Advancing the Competitiveness and Efficiency of the U.S. Construction Industry

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Lloyd Duscha, U.S. Army Corps of Engineers (retired). Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

Summary

In 2008, the National Institute of Standards and Technology (NIST) requested that the National Research Council (NRC) appoint an ad hoc committee of experts to provide advice for advancing the competitiveness and productivity of the U.S. construction industry. The committee's specific task was to plan and conduct a workshop to identify and prioritize technologies, processes, and deployment activities that have the greatest potential to advance significantly the productivity and competitiveness of the capital facilities sector of the U.S. construction industry in the next 20 years.[1]

Because the concept of *productivity* can be difficult to define, measure, and communicate, the committee determined that it would focus on ways to improve the *efficiency* of the capital facilities sector of the construction industry. It defines *efficiency improvements* as ways to cut waste in time, costs, materials, energy, skills, and labor. The committee believes that improving efficiency will also improve overall productivity and help individual construction firms produce more environmentally sustainable projects and become more competitive.

To gather data for this task, the Committee on Advancing the Competitiveness and Productivity of the U.S. Construction Industry Workshop commissioned three white papers by industry analysts and held a 2-day workshop in November 2008 to which 50 additional experts were invited. A range of activities that could improve construction productivity were identified in the papers, at the workshop, and by the committee itself. From among these, the committee identified five interrelated activities that could lead to breakthrough improvements in construction efficiency and productivity in 2 to 10 years, in contrast to 20 years. If implemented throughout the capital facilities sector, these activities could significantly advance construction efficiency and improve the quality, timeliness, cost-effectiveness, and sustainability of construction projects. Following are the five activities, which are discussed in the section below entitled "Opportunities for Breakthrough Improvements."

1. Widespread deployment and use of interoperable technology applications,[2] also called Building Information Modeling (BIM);
2. Improved job-site efficiency through more effective interfacing of people, processes, materials, equipment, and information;
3. Greater use of prefabrication, preassembly, modularization, and off-site fabrication techniques and processes;
4. Innovative, widespread use of demonstration installations; and
5. Effective performance measurement to drive efficiency and support innovation.

The five activities are interrelated, and the implementation of each will enable that of the others. Deploying these activities so that they become standard operating procedures in the capital facilities sector will require a strategic, collaborative approach led by those project owners who will most directly benefit from lower-cost, higher-quality sustainable projects, namely, the large corporations and government agencies that regularly invest hundreds of millions of dollars in buildings and infrastructure

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[1] The *capital facilities sector* includes commercial (including high-rise and multifamily residential), industrial, and infrastructure projects. It does not include single-family and low-rise residential projects.

[2] *Interoperability* is the ability to manage and communicate electronic data among owners, clients, contractors, and suppliers, and across a project's design, engineering, operations, project management, construction, financial, and legal units.

in order to conduct their operations. However, these owners cannot effect widespread change without the collaboration and support of large contractors, subcontractors, architects, engineers, and researchers. The committee suggests a path forward for implementing the changes required to advance the competitiveness and efficiency of the U.S. construction industry significantly in the 21st century.

BACKGROUND

The quality of life of every American relies in part on the products of the U.S. construction industry—houses, office buildings, factories, shopping centers, hospitals, airports, universities, refineries, roads, bridges, power plants, water and sewer lines, and other infrastructure. Construction products—buildings and infrastructure—provide shelter, water, and power, and they support commerce, education, recreation, mobility, and connectivity. They also have significant environmental impacts, annually accounting for 40 percent of primary energy use in the United States and 40 percent of the U.S. greenhouse gas emissions linked to global climate change. Each year, new construction projects in this country account for 30 percent of the raw materials and 25 percent of the water used, and for 30 percent of the materials placed in landfills (NSTC, 1995).

The construction industry itself is a major generator of jobs and contributes an important component of the gross domestic product (GDP). In 2007, almost 11 million people, about 8 percent of the total U.S. workforce, worked in construction. The value of the buildings and infrastructure that they constructed was estimated to be $1.16 trillion (U.S. Census Bureau, 2008a). The construction industry accounted for $611 billion, or 4.4 percent of the GDP, more than many other industries, including information, arts and entertainment, utilities, agriculture, and mining (BEA, 2009). Construction’s portion of the GDP would increase to 10 percent if the equipment, furnishings, and energy required to complete buildings were included (NSTC, 2008).

Construction productivity—how well, how quickly, and at what cost buildings and infrastructure can be constructed—directly affects prices for homes and consumer goods and the robustness of the national economy. Construction productivity will also affect the outcomes of national efforts to renew existing infrastructure systems; to build new infrastructure for power from renewable resources; to develop high-performance “green” buildings; and to remain competitive in the global market. Changes in building design, construction, and renovation, and in building materials and materials recycling, will be essential to the success of national efforts to minimize environmental impacts, reduce overall energy use, and reduce greenhouse gas emissions (NSTC, 2008).

However, industry analysts differ on whether construction industry productivity is improving or declining. Some analyses for the industry as a whole indicate that productivity has been declining for 30 years or more. Other studies document improved productivity for construction projects and construction tasks (e.g., the laying of pipe or concrete).

One note of agreement is that there is significant room for improvement. Studies focusing on construction efficiency, in contrast to productivity, have documented 25 to 50 percent waste in coordinating labor and in managing, moving, and installing materials (Tulacz and Armistead, 2007); losses of $15.6 billion per year due to the lack of interoperability (NIST, 2004); and transactional costs of $4 billion to $12 billion per year to resolve disputes and claims associated with construction projects (FFC, 2007).

A key message of the present report is that advances in available and emerging technologies offer significant opportunities to improve construction efficiency substantially in the 21st century and to help meet other national challenges, such as environmental sustainability.

