Construction Engineering—Reinvigorating the Discipline

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Abstract: Construction engineering is all about production, and producing something useful is the very reason for projects to exist. How then to explain why construction engineering has progressively fallen out of focus in construction project management education and research? For an answer, the development of the discipline of construction management since the 1950s must be understood, a development that yielded a non-production-oriented approach to project management, one that provides the currently accepted operating system for managing the work in projects. This paper first traces the history of the development of the traditional operating system and related commercial terms and organizational practices. It argues that traditional practices rest on an assumption that careful development of a project schedule, managing the critical path, and maximizing productivity within each activity will optimize project delivery in terms of cost and duration. Subsequently, an alternative operating system, developed and proposed by the Lean Construction community, is described. In contrast to the traditional approach, lean defers detailed planning until closer to the point of action, involves those who are to do the work in designing the production system and planning how to do it, aims to maximize project performance (not the pieces), and exploits breakdowns as opportunities for learning. The history of this development will be traced in broad strokes. **DOI: 10.1061/(ASCE)CO.1943-7862.0000276.**

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Introduction

Professor Henry Parker at Stanford University completed a report for the Bureau of Yards and Docks of the US Navy in 1965. His observation in the third paragraph of the introduction is clear and bold (Parker 1965).

"This study includes the observation and recordings of hundreds of jobs. It has reinforced an earlier conclusion that, in general, contractor organizations are abdicating their responsibilities to run their work efficiently. Procedures for doing the job are, too often, being controlled by semiskilled supervisors, craftspeople, and laborers. Management guidance is lacking at the level where many dollars are actually being wasted."

Now 45 years later, little has changed in relation to the way work is structured—who does what, when, where, and how. The authors attribute this lack of development to a combination of factors:

- Dominance of the activity centered operating system (ACOS) of current project management,
- Increased reliance on specialty contractors (this may itself be a function of the ACOS), and
- Increased technical, organizational, and regulatory complexity of projects (complexity means both more complicated because of lots of pieces and complex in the sense that the cause-and-effect relationships between components or dimensions of performance are not understood in key areas).

The paper will review the development of ACOS, its relationship with organizational practices and commercial terms as they developed in the context of the times, and efforts to improve project performance. It is proposed that the development of a lean operating system creates new research and practice opportunities for the discipline of construction engineering.

Domains of Project Delivery

The development of traditional project management and how practices evolved can be understood and explained in terms of three domains: operating system, organization, and commercial terms. These are also listed in Table 1.

Traditional Project Management

How Did the Current Approach to Project Management Develop?

The roots of current project management lead at least back to Karol Adamiecki (1866–1933), who developed a "Theory of Work Harmonization" and a tool for graphical analysis similar to those of Gantt, the "harmonogram" (Marsh 1975). Peter Morris traces the development of the critical path method (CPM) back to Adamiecki and forward to the development of project management applied today (Morris 1994). Morris details the role of military planning and the Second World War and how this led to the development of CPM. There are two commonly understood sources for its application in construction: program evaluation and review technique (PERT), the probabilistic approach used by the U.S. Navy for contract control, and the deterministic approach developed by E. I. DuPont de Nemours and Sperry-Rand Corporation.

The U.S. Navy's Bureau of Yard and Docks contracted with Stanford in the late 1950s to report on "The Application of

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J. Constr. Eng. Manage., 2011, 137(10): 740-744

Operations Research and Other Cost Reduction Techniques to Construction" (Fondahl 1961). John Fondahl joined the Stanford faculty with significant experience managing large civil engineering projects. He wrote, "To develop any sort of detailed schedule, a project must first be broken down into the operations necessary for its completion." (The occasion of the shift in language from operations to the more current "activities" is hard to trace. It may have occurred later when the requirement for CPM was established in contracts.) When the report was published, far more work was managed and done by the forces of a general contractor (GC) than is today. Fondahl expected the GC would provide the duration for operations and information on the time/cost trade-off within each operation. He believed duration for operations were more-or-less predictable and could be reduced by adding resources and increasing cost. Optimizing the duration and cost by the allocation of resources within activities was the key to optimizing a project.

