble clearing (*Japan Economic Journal* Nov. 8, 1983).

Constructability also may be enhanced with the use of devices that enable remote inspections or monitoring of performance. Two examples include a climbing inspection machine for exterior masonry walls, and a stairclimbing inspection robot (Guy 1985).

Automated equipment that enhances constructability by reducing the labor-intensity of operations includes the horizontal concrete distributor (*Japan Mechatronics Letter* April 20, 1984), and a manipulator for the placement of heavy reinforcement steel (Guy 1985).

Hazard-eliminating equipment also enhances constructability. Examples include a window cleaning robot (Guy 1985), and a robot for working inside a nuclear reactor (Armstrong 1983).

Automated construction equipment presents both challenges and opportunities for the industry. Needs for advanced training for both labor and management will be substantial, and the need for on-site machine technicians will continue to grow. Likewise, opportunities for enhancing constructability during field operations also will increase in number.

Constructor-Optional Preassembly

While most modularization/preassembly work requires extensive design and procurement support for effective execution, constructor-optional preassembly work consists of that which does not require such support. Such preassembly work is strictly at the option of the constructor, and may offer substantial opportunity for enhancing constructability during field operations.

Constructors may be motivated toward preassembly for several reasons. Elevated work is typically more constructable at grade, and eliminates the need for scaffolding. Productivity and safety can be enhanced by transferring work in congested areas to less congested areas and quality-sensitive work is more easily accomplished in shop-like conditions. Of course, shop preassembly also is beneficial under adverse weather conditions.

Examples of effective constructor-optional preassembly include the following:

1. Elevated pipe spool welding and pipe/valve assemblies.
2. Concrete reinforcement steel cages.
3. Anchor bolt grouping.
4. Cable tray runs and turns.
5. HVAC ductwork.
6. Silo and storage tank sections.

Innovative Temporary Facilities

Constructability can be well-served with innovative temporary facilities that are directly supportive of field operations. Three types of temporary facilities are addressed here:

1. In adverse weather conditions, enclosure of work space can be extremely beneficial and need not be expensive. Examples of transportable, easily erectable

means of enclosure include the attachment of tent cloth to the permanent structural frame, the use of large shipping containers available around port areas, and the use of ribbed tents or air-inflated bubbles for moderately large enclosures needed over extended periods of time. On one project, space was inexpensively enclosed by bridging the area between two trailers with roof trusses and tent cloth. Of course, the design of such facilities must consider potential wind and snow loads. (*Engineering News Record* Feb. 27, 1986)

2. Centralized utility supply networks should be considered when outlet demands are high, or where access for conventional systems is difficult. Applications include welding utilities, compressed air, and electricity. On one building site, welding gas was contained in one large tank adjacent to the building, with outlets on each floor. The need to periodically transport several smaller tanks from floor to floor was eliminated.

3. Where conditions tend to be muddy, inexpensive, locally available material should be considered for "site pavement" to provide a clean and firm work surface. Shell is commonly used for such a purpose in coastal areas; culm in mining areas; and crushed, recycled highway pavement available in some urban areas. At a minimum, these materials should be considered for temporary construction roads.

Post-Bid Constructor Preferences

Constructability occasionally can be enhanced with the solicitation and implementation of post-bid constructor preferences related to the layout, design, and selection of permanent materials. Ideally, however, as discussed in the *Constructability Concepts File,* constructor preferences are identified early-on, prior to bid, and are effectively treated during design and procurement and reflected in the initial issue of drawings and specifications. Under such ideal circumstances, "design breakage" is minimal and the preferences are given full considerations by design and procurement personnel.

While post-bid constructor preferences are often of limited value due to their untimeliness, such options are introduced with open "or equal" specifications, value engineering clauses, and deliberate solicitations of alternates, and can substantially enhance constructability. In addition, the reality of design is such that post-bid preferences are sometimes remedial tactics that are desirable, if not required, for project constructability.

Of course, the nature of constructor preferences can vary a great deal, and the list is nearly limitless. Some examples of beneficial preferences are given:

1. Layout and configuration of field-run small bore piping and conduit.
2. Use of pre-insulated tubing and pre-molded insulation for piping valves and flanges.
3. Inclusion of admixtures in concrete to increase workability (e.g., superplasticizers and air-entrainment agents).
4. Use of non-destructive methods of pipe reconstruction (Utz 1983).
5. Use of fly ash soil stabilization to reduce lateral soil pressure and simplify retaining wall design and construction.
6. Constructor preferences for structural backfill material.
7. Use of customized 4 × 10 sheet rock in 10 ft wall construction to reduce labor and material waste.

The solicitation of constructor preferences need not be a costly effort, and should not be discouraged. Of course, the decision to implement preferences should be based on thorough analysis. As a minimum, constructor preferences that do not sacrifice quality should be documented for the benefit of future projects. In this way, future opportunities for constructability enhancement may be exploited in an optimal manner.