OBSTACLES TO IMPROVEMENT

Studies of the construction industry over the past 30 years have documented a wide array of organizational issues, policies, and practices that result in inefficiencies and loss of productivity.

The sheer number of construction firms (710,000 in 2002) and their size—only 2 percent had 100 or more workers, while 80 percent had 10 or fewer workers (CPWR, 2007)—make it difficult to deploy new technologies, best practices, or other innovations effectively across a critical mass of owners, contractors, and subcontractors. The industry is also segmented by industry analysts and practitioners into at least four distinct sectors—residential, commercial, industrial, and heavy construction.[3] These sectors differ from each other in terms of the following:

- The characteristics of project owners, their sophistication, and their involvement in the construction process;
- The complexity of the projects;
- The source and magnitude of financial capital;
- Required labor skills;
- The use of specialty equipment and materials;
- Design and engineering processes; and
- Knowledge and other factors.

Nonetheless, these sectors also share common issues and obstacles to improving construction productivity, including:

- A diverse and fragmented set of stakeholders: owners, users, designers, builders, suppliers, manufacturers, operators, regulators, manual laborers, and specialty trade contractors, including plumbers, electricians, masons, carpenters, and roofers;
- Segmented processes: planning, financing, design, engineering, procurement, construction, operations, and maintenance. Each process is typically performed sequentially and each involves different groups of stakeholders, shifting responsibilities, and shifting levels of financial risk, which in turn often leads to adversarial relationships, disputes, and claims;
- The image of the industry—work that is cyclical, low-tech, physically exhausting, and unsafe—which makes it difficult to attract and retain skilled workers and recent graduates;
- The one-of-a-kind, built-on-site nature of most construction projects;
- Variation in the standards, processes, materials, skills, and technologies required by different types of construction projects;
- Variation in the building codes, permitting processes, and construction-related regulations propagated by states and localities;
- The lack of an industry-wide strategy to improve construction efficiency;
- The lack of effective performance measures for construction-related tasks, projects, and the industry as a whole; and
- The lack of an industry-wide research agenda and levels of funding for research that are inadequate.

In an industry of thousands of small establishments, an array of stakeholders, dynamic processes, diverse products, and no overall strategy or research agenda, three major issues arise:

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[3] Some practitioners would suggest that transportation-related projects be treated as a fifth segment of construction based on the characteristics of these types of projects (Hinze, 2001).

1. Identifying the technologies, processes, materials, or other actions that can result in the greatest benefits to the industry as a whole;
2. Determining who should be responsible and accountable for driving change and improving productivity; and
3. Mitigating the risks to owners, clients, contractors, and suppliers from using innovative technologies, materials, and processes.

CHARACTERISTICS OF AN EFFICIENT CAPITAL FACILITIES SECTOR

To help determine which activities offer the greatest potential for resulting in breakthrough improvements, the committee first identified the attributes that characterize an efficient capital facilities sector:

- Production of quality products that meet owners' and the nation's needs;
- Competitiveness in the global marketplace;
- Well-integrated processes, supply chains, and work flows;
- Promotion of sustainability through the efficient use of time, materials, skills, and dollars;
- Attractiveness to a diverse, well-trained, knowledgeable, professional, skilled labor force able to work collaboratively to meet owners' and clients' objectives;
- Ability to adapt to new conditions and to deploy new technologies effectively;
- Use of best practices to reduce rework and delivery time, and to improve job-site safety and project quality; and
- Measurement of performance to enable innovation and improvements in products and processes.

OPPORTUNITIES FOR BREAKTHROUGH IMPROVEMENTS

From among many suggestions, the committee identified five interrelated activities that could result in breakthrough improvements in the capital facilities sector of the construction industry in the next 2 to 10 years. Following is a brief discussion of each activity.

1. *Widespread deployment and use of interoperable technology applications, also called Building Information Modeling (BIM). Interoperability* is the ability to manage and communicate electronic data among owners, clients, contractors, and suppliers, and across a project's design, engineering, operations, project management, construction, financial, and legal units. Interoperability is made possible by a range of information technology tools and applications including computer-aided design and drafting (CADD), three- and four-dimensional visualization and modeling programs, laser scanning, cost-estimating and scheduling tools, and materials tracking.

Effective use of interoperable technologies requires integrated, collaborative processes and effective planning up front and thus can help overcome obstacles to efficiency created by process fragmentation. Interoperable technologies can also help to improve the quality and speed of project-related decision making; integrate processes; manage supply chains; sequence work flow; improve data accuracy and reduce the time spent on data entry; reduce design and engineering conflicts and the subsequent need for rework; improve the life-cycle management of buildings and infrastructure; and provide the data required to measure performance. Barriers to the widespread deployment of interoperable technologies include legal issues, data-storage capacities, and the need for "intelligent" search applications to sort quickly through thousands of data elements and make real-time information available for on-site decision making.

2. *Improved job-site efficiency through more effective interfacing of people, processes, materials, equipment, and information.* The job site for a large construction project is a dynamic place, involving numerous contractors, subcontractors, tradespeople, and laborers, all of whom require equipment, materials, and supplies to complete their tasks. Managing these activities and demands to achieve the maximum efficiency from the available resources is difficult and typically not done well. Time, money, and resources are wasted when projects are poorly managed, causing workers to have to wait around for tools and work crews' schedules to conflict; when work crews are not on-site at the appropriate time; or when supplies and equipment are stored haphazardly, requiring that they be moved multiple times.

Greater use of automated equipment (e.g., for excavation and earthmoving operations, concrete placement, pipe installation) and information technologies (e.g., radio-frequency identification tags for tracking materials, personal digital assistants for capturing field data), process improvements, and the provision of real-time information for improved management at the job site could significantly cut waste, improve job-site safety, and improve the quality of projects. A primary barrier to more effective use of such technologies is the segmentation and sequencing of planning, design, engineering, and construction processes. Improved job-site efficiency also requires a skilled labor force with communication, collaboration, and management skills as well as technical proficiencies.