This approach brought a sense of order and logic to project management and improved performance, but there were problems in practice. In 1974, Shlomo Peer observed, "It should be recognized that none of the present network methods includes in its algorithm any calculations or considerations for solving the practical organizational problems of the production process on the site. Consequently, as experience has shown, the resulting schedule is of very limited use for site management, and the plans are quickly put aside before the work is really underway. The following updating is then a permanent adjustment of the plan to the real situation of the progress on site." (Peer 1974).

Despite these problems, CPM became the "kernel" of the operating system and an industry standard foundation for planning, organizing, and contracting for projects.

A speculation on context: CPM provided a superior way to organize the management of work. It fit the culture, the common understanding of management, and the nature of projects and technology of the time. CPM came into the industry in a time of great confidence in the power and effectiveness of authoritarian management. The Whiz Kids of Secretary McNamara's Department of Defense and William Whyte's book in 1956, "The Organization Man," typify that time and perspective. Centralized command and control made sense to those who had served in the military and believed cause and effect were understood. In these circumstances, a coherent decomposition approach to project management evolved with simple sequential cause and effect, centralized planning, command-and-control organization, and communication.

Commercial Terms

The activity centered operating system of project management fit well with the traditional two-contract approach—one for design, "what" was to be built, and another for "how" it was to be built—with the construction contractor. These two transactional contracts each foresaw a single outcome—a complete design and a complete project. Lump-sum contracts made it easy for government agencies and boards of directors to demonstrate that they were paying a market price and reduced the possibility of collusion and fraud. The CPM-based operating system coupled with lump-sum contracting for each trade extended that protection. Market competition between specialty contractors surely gave incentives for each to innovate within their organizations to reduce cost of their work. Although this competition may have reduced the contracted price, conditions on projects rarely reflected the simple sequential interaction between trades as shown on the project schedule. Whether the lower costs created by market competition actually produced projects at the least cost is difficult to prove, particularly in light of the extent of claims and litigation. Market competition focused attention on improving productivity within each trade but reduced if not ignored opportunities for gains at the project level made possible by changing the structure of work. Opportunities of this sort became apparent as the principles and practice of lean construction developed. This will be discussed subsequently in this paper.

Over time, the difficulty of maintaining the single outcome established by a transactional contract increased. As Fondahl had feared, CPM became the most powerful tool to analyze the impact of changes and created a way for contractors general and specialty to recover from changes and deficiencies (Fondahl 1961). Sharp contractors could bid lower with confidence they could recover when the need to make changes was discovered. A case can be made that this led to a downward spiral as designers took less responsibility for their work (Duffy 2010). In any case, the ability of CPM to demonstrate the impact of delays created a new way for contractors to increase their profit on fixed price contracts. CPM analysis revealed the consequence of design issues previously resolved by contractors covering the cost included in their contingency or by the parties jointly solving the problem quickly instead of arguing over responsibility and impact.

As time passed, the industry and projects became more fragmented with less work managed directly by the GC. One report shows that the building general contractors' share of the workforce has declined by about a third since 1967, from 35 to 24% in 1997, and about a third of those are project staff, not construction workers. By contrast, the share of labor employed by specialty trade contractors has risen from 48% in 1967 to 63% in 1997. It seems reasonable to believe that GCs learned to contract out portions of the work where they either lacked essential capability or lost money doing that work. It is also likely that the rapid development of technical specialization contributed to this fragmentation.

"Construction management" (CM) became a distinct discipline from construction engineering with its own academic standing and industry associations during the 1970s and 1980s. The American Institute of Contractors (AIC) and the American Council for Construction Education (ACCE) were established in 1971. The program accredited by ACCE was at the University of Florida in 1975 (for a timeline of this history, see http://www.bcn.ufl.edu/dcp_prospective/history.shtml). The Construction Management Association of America (CMAA) was established in 1984. The design of project-based production systems and the structure of work are not addressed in CM beyond specifying trades. CM is taught in these programs and understood more broadly in the industry as the management of contracts organized by CPM.

Work is managed on projects under this approach from the top down by establishing a schedule and enforcing the contract. Projects are understood as networks of activities where each contractor manages their work to maximize their interest, and the GC and/or construction manager serves as a more-or-less biased referee. Commercial contracts typically include clauses that give the GC the authority to direct when and where the specialty contractors shall do their work. Means and methods necessary were left to the specialty contractor, as Professor Parker noted. The situation created by this approach was summarized by Robert Fluor in 1983: "The bottom line of this adversarial dance is a constant state of confrontation" (Business Roundtable 1983).