Analysis: "Innovative" Construction and Its Prompters

For the purposes of this research, "innovative" construction methods refer to methods that are not generally considered common practice across the industry and are generally creative solutions responsive to field challenges. Recent high-tech advances may be readily thought of as "innovative," as may new or modified applications of proved construction methods, materials, or devices. Recent adaptations of non-construction developments for construction purposes, as discussed here, also may be thought of as innovative. There is, however, some disagreement as to what is considered innovative. As a result, readers should recognize the subjective, relative nature of the term "innovative."

What prompts construction innovation? Several theories have been discussed in the literature. Many believe that innovation simply results when "the right people" respond to the demands of their job. "Innovation is a by-product of people who are acting on their unique strengths and who are refining their gifts" (Cox 1985). Such individuals tend to be driven by higher project objectives, and generally have a balanced perspective on change. They are challenged by the inadequacies of current technology and seek to maintain an awareness of available new technologies. They may employ an aggressive, "attacker" approach (Foster 1986), or serve in the role of a "champion" in assuring the implementation and success of their ideas (Tatum 1986). Given the relatively autonomous nature of construction-related jobs, the "right people" theory may be particularly meaningful in explaining how innovative construction methods come about.

Beyond relying upon personal self-motivation, most companies, of course, cultivate innovation with traditional reward systems such as job promotions, financial incentives, and at the very least, job security. Others go beyond these by incorporating into their business plan semi-permanent *organizational mechanisms* that promote team communication and analyses. These include quality circles (Fitzgerald 1982), performance improvement councils, value engineering, and constructability programs (O'Connor et al. 1986). Such mechanisms promote a proactive approach toward innovation and, as a result, organizations are more likely to challenge the competition. Some will even take calculated risks to the extent of funding research and development.

What *project circumstances* prompt field construction innovation? Field research activities found innovative solutions formulated from ad hoc detailed analyses with models, "work-around" solutions responsive to actual field problems, and risk management solutions that dealt with potential problems that could be avoided.

In conjunction with task planning, constructors often formulate problem-solving teams focused on specific issues dealing with equipment utilization, definitive sequencing, accessibility, or repetitive operations, to name a few. In some cases, mock-ups or models are constructed in an attempt to better understand an operation or to fine-tune a plan. On one project, a scale model

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of a parking structure was devised to assist in the sequencing of construction activities. On another site, sections of a steel boiler structure were modeled with wood blocks as an aid to the planning of the steel erection sequence. On a third project, a sample junction box was utilized effectively to demonstrate complex installation procedures.

Going a step beyond physical modeling, large projects comprised of complex operations may also benefit from analyses that employ computerized activity simulation. Three examples are cited:

1. On several large nuclear power plant projects, computer simulation was successfully employed to determine the strategic locations of temporary facilities and services. One aspect of the simulation process was the optimal locating of temporary buildings with respect to the construction workface. Another analysis identified construction equipment needs and the best locations for the equipment.
2. A simulation program was used to model the concrete placement sequence for the 70-story Peachtree Plaza Hotel in Atlanta. From simulation, the cycle time for concrete forming and placement was substantially reduced (e.g., 20% for shear wall construction) (Lluch and Halpin 1982).
3. Floor slab construction was simulated on a 22-story apartment building in Maryland. Various crew/equipment mixes were studied, and an optimum resource mix was determined. The results led to increased productivity and reduction in costs.

Construction innovation is also prompted with "work-around" solutions that are responsive to problems encountered in the field. Generally, such innovations isolate delays and allow for progress of adjacent work. Two instances of innovative work-around solutions are described below:

1. When steel deliveries were late, an innovative method of fireproofing beams was devised to minimize further delay. The approach involved bolt-in-place fireproofing. This fireproofing resembles wallboard and forms a box around the beam. The approach limited the area-sterilization that is commonly associated with spray-on fireproofing and is generally quicker than pouring concrete fireproofing in place. The overall cost of this approach is comparable to that of the other methods.
2. A wall was constructed in the field to separate an excavated area where a delay had occurred in underground pipe installation due to late material delivery. Once the wall was in place, the remaining adjacent area could be backfilled and above-ground work could resume.

Potential field problems also may prompt construction innovation. A form of risk management, constructor responses to potential field problems often relate to inclement weather, alignment/fit-up difficulties, or possible damage to completed work. For example, on one project a V-shaped metal plate was welded to the top of the flange of each pipe rack column to facilitate overhead alignment of pipe rack modules. On another project many hardened steel rollers were placed at the base of a heavy vessel to facilitate rotation of the vessel and alignment of the bolt holes.