3. *Greater use of prefabrication, preassembly, modularization, and off-site fabrication techniques and processes*. Prefabrication, preassembly, modularization, and off-site fabrication involve the fabrication or assembly of systems and components at off-site locations and manufacturing plants. Once completed, the systems or components are shipped to a construction job site for installation at the appropriate time. These techniques offer the promise (if used appropriately) of lower project costs, shorter schedules, improved quality, and more efficient use of labor and materials. Various obstacles stand in the way of the widespread use of such technologies, including building codes that hinder innovation as well as conventional design and construction processes and practices.

4. *Innovative, widespread use of demonstration installations.* Demonstration installations are research and development tools that can take a variety of forms: field testing on a job site; seminars, training, and conferences; and scientific laboratories with sophisticated equipment and standardized testing and reporting protocols. Greater and more collaborative use of demonstration installations can be used to test and verify the effectiveness of new processes, technologies, and materials and their readiness to be deployed throughout the construction industry. By allowing determinations to be made about whether innovative approaches are mature enough for general use, demonstration installations can help to mitigate innovation-related risks to owners, contractors, and subcontractors.

5. *Effective performance measurement to drive efficiency and support innovation*. Performance measures are enablers of innovation and of corrective actions throughout a project's life cycle. They can help companies and organizations understand how processes or practices led to success or failure, improvements or inefficiencies, and how to use that knowledge to improve products, processes, and the outcomes of active projects. The nature of construction projects and the industry itself calls for lagging, current, and leading performance indicators at the industry, project, and task levels, respectively.

- *Industry-level measures* are needed to determine whether the productivity of the construction industry as a whole is improving or declining over time. Lagging indicators can be used to track industry trends for several years to help identify the root causes of improvement or decline. Information relating to root causes in turn can be used to develop industry-wide strategies for improvement, including the improvement of policies, procedures, practices, and research. Industry-level measures can also be used to track the impact of innovations, such as the greater use of prefabricated components, interoperable technologies, and automated equipment.

Industry-level measures are of greatest interest and value to government agencies, policy makers, and research-oriented organizations.

- *Project-level measures* are needed to contribute to the understanding of how an individual project compares with other, similar projects (e.g., other school buildings, other oil refineries) in terms of total cost, schedule, cost changes, labor hours, and other factors. Such current measures are of greatest value to owners of multiple projects and to large contractors who are seeking to reduce the costs and delivery time of projects, to improve worker safety, or to initiate some other change in construction-related processes and practices.
- *Task-level measures* are leading indicators that are commonly used by contractors and subcontractors that need to evaluate the efficiency of their workforces on a daily or weekly basis so that problems on active projects can be detected and corrected quickly.

As stated, all five activities listed above are interrelated, and the implementation of each will enable that of the others. For example, the widespread deployment of interoperable technologies will help to improve the supply chain management that is essential to the improvement of job-site efficiency and the greater use of preassembled components. Similarly, the innovative, widespread use of demonstration installations will help to mitigate the risk associated with new technologies, materials, and processes. Effective performance measures will help document which innovations result in improved efficiency and productivity and will help to build a "business case" for using such innovations throughout the industry. It cannot be stressed too strongly that finding ways to attract and retain skilled workers and recent graduates will be essential to achieving success.

The committee believes that implementing these five activities for capital facilities and infrastructure will help to achieve the following:

- Overcome fragmentation by requiring greater collaboration up front among project stakeholders;
- Lead to more efficient use and better integration of people, processes, materials, and equipment through all phases of a construction project; and
- Create more useful and more accurate information for the development of performance measures that can facilitate innovation in technologies and materials and improvement in products and processes.

DRIVING CHANGE STRATEGICALLY THROUGH COLLABORATION

Implementing the five activities identified above in order to achieve breakthrough improvements in efficiency and competitiveness for capital facilities and infrastructure projects will require a strategic, collaborative, evidence-based approach. The approach needs to be strategic because no single group of stakeholders or individual organization can drive change through the entire capital facilities sector. It needs to be collaborative in order to create a critical mass of stakeholders who can work together to overcome obstacles to the effective use of interoperable technologies and prefabricated components, to the improvement of job-site efficiency, and to the identification and use of appropriate demonstration installations. Collaboration will also help mitigate the risks and spread the costs and benefits of innovation. The approach needs to be evidence based because evidence-based best practices and effective performance measures will make a compelling business case for the adoption of new processes and technologies on a widespread basis throughout the construction industry.

Large corporations and government agencies—the owners that regularly invest in capital facilities and infrastructure—are in the best position to lead an effort to drive change in the construction industry. Because they are contracting and paying for capital facilities, such owners can facilitate innovation in processes, technologies, and behaviors through contract provisions, incentives, and contractor selection processes. These owners will also realize the greatest, most direct benefits from improvements in construction efficiency—higher-quality, more environmentally sustainable buildings and infrastructure, produced at lower cost, and in less time.

However, these owners cannot drive change without the collaboration and support of large contractors, subcontractors, equipment manufacturers, standards-setting organizations, and researchers. A critical mass of these stakeholders will need to develop methods collaboratively to share the risks, costs, and rewards of more efficient projects and processes.