Organization

Command-and-control organizations were the logical outgrowth of the ACOS and commercial terms. Authority and communication protocols are clearly established to maintain the authority of the GC and focused on vertical communication. Likewise, quality and safety are managed by inspection and enforcement.

J. Constr. Eng. Manage., 2011, 137(10): 740-744

These protocols were designed to organize the work, make certain that the source, nature, resolution, and impact of changes could be clearly documented, and to solve the problem at hand within the specific trade. It was usually difficult and often impossible to establish the cost and schedule impact of changes before work commenced. The GC, under the pressure of time, often directed the work to be done before agreement on impact was reached. Profit and loss, overruns, and project delays were risks faced by all parties. Cooperative solutions that might benefit the project team as a whole or increase value delivered to the client were difficult if not rare, as the management approach and communication protocols kept parties in their silos. Perhaps worse in the longer run, learning in projects, particularly at the management level, became more about how to win the game created by the rules than about how to manage or improve the way work was done.

There is little wonder that reports by organizations such as the CMAA regularly reported projects run over budget 40–50% of the time. (Thomsen 2010)

A Curiosity

The authors know of no effort to measure the performance of the traditional approach to project planning or management. There is no shortage of data showing that projects cost more than expected and are frequently delivered late, with significant defects, all at a terrible cost to life and limb. Although there is significant data on the performance of projects, no reports were found that assess the performance of the current approach to managing them, perhaps because it has become "common sense." Learning at the system level and process improvement at the workface is mostly missing.

Attempts to Improve Traditional Practice

The traditional operating system coupled with transactional contracts and the resulting command-and-control organizations created an approach that fit the culture, the times, and the technology of the late twentieth century. Problems encountered on traditionally managed projects were often blamed on individuals or contractors for failing to do their job because of lack of skill or motivation.

Two attempts to improve project performance at the project level can be mapped on the matrix in Table 1: partnering and design/build contracting. Both tried to shift the focus from narrow local optimization to maximizing project-level performance. Partnering in the United States was an organizational approach built on the premise that working collaboratively would benefit all. Partnering meetings were usually opened with a statement that commercial terms were not be changed. Partnering meetings were organized, usually with a neutral facilitator, to help the project team get know one another, to better understand concerns, and to establish decision-making and escalation protocols. The client often explained important aspects of the project beyond those contained in the contract. Project strategy and difficult issues were often discussed and resolved. The process maintained the contractually required communication protocols but opened other less formal channels. This produced solid results in many cases, but cynicism developed when follow-through was weak or response to issues was limited by the ability to move funds to resolve issues. People began to refer to the meetings as Kum-ba-yah sessions. Looking back, it appears that partnering was a partial solution that changed neither commercial terms nor the operating system.

Design/build is a successful contracting approach that eliminated separate design and construction contracts. It rests on the reasonable belief that projects will be easier to manage and more effective if the owner has a single point of contact with an organization responsible for both what and how. The Design Build Institute of America (DBIA) now claims that 40% of nonresidential projects in the United States are delivered under this form of contract and 10% under "Construction Manager at Risk" (DBIA 2010).

Advocates of design/build contracting and partnering can point to solid success, but neither approach changed the basic operating system of project management. Neither partnering, design build contracting, project management, nor construction management provide a mechanism to structure work beyond allocating by discipline or craft or to manage work itself. Rather, all rely on the critical path schedule to establish when work will take place and on enforcing the terms of the commercial contract to direct its execution.

Table 1. Domains of Project Delivery

	Operating system	Commercial terms	Organization
Traditional project management	Activity centered—CPM based	Transactional	Command and control

Interim Summary

Traditional activity-centered management coupled with command-and-control organizations and transactional contracts now form a coherent approach supported by industry, trade and academic education, industry associations, and law. This approach forms the current common sense, a widely held understanding in the community. Work itself is managed by enforcing contracts with details of logistics left to purchasing and field production to craft level supervision. Although some civil engineering projects managed in this way do apply some principles and practices of production management, many do not. Building projects, offices, hotels, power and process plants, refineries, and the like are not designed and managed as production systems. Engaging in these projects is the opportunity for construction engineering.