Analysis: Constructability and Technology Postures

The linkage between project constructability during field operations and construction technology is a strong one. At an increasing rate, both the chal-

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lenges posed by constructability and the nature of constructability enhancements appear to be driven by advanced machines and materials. But how aware are we of such advances? On a routine basis, designers and constructors should assess their posture relative to various advanced construction technologies, and take appropriate action.

Beyond historical usage or recent usage, postures or relationships with technologies may be characterized in one of four ways: (1) Planned usage; (2) familiar/unused technology; (3) unfamiliar technology; and (4) undiscovered technology. Each of these relationships is associated with unique challenges that designers and constructors should concern themselves with.

Of course, the primary challenge for planned usage of state-of-the-art technology lies in advanced training. As previously stated, this will be particularly significant in the implementation of automated construction equipment. The challenge associated with familiar/unused technology lies in maintaining a current awareness and periodically considering new developments for application. Common hurdles in this process are poor documentation of "lessons learned" and the inability to efficiently retrieve such documented information. Designers and contractors should consider the use of information management systems. Kajima, a Japanese contractor, operates a Civil Engineering Technical Information System, a 25,000-record system linked to 200 offices and sites (*Nikkei Sangyo* March 10, 1987).

The initial challenge linked with unfamiliar technology is in acquiring an awareness. Seemingly straightforward, information resources must be made available and staff time for research and analysis must be budgeted. Unfortunately, financial limitations or management reluctance often stall progress in either case.

Finally, discovery and development are the challenges posed by emerging technologies. These challenges are particularly serious in the construction industry, where funds for R & D are severely limited. Constructors could, however, play a more active advisory role in the development of construction materials, equipment, and tools.

Perhaps insight into field operations constructability may be gained from analyzing the adaptation of non-construction technologies to construction. Historically, construction equipment advances have benefited significantly from developments in other industries. Some examples include hydraulic cylinders from mechanical engineering developments in pneumatic equipment and lasers from instrumentation and telecommunication developments. Developments in lighter, more durable construction materials such as plastics and fiberglas initially occurred in the automobile, aerospace, and manufacturing industries. Construction "process" developments that have enhanced project constructability, such as computer-aided design, modularization, and numerical-control machining of parts, were also born in other industries. In every case these developments have had a significant impact on the construction industry, often resulting in constructability advancements.

It is highly likely that constructability will continue to be served by future adaptations of non-construction technologies to construction. For example, the bar-coding systems of the retail industry are beginning to play a role on some job sites (Stukhart and Chang 1987). Simulation technologies that were born in the defense and manufacturing industries likely will play a role in construction activity sequencing, resource allocation, and accessibility analysis. Sensor developments in the instrumentation industry will play a critical

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role in construction automation, as will artificial intelligence.

Of course, other industries will continue to out-spend the construction industry in research and development, and the construction industry will continue to take advantage of outside developments. However, the industry must ask itself: Can this type of technology transfer be made more efficient? Can the industry play a role in directing outside, yet critically needed developments? Can the industry be more aggressive in its adaptation of non-construction technologies?

SUMMARY AND CONCLUSIONS

A single primary constructability concept for field operations is concluded from this research:

> *Constructability is enhanced when innovative construction methods are utilized.*

Just as there is a need to draw upon—and thus communicate construction knowledge and experience during conceptual project planning, design, and procurement—there is also a need to share construction knowledge and experience within and across field organization boundaries. Constructors need to share their constructability experiences as well as learn from other segments of the industry, and even from other industries. Accordingly, while previous constructability research efforts have been primarily directed toward owners and designers, this research is primarily directed toward constructor organizations.

This concept goes beyond a call for "good project management." Field operations constructability is not a repackaging of the basics of construction management, namely control of cost, schedule, quality, and safety and the management of materials and manpower. Rather, the focus is on the development and effective utilization of innovative field construction methods that simplify construction effort and reduce project costs.

The nature of innovative construction methods is diverse. Innovations can relate to definitive sequencing of field tasks, temporary construction materials/systems, hand tools, construction equipment, constructor-optional preassembly, temporary facilities directly supportive of field methods, or post-bid constructor preferences related to layout, design, or selection of permanent materials. Construction method innovations are numerous and are largely comprised of what are considered as "small" advances. These should not be overlooked or under-valued, however. Collectively, the potential contribution or benefit is substantial.

Insight into the advancement of field operations constructability may be gained from analyses of innovation in construction and of construction technology. Prompters of construction innovation include self-motivation, performance incentives, and programs such as value engineering, performance improvement councils, quality circles, and constructability teams. Circumstantial "natural" prompters of construction innovation include needs for ad hoc focused studies, needs for "work-around" solutions to actual problems, and risk-management solutions to potential field problems.

The relationship between technology and field operations constructability is strong and, in the opinion of the authors, the average construction organization should be more eager to advance and implement new technologies. The importance of adaptations of non-construction technologies for construction purposes should not be overlooked and deserves more attention from the industry.

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