The committee believes that the critical mass of stakeholders needed to achieve breakthrough improvements can be assembled through a coalition of professional industry and government organizations. Such organizations include the Construction Users Roundtable, the Associated General Contractors of America, the Construction Industry Institute, the Associated Builders and Contractors, the American Council of Engineering Companies, the American Institute of Architects, the National Academy of Construction, the National Institute of Standards and Technology, and the National Science Foundation. These organizations collectively represent a critical mass of project owners, construction firms, designers, engineers, and researchers, all of whom have a direct stake in improving the competitiveness and efficiency of the capital facilities sector of the construction industry. These organizations provide the venues required for the collaborative activities necessary to change existing processes and practices. They have the resources for and, in some cases, the explicit mission of conducting research. And they have access to the industry media (e.g., trade journals such as *Engineering News Record*) and academic journals, which can be used to disseminate research results and evidence-based information regarding best practices, new technologies, and innovations in construction.

The committee believes that as these owners, contractors, and researchers effectively use innovative technologies, they will improve their own efficiency and competitiveness. And as these owners, contractors, and researchers disseminate the results of their efforts through trade and research journals, presentations, and best practices, smaller firms that wish to remain competitive can follow their example. In this way it will be possible to effect widespread change throughout the capital facilities sector.

The committee is not in a position to mandate action by leading construction firms or professional organizations, but it can suggest a path forward. The committee believes that the sponsor of this study, the National Institute of Standards and Technology, is well positioned to work with the construction-related organizations in the public and private sectors to develop a collaborative strategy for improving the productivity of the capital facilities sector. NIST's mission is to "promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life." To fulfill this mission, NIST staff routinely work with a range of construction stakeholders, including owners, contractors, and researchers from industry, academia, and government to support the development of construction-related standards and technologies. NIST also has sophisticated testing facilities that can be used for evaluating high-cost, high-risk, high-impact innovative technologies, demonstrating their capacity for improving effectiveness and productivity and verifying their readiness for deployment throughout the capital facilities sector.

RECOMMENDATIONS

The committee identified the five interrelated activities discussed above that it believes have significant potential to advance the competitiveness and efficiency of the capital facilities sector within 2 to 10 years. To expedite the deployment of these activities on a widespread basis, the committee makes the following recommendations:

Recommendation 1: The National Institute of Standards and Technology should work with industry leaders to bring together a critical mass of construction industry stakeholders to develop a collaborative strategy for advancing the competitiveness and efficiency of the capital facilities

sector of the U.S. construction industry. The collaborative strategy should identify actions needed to fully implement and deploy interoperable technology applications, job-site efficiencies, off-site fabrication processes, demonstration installations, and effective performance measures.

NIST is uniquely positioned to work with public- and private-sector owners, contractors, researchers, and standards-setting organizations. The committee recommends that NIST convene a series of meetings involving representatives of the Construction Users Roundtable, Associated General Contractors of America, the Construction Industry Institute, the Association of Builders and Contractors, the American Council of Engineering Companies, the National Academy of Construction, the American Institute of Architects, the National Science Foundation, and other government organizations. The purpose of the meetings should be to develop a collaborative strategy for fully implementing the five activities identified by the committee that could lead to breakthrough improvements in efficiency and competitiveness for the capital facilities sector of the U.S. construction industry.

Recommendation 2: The National Institute of Standards and Technology should take the lead in developing a "technology readiness index" similar to indexes developed by the National Aeronautics and Space Administration and the Department of Defense, for high-risk, high-cost, high-impact construction-related innovations. Such an index could help mitigate the risks of using new technologies, products, and processes by verifying their readiness to be deployed on a widespread basis.

A technology readiness index is most appropriate for evaluating the maturity of high-cost, high-risk, and high-impact technologies. Such an index could be used to provide a common understanding of the status of a technology and its level of risk. It could also be used to help make decisions about funding for additional research and development or for deploying the technology into widespread practice.

Recommendation 3: The National Institute of Standards and Technology should work with the Bureau of Labor Statistics, the U.S. Census Bureau, and construction industry groups to develop effective industry-level measures for tracking the productivity of the construction industry and to enable improved efficiency and competitiveness.

With its stated mission of measurement science and its resources, NIST is the organization best positioned to take the leading role in developing industry-level measures for construction. Collaboration with the Bureau of Labor Statistics, the U.S. Census Bureau, and industry organizations will be required in order to develop industry-level measures that help identify trends in construction industry productivity. Industry organizations can help NIST and others to determine which types of data can reasonably be collected and validated for this purpose.

1

Background

The U.S. construction industry produces all types of buildings and infrastructure—homes, workplaces, shopping centers, hospitals, airports, universities, refineries, roads, bridges, water and sewer lines—in every community across the country. In doing so, it touches the daily life of every American. The construction industry also affects the budget of every individual for this reason:

> [The] price of every factory, office building, hotel, or power plant that is built affects the prices that must be charged for the goods and services produced in or on it. And that effect generally persists for decades. (BRT, 1983, p. 12)

A variety of statistics illustrate the importance of the construction industry to the national economy. In 2007 (the latest year for which data are available as of this writing), the construction industry conservatively accounted for $611 billion, or 4.4 percent of the gross domestic product (GDP), more than the amount contributed by many other industry sectors[1] (BEA, 2009). If the value of installed equipment, furnishings, and other elements necessary to complete a building were included, construction would account for 10 percent of the GDP (NSTC, 1995).

The construction industry is also a major generator of jobs. Almost 11 million people (BLS, 2008), about 8 percent of the total U.S. workforce, were directly employed by construction firms in 2007. The value of the buildings and infrastructure that they constructed was estimated at $1.16 trillion (U.S. Census Bureau, 2008a).

Also in 2007, construction projects valued at $4.6 trillion were built worldwide. The United States was the largest single-country market for such projects, while Western Europe was the largest regional market ($1.4 trillion) (McGraw-Hill Construction, 2008).

The importance of construction to the national economy is also reflected, in part, by the American Recovery and Reinvestment Act of 2009 (Public Law 111-5). This legislation authorized the investment of hundreds of billions of dollars in construction-related activities to stimulate the economy and create jobs.