But which set of production principles should applied? The authors believe the choice is clear. Mass production with large batches may be useful for standard components, although even there, manufacturers are going lean to reduce cost and speed delivery. Principles and practices that fall under the lean umbrella have proven effect on projects once workflow can be made predictable. Given the unique one-off nature of some projects, the best approach must reduce uncertainty both in terms of what is to be built and how it is to be built to produce reliable and speedy workflow.

Lean Construction: Seeing Something New

Interest in applying lean approaches occurred in a number of construction organizations in the late 1980s and early 1990s. Glenn Ballard's discovery of the extent and cause of unpredictable workflow in the 1980s and early 1990s (Ballard 1981, 1994) was a key turning point, as it revealed something experienced yet invisible on every project. Managing projects on a lean basis across the three domains of project delivery followed as practitioners came to grips with the opportunity created by changing planning practice. Table 2 compares lean project delivery with traditional project management.

Managers working in traditional and lean approaches agree on the project-level objectives of delivering value and minimizing waste. However, they have very different definitions and take different actions, because they see different sorts of waste and value. Those in traditional practice are unlikely to interpret contingency as waste or understand the concept of value and its creation from a lean perspective, that is, what the customer says it is. Less obvious,

J. Constr. Eng. Manage., 2011, 137(10): 740-744

Table 2. Domains of Project Delivery

	Operating system	Commercial terms	Organization
Traditional project management	Activity centered—CPM based	Transactional	Command and control
Lean project delivery	Flow—lean based	Relational	Collaborative

but far more important, is the difference in the underlying strategy for achieving optimal project performance. Although optimal results are achieved in traditional practice by improving productivity within each activity and reducing activity duration, managers and subcontractors are caught in the dilemma. As Fondahl identified, reducing activity duration requires spending more for additional resources and people who may not work as efficiently.

Lean construction's strategy, framed succinctly in the Sutter Health initiative, is to optimize the project and not the piece. Reliable flow of work is understood as the necessary prerequisite that makes possible the design and management of the work itself as a production system. Improving workflow predictability makes it possible to reduce both duration and cost. (Howell et al. 2001)

Lean Operating System

Lean production requires predictable workflow. The kernel of the lean operating system is a planning system that produces predictable workflow. One such system, the Last Planner System (LPS) of production control was invented by Glenn Ballard and is the registered trademark of the Lean Construction Institute (LCI). (Information on the principles, practices and implementation of the LPS is freely available without restriction on the LCI website, http://www.leanconstrucition.org. The trademark was established to assure that those selling the service of implementing LPS were capable and approved by LCI. Any person or organization may implement this system without restriction; no organization or person may sell the service to train others without the permission of LCI. This action was taken to prevent organizations from presenting current practice planning practice as LPS.) The system is now widely used on projects ranging from social housing in remote areas of Africa to complex, uncertain, and quick projects, such as hospitals in the United States.

The word "lean" brings with it images of manufacturing and the instinctive response that projects are different. There are obvious differences. The most important difference from a production management perspective is the mechanism that causes work to move from one specialist to the next. In manufacturing, work moves because of the way the line is designed. One person puts on the fender and the next, the headlight, as work moves down the line. There is no such line in projects. Work in projects moves from one specialist to the next because of the administrative act of making an assignment. A project cannot be under control, that is, produce predictable results, if the assignment system is not able to produce predictable workflow. With this key difference in hand, it becomes possible to design the project delivery system on the basis of the theories and fundamental practices of production management. This is a well-established discipline and includes the now dominant set of principles and tools applied as lean manufacturing.

For the purposes of this paper, lean is neither the issue nor a magic cure. Rather, lean construction has revealed the opportunities open to construction engineering offered by shifting from an ACOS to a production-management-based operating system. Engineering practice in every discipline rests on scientifically tested theories that provide the foundations for practice and learning. No such principles or practices underpin the traditional approach project management (Koskela and Howell 2002). The Lean Construction Institute has endeavored from the first to establish such theories. Essential foundations include those from queuing theory that explain the combined effect of dependence and variation on system performance (Howell et al. 2001), Little's Law and Goldratt's Theory of Constraints in production system design (Hopp and Spearman 2001), the language action perspective (Flores 1982) in human coordination and organization, and relational contracting for commercial contracting (Macneil 1974). The lean construction community has begun to explore the possibilities and consequences of applying these concepts to production system design on projects. The results of applying new principles and practices are significant. Although raw results rarely persuade without significant context and careful explanation connecting results to principles and practices, cost and duration are often reduced more than 10%, overruns are extremely rare, accidents and injuries reduced by half, quality is improved with the time from occupancy to operation reduced, and no significant litigation has been reported.