Prior to the 2008-2009 financial crisis, the Bureau of Labor Statistics (BLS) in the U.S. Department of Labor projected a net increase of 780,000 construction-related jobs in the United States between 2006 and 2016 (BLS, 2007). Worldwide construction spending was also projected to increase between 2009 and 2016, although it is likely that the financial crisis has affected these projections (Global Insight, 2007). The drivers behind the projected increases for the U.S. market were population growth, the construction of new buildings, the renovation of existing ones, and the renewal of existing infrastructure. In the global market, the driving forces included population growth and urbanization in China, India, the Middle East, and Africa and their demands for infrastructure (transportation, power, telecommunications, water, wastewater treatment) and other facilities (e.g., multifamily housing, health care facilities, schools).

U.S. construction firms and the industry face significant challenges now and in the future.

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[1] The contribution of construction was more than that of agriculture, forestry, fishing, and hunting ($168 billion); mining ($275 billion); utilities ($281 billion); transportation and warehousing ($407 billion); information ($586 billion); and arts, entertainment, accommodation, recreation, and food services ($513 billion) (BEA, 2009).

Construction firms need the capacity to execute projects quickly, to design and build facilities that are environmentally sustainable or "green," and to do so at a competitive cost. They need to find ways to compete with firms in other industries in order to attract skilled workers and recent graduates. And they need to improve their efficiency in order to remain competitive when bidding for new projects at home and abroad. How well the industry as a whole meets these challenges will affect the prices that U.S. consumers pay for durable and nondurable goods and that communities pay for infrastructure. It will also affect the robustness of the national economy.

The productivity of the construction industry—how well, how quickly, and at what cost buildings and infrastructure can be produced—will also help determine how well the United States meets the challenges of environmental sustainability, energy independence, and disaster resilience.

Today in the United States, buildings and infrastructure account for 40 percent of primary energy use. The heat and power used in buildings account for approximately 40 percent of the greenhouse gases produced in the United States linked to global climate change. Buildings and infrastructure also account for approximately 30 percent of the raw materials and 25 percent of the water used annually in this country. Each year U.S. construction projects generate 164,000 million tons of material waste and demolition debris, accounting for about 30 percent of the content in landfills (EPA, 2004). Changing how buildings and infrastructure are designed, built, and renovated; what materials are used; and how those materials are recycled will be essential to the success of the nation's efforts to minimize environmental impacts, reduce overall energy use, and reduce greenhouse gas emissions.

Design and construction quality and materials are also essential to the durability and resiliency of buildings and infrastructure during and after natural and human-made disasters. The quality of building design, engineering, and construction and the technologies and materials used will help determine how well buildings and infrastructure can withstand earthquakes, tornadoes, floods, or bomb blasts. Their robustness and resiliency, in turn, will help determine the magnitude of property losses and the speed at which communities recover from disasters.

CHARACTERISTICS OF THE CONSTRUCTION INDUSTRY

The construction industry can be differentiated from other industries by its organization and products, its stakeholders, its projects, its processes, and its operating environment.

Organization and Products

The construction industry is composed overwhelmingly of small businesses, but it is also stratified. Of the 710,000 construction firms with payrolls in the United States in 2002, almost 80 percent had fewer than 10 employees, accounting for 24 percent of the construction workforce. In contrast, only 585 construction firms (less than 1 percent) had 500 or more employees (8 percent of construction workers). Looked at another way, 98 percent of all construction firms had fewer than 100 workers (79 percent of the construction workforce), while 2 percent of all firms had 100 or more workers (21 percent) (CPWR, 2007). These statistics do not include the almost 2.5 million self-employed "one-person" businesses or approximately 1.5 million public employees performing construction (U.S. Census Bureau, 2005).

National statistical data divide the construction industry into three subsectors: construction of buildings, heavy and civil engineering construction, and specialty trade contractors. The construction of buildings subsector comprises establishments involved in constructing residential, industrial, commercial, and institutional buildings. The heavy and civil engineering subsector includes establishments involved in infrastructure projects—for example, water, sewer, oil, and gas pipelines; roads and bridges; and power plants. The specialty trade contractors subsector engages in activities such as plumbing, electrical work, masonry, carpentry, and roofing that are generally needed in the construction of all building types. Thus,

TABLE 1.1 Number Employed in 2005 in U.S. Construction Industry Subsectors and Construction Sector as Defined by the North American Industry Classification System (NAICS)

NAICS Code	Industry Subsectors and Construction Sector	Number Employed in 2005[a]
236	Construction of Buildings	1,782,200
237	Heavy and Civil Engineering Construction	974,800
238	Specialty Trade Contractors	4,714,000
23	Construction Sector	7,571,000

[a] Excludes self-employed and publicly employed workers.
SOURCE: CPWR (2007).

while two of the subsectors refer to types of construction projects, the third refers to types of workers who work on all types of projects. This statistical breakdown masks significant differences within segments of the industry, including the wide array of construction projects, the percentages of workers in skilled trades, and those in unskilled or manual labor jobs (Table 1.1).

In contrast to the division of the construction industry into three subsectors by national statistical data, many industry analysts and practitioners consider construction to have at least four distinct sectors—residential,[2] commercial, industrial, and heavy construction.[3] Specialty trade contractors (e.g., carpenters, plumbers, masons) and manual laborers are involved in each of these sectors. In this report, the combined sectors of commercial, industrial, and heavy construction projects are referred to as the capital facilities sector.

The commercial sector, which builds schools, churches, high-rise multifamily buildings, offices, and retail buildings, among other projects, accounts for about 25 percent of the total construction value put in place in the United States each year. Construction firms and contractors working in this sector may have a mix of large and small projects and a larger group of full-time workers and subcontractors. Some of this sector's workers may belong to labor unions and may have specialized training through apprenticeships (NRC, 2009).

The industrial sector delivers manufacturing plants, oil refineries, power plants, and similar projects, accounting for another 25 percent of total construction value put in place in the United States annually. The owners of industrial projects, usually large corporations, typically build them to produce the products that they market. Because such projects are specialized, cost hundreds of millions of dollars, and are integral to the "bottom line" of such businesses, owners are more likely to be closely involved in such projects. Contractor firms working in this sector tend to be large and sophisticated, and their workers are likely to be trained and certified—by trade associations, contractors, and labor unions. For some types of projects, both owners and contractors are members of professional organizations that share best practices (e.g., Construction Users Roundtable [CURT],[4] the Associated General Contractors of America [AGC],[5] the Construction Industry Institute [CII],[6] the Associated Builders and Contractors [ABC],[7] and the American Council of Engineering Companies [ACEC]).[8]

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[2] This report does not address the residential sector except for high-rise residential construction.

[3] Some practitioners would suggest that transportation-related projects be treated as a fifth segment of construction based on the characteristics of these types of projects (Hinze, 2001).

[4] CURT is an independent not-for-profit organization that describes itself as the "owners' voice to the construction industry." Additional information is available at http://www.curt.org. Accessed February 4, 2009.

[5] AGC is a construction trade association representing all facets of commercial construction. Additional information is available at http://www.agc.org. Accessed February 4, 2009.

[6] CII is a consortium of owners, engineering and construction contractors, suppliers, research universities, and other stakeholders whose mission is to improve the cost-effectiveness of the capital facility project life cycle. Additional information is available at http://www.construction-institute.org. Accessed February 4, 2009.

[7] ABC is a national association representing all specialties within the U.S. construction industry and is composed primarily of firms that perform work in the industrial and commercial sectors of the industry. Additional information is available at http://www.abc.org. Accessed February 4, 2009.

The heavy construction sector delivers dams; water, sewer, and gas lines; tunnels, highways, and bridges; and airports and other infrastructure. Governmental entities serve as the owner of many but not all such projects. Construction firms working in this sector range from relatively small, specialized contractors to large national and international firms. Much of the work involves the use of heavy equipment and may require fewer workers per project than are needed in other sectors. As with industrial-type projects, the awareness and involvement by owners and contractors in the heavy construction sector are at a relatively high level.

The commercial, industrial, and heavy construction sectors, then, are stratified and differ from each other in terms of the following:

- The characteristics of project owners, their sophistication, and their involvement in the construction process;
- The complexity of the projects;
- The source and magnitude of financial capital;
- The labor skills required;
- The use of specialty equipment and materials;
- The design and engineering processes; and
- The knowledge required and other factors.

Stakeholders

Construction projects involve a diverse set of stakeholders—owners, users, designers (architects, engineers, interior designers), general contractors, subcontractors, skilled tradespeople, manual laborers, suppliers, manufacturers, and operators, as well as regulators, financing institutions, legal representatives, insurance and bonding companies, and others. Each of these groups comes to a project from a different discipline and has its own objectives as it participates in the project.

Every construction project is initiated by an “owner,” which may be a government entity, a corporation, or an individual. Even though most owner organizations typically outsource the design and construction of a capital facility to architectural and engineering construction firms, the owner organization ultimately is responsible for the successful completion of the project and has the greatest stake in its outcome. A “smart” owner of capital facilities has been defined as one that has the skill base necessary to plan, guide, and evaluate the facility acquisition process (NRC, 2000). To accomplish this, a smart owner organization must be capable of performing four interdependent functions:

1. *Establishing a clear project scope of work or definition*. Industry research has repeatedly shown that preproject planning (assessing requirements, setting objectives, conceptual planning, and budgeting) has the greatest impact on the outcome of a project (FFC, 2003; CII, 2006).
2. *Translating project objectives into measurable criteria (metrics).* Such criteria can include constraints (budget, delivery schedule, performance specifications) and can be used to determine whether a project is likely to be completed successfully within those constraints.
3. *Monitoring project progress using detailed data collected from the field and aggregated*. The objective is to actively identify and mitigate project risks as they arise.
4. *Providing commitment and stability to ensure the successful completion of a project* (NRC, 2000).

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[8] ACEC is a national association representing more than 5,500 private-sector engineering firms. Additional information is available at http://www.acec.org. Accessed June 17, 2009.

FIGURE 1.1 Examples of on-site construction methods and weather issues. SOURCE: Thomas (2008).

Projects

The construction of capital facilities is a high-stakes, high-risk endeavor that produces long-term, unique, and complex projects. Project costs include those for land acquisition, planning, financing, design, construction, operations (heating, lighting, utilities), maintenance, and repairs. Operations and maintenance costs include energy, water, and other utilities and the replacement of building components and systems as they wear out. The time and funds spent on planning, design, and construction (often referred to as “first” costs) are only a fraction of the total costs and resources (operations, maintenance, repair, and disposal costs) that will be invested in a project over the 30 to 50 years or more during which it is in use.

The standards and regulations—building codes, permitting processes, wage rates—governing the construction of capital facilities vary by the type of project and the jurisdiction in which a project is located. Because most projects are fully constructed on-site (e.g., foundations dug and footings poured, shell and core erected, equipment and furnishings installed), construction schedules, work sequencing, and worker productivity are also affected by local weather conditions and climate (Figure 1.1).

Processes

Taking a construction project from concept to realization involves a complex set of processes, materials, technologies, and regulations and may take from 1 to 5 or more years. Operating conditions and stakeholders may change as the project progresses (FFC, 2007).