Adopting a new operating system for project management calls for a different kind of organization and is easier to implement and improve under an integrated form of agreement (IFOA). Improving performance of production systems is limited by the ability of the organization to move money across boundaries and to make investments here and now for savings there and then over the life of the projects. Many of these cross-trade-boundary opportunities can be discovered when work is structured early in design by cross-functional teams using computer-driven building information modeling (BIM) and virtual building. These teams are better able to structure workflow to be both predictable and fast. Additional opportunities for improvements will appear throughout the construction process. Taking advantage of them is possible when management's view of project control balances controlling costs with investing wisely.

It is little wonder, then, that a planning system designed to produce predictable workflow and rapid learning "crashes" frequently when installed in traditionally managed construction organizations. Key features and functions are compromised because the imperatives of existing planning and control systems focus on optimizing local productivity over predictable workflow. Likewise, centralized planning and control systems provide no transparent mechanism to assure work is ready when required. These differences reveal the consequences of choosing traditional planning practice over those that produce predictable workflow. For example, extending the make-ready period from two to six weeks will typically reduce the material stored on-site and reduce the risk of injuries attributable to double handling. Subordinating measurement of planning system performance to more traditional productivity measures will reduce the reliability of workflow. The earned value method can lead to a focus on local productivity and doing work out of sequence. This both reduces workflow predictability and creates a false impression of project status.

However, improving the predictability of workflow on traditionally managed projects does improve performance, even as greater opportunities are lost. In the ACOS model, work is structured as Professor Parker said 45 years ago, by traditions of craft and contract. Opportunities for off-site or modular construction are mostly lost because traditional practice relies on central control "push" to time the arrival of materials and resources to match project readiness for installation. (There are two ways to advance the necessary wherewithal to site. Push advances it on the basis of a schedule. Pull advances materials and resources when the site is ready to use it. Pull can be understood as a request timed to assure that what

J. Constr. Eng. Manage., 2011, 137(10): 740-744

is needed arrives at the right time. But how can one deliver things just in time if "what time it is" is unknown?) For a better understanding of the function and consequences of shifting from push to pull, see the study by Tommelein (1998).

Commercial Terms

Transactional contracts applied in traditional practice establish the rules and procedures for managing the project and allocating risk. The duration of the project is established with an agreed CPM schedule and cost is allocated to each activity at the project level with subcontracts or budget allocations to activities. The contract establishes which party bears the risk of overrun or reward for improved performance. Project controls in traditional practice are designed to assure the established cost is not exceeded and the party responsible for the overrun pays that bill. The estimating and bidding processes are assumed to allocate money in ways that maximize project performance. In a sense, bidding validates the project budget.

Unexpected low prices at bid can be as disappointing as high prices. Low prices may mean the client cannot easily take advantage of available funds to increase the value received from the project. High prices may require the client to scale back the project, engineer out key features, shift money from other initiatives, or give up altogether.

The allocation of money to activities under an IFOA is less rigid. Costs are paid and profits shared on a preestablished basis. Risks and rewards are shared by agreement among parties, the latter often from an incentive pool. This arrangement keeps people's attention on the effective application of money. The motivational aspect of the incentive pool is likely less important than the ability to increase its size by moving money across boundaries to achieve better total performance.

Risk itself is understood differently from traditional practice on projects managed on a lean basis. In traditional practice, risk is assumed to arise more from the outside the project or from mistakes people make. This approach misses the opportunity to reduce risk by planning that improves the predictability of workflow, collaborative design that reduces uncertainty, an organization where everyone stands to lose from any failure and to gain by careful investment, and where everyone is watching for mistakes and errors.

Organization

Management on lean projects better conforms to Fernando Flores' definition of management, "The design and activation of a network of commitments" (Flores 1982) than to the traditional project management's ACOS command-and-control model driven by the CPM. Perhaps the biggest shift required in practice arises from this shift in the way management is understood. Crew-level assignments become more reliable when they are in response to a request—a "pull" signal—and result in a promise to the following crew. Under this approach, it is the responsibility of the supervisors to reject unsound assignments, to say "no" if they are not confident they can deliver on the request. Acknowledging the autonomy of the supervisor in this way contradicts the command-and-control nature of traditional project organizations.