Most construction projects are developed in stages: planning, financing, design, engineering, procurement,[9] construction, operations, and maintenance (Figure 1.2). Typically these stages are performed in sequential order, with different parties and disciplines involved at each stage. This level of segmentation limits opportunities for the sharing of expertise across disciplines. Inefficiencies in labor, time, and knowledge management are created as each phase starts and stops and as project responsibilities and information are handed from one group to the next. This way of operating also has implications for the quality of the final project because choices made in the earliest stages of project planning about materials, technologies, and other factors determine the durability, energy efficiency, and total costs of a project for its entire life cycle. The importance of effective planning up front to successful projects is well documented (FFC, 2003; CII, 2006). An essential factor for effective planning up front is bringing the stakeholders from each phase together to agree on a project's objectives and design before construction begins.

As a project progresses from planning through design and construction to operations, its associated risk also shifts among general contractors, subcontractors, lending institutions, and others. The one constant is the project owner, who is exposed to risk at every project phase.

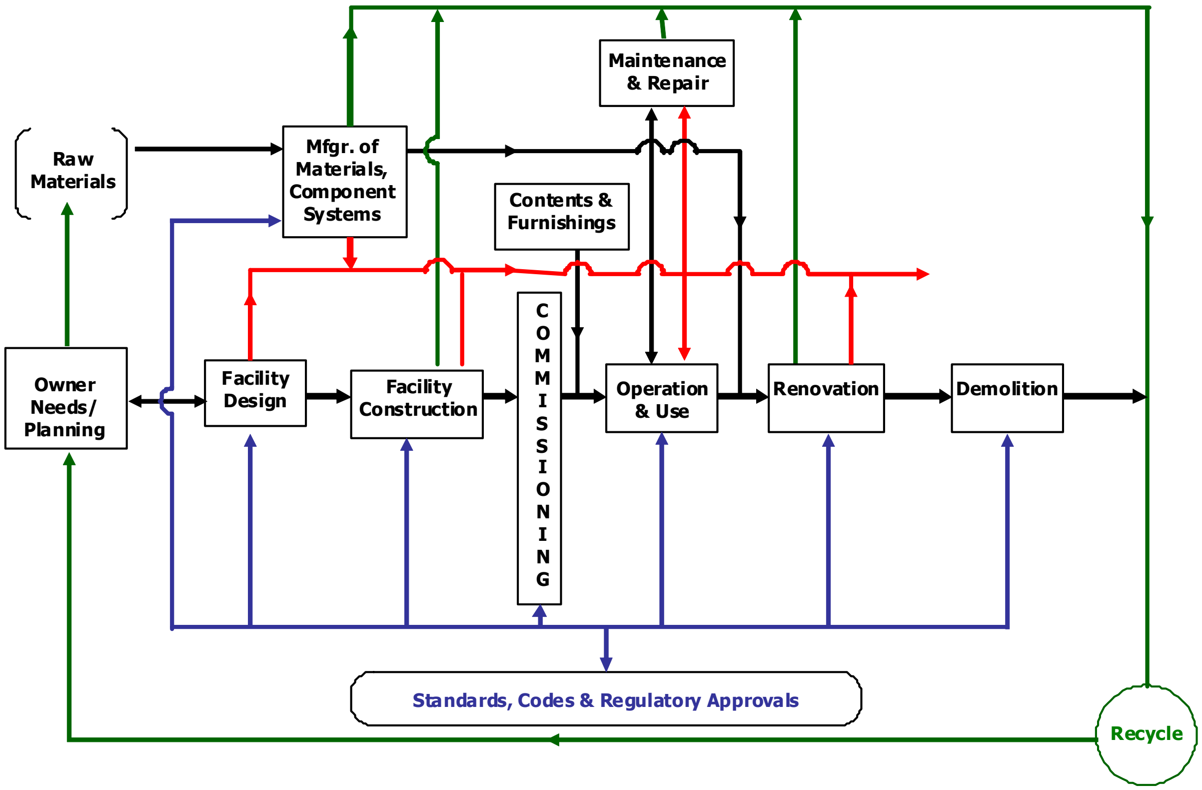

FIGURE 1.2. Construction-related processes. SOURCE: Adapted from presentation "Advancing the Competitiveness and Productivity of the U.S. Construction Industry" to the committee by Dr. Shyam Sunder of the National Institute of Standards and Technology, July 17, 2008.

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[9] *Procurement* can include the acquisition of equipment, materials, or services (e.g., design). Industry and government organizations use an array of contracting methods for procurement, including design-bid-build, design-build, lump-sum contracting, construction manager-general contractor, and public-private partnerships.

Operating Environment

Construction project stakeholders operate in an environment in which there is continual pressure to deliver projects in less time and at lower cost. Given the complexities of delivering a project, the multiplicity of organizations and individuals involved, and the magnitude of the financial risk, it is not surprising that many projects are characterized by an adversarial operating environment that generates disputes and claims over schedule targets, performance guarantees, or deviations from the original contract. The root causes of construction disputes include an inequitable allocation of risk among owners, contractors, and subcontractors; inappropriate contracting strategies; the low-bid process; a lack of alignment among the objectives of the owner, the general contractor, and the subcontractors; inadequate owner involvement; poor communication; poor project management; and fast-track scheduling (FFC, 2007).

Some researchers estimate that the transactional (e.g., litigation) costs for resolving disputes and claims on construction projects range from $4 billion to $12 billion per year (FFC, 2007). Indirect costs include inefficiencies and delays in the process, loss of quality in the project, and poor working relationships among parties who might otherwise profit from continued long-term working relationships (FFC, 2007).