Call to Action

Designing production systems for projects is at the leading edge of production management. Construction engineering can lead this development, extend its research agenda, and develop practitioners with capabilities long missing in the industry. The research agenda could begin with descriptive studies informed by distinctions from production system design (Hopp and Spearman 2001) and LCI. For example, how does planning actually work now, and what are the consequences and costs incurred by its inadequacy? Hollnagel's efficiency-thoroughness trade-off (ETTO) principle offers a rich opportunity to understand how engineers make the decisions they do in the face of uncertainty (Hollnagel 2009). Likewise, the Last Planner System developed at LCI provides an example of new ways to manage planning and measure its effectiveness; e.g., how well is the project team and its network of suppliers making ready what *should* be done so it *can* be done? For instruction, the authors suggest faculty begin to balance emphasis on CPM scheduling and related project management issues with course work and field assignments that help students understand principles of production system design and management. Course work and research in safety can be enriched by Dekker's focus on system design (Dekker 2005) and Weick's on high reliability organizations (Weick 2007).

References

Ballard, G. (1981). "Crew level planning." *Proc. 1981 Conf. on Construction Productivity Improvement*, Univ. of Texas at Austin, Austin, TX.

Ballard, G. (1994). "The last planner." *Northern California Construction Institute Spring Conf.*, Monterey, CA.

Business Roundtable. (1983). "More construction for the money." *Summary Rep. of the Construction Industry Cost Effectiveness Project*, New York, 96.

Dekker, S. (2005). *Ten questions about human error*, CRC Press, Boca Raton, FL.

Design Build Institute of America (DBIA). (2010). 〈http://www.dbia.org/pubs/research/rsmeans110606.htm〉 (Oct. 9, 2011).

Duffy, R. (2010). "The architects transformative role in the building process." *Keynote Address: Columbia Building Intelligence Project*, Columbia Univ., New York 〈http://www.arch.columbia.edu/school/section/c-bip/f09-think-tank〉.

Flores, F. (1982). "Management and communication in the office of the future." Ph.D. dissertation, Univ. of California, Berkeley, CA.

Fondahl, J. (1961). "A non-computer approach to the critical path method for the construction industry." *Technical Rep. 9*, Stanford Univ., Palo Alto, CA.

Hollnagel, E. (2009). *The ETTO principle: Efficiency-thoroughness trade-off*, Ashgate Publishing, Burlington, VT.

Hopp, W., and Spearman, M. (2001). *Factory physics*, McGraw-Hill, New York.

Howell, G., Ballard, G., and Hall, J. (2001). "Capacity utilization and wait time, a primer for construction." *Proc. 9th Annual Meeting of the Int. Group for Lean Construction*, Singapore.

Koskela, L., and Howell, G. (2002). "The underlying theory of project management is obsolete." *Proc. PMI Research Conf.*, 293–302.

Macneil, I. (1974). "The many futures of contracts." *South. Calif. Law Rev.*, 47, 691–816.

Marsh, E. (1975). "The harmonogram of Karol Adamiecki." *Acad. ATTEMPTS TO IMPROVE TRADITIONAL PRACTICEManage. J.*, 18(2), 358–364.

Morris, P. (1994). *The management of projects*, Thomas Telford, London, 18.

Parker, H. (1965). "Methods improvement techniques for construction and public works managers." *Technical Rep. 51*, Dept. of Civil Engineering, Stanford Univ., Stanford, CA, 119.

Peer, S. (1974). "Network analysis and construction planning." *J. Constr. Div.*, 100(3), 203–210.

Tommelein, I. D. (1998). "Pull-driven scheduling for pipe-spool installation: Simulation of lean construction technique." *J. Constr. Eng. Manage.*, 124(4), 279–288.

Thomsen, C., Darrington, J., Dunne, D., and Lichtig, W. (2010). "Managing integrated project delivery." *White paper of the Construction Management Association of America*, McLean, VA 〈http://www.cmaanet.org/fellows〉.

Weick, K., and Sutcliffe, K. (2007). *Managing the unexpected*, Wiley, San Francisco.

J. Constr. Eng. Manage., 2011, 137(10): 740-744