MEASURING CONSTRUCTION PRODUCTIVITY

U.S. industries have experienced almost continuous productivity growth for the past several decades. The one anomaly has been the construction industry, for which overall productivity declined from 1995 to 2001 (Triplett and Bosworth, 2004). For industries other than construction, improved productivity could be attributed to advances in and increased usage of information technologies, increased competition due to globalization, and changes in workplace practices and organizational structures (Triplett and Bosworth, 2004).

Measuring productivity for the construction industry is challenging. Despite its importance to the national economy, there is no official productivity index for this industry. Such indexes are available for manufacturing, agriculture, and other industries that produce outputs that are easily recognizable and measured: for example, numbers of vehicles, tons of steel, or bushels of wheat (Haskell, 2004). In contrast, the highly varying projects that comprise the construction industry's output are difficult to compare and measure even within the industry: for example, imagine comparing single-family houses to roads, schools to bridges, or office buildings to shopping centers. Even comparing the same types of projects—schools to schools, water treatment plants to water treatment plants—is difficult because the characteristics of projects vary by size, region, climate, and other factors. Factors affecting construction and labor productivity include resources (materials, information, tools, equipment, workforce skills, and support services), the quality of on-site supervision, project management, work flow sequencing, weather, and safety.

Industry analysts have reached different conclusions when asked to determine whether construction industry productivity is improving or declining. One analysis of the entire industry (Teicholz, 2004) measured labor productivity as a function of constant contract dollars of new construction work per hourly work hour. The author noted that this measurement indicates that construction projects have required significantly more field work hours per dollar of contract, or more simply, that the construction industry seriously lags other industries in developing and applying labor-saving ideas and in finding ways to substitute equipment for labor (Teicholz, 2004). The author concluded that relative to other industries, productivity in the construction industry as a whole, has been declining for 30 years or longer (Teicholz, 2004) (Figure 1.3). Another author (Harrison, 2007) used a different set of data but reached the same general conclusion, estimating that construction productivity in the United States declined by 1.44 percent annually between 1961 and 2005.

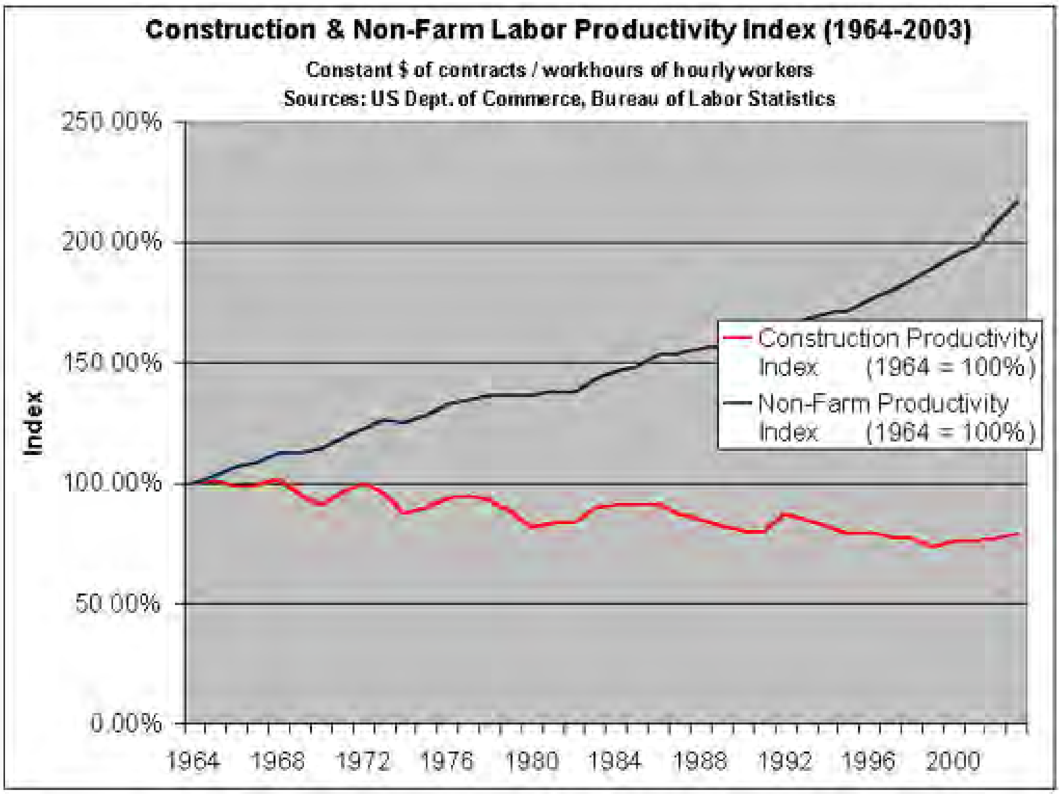

FIGURE 1.3 Labor productivity index for the U.S. construction industry and all non-farm industries, 1964-2003. SOURCE: Teicholz (2004).

However, analysts measuring construction productivity at the project and task levels have reached very different conclusions. Haskell (2004) measured *project-level* productivity using two different methodologies.[10] He concluded that productivity for individual projects increased about 33 percent, or 0.78 percent per year, between 1966 and 2003, and stated:

> We are receiving more building for less money than we did 37 years ago, and moreover, the product is qualitatively superior. These improvements are the result of increased productivity made possible by mechanization, automation, prefabrication, less costly and easier-to-use materials, and lower level of real wages (which, unlike the other drivers, is not a good thing). (Haskell, 2004, p. 8)

Research conducted through the Sloan Center for Construction Industry Studies focused on a wide range of construction-related *tasks*, yet another level of measurement. It examined labor and partial factor productivity trends as part of a larger effort to analyze the relationship between equipment technology and construction productivity (Goodrum and Haas, 2002). The results indicated widespread improvement in construction labor productivity across multiple construction tasks, ranging from 0.2 percent to 2.8 percent per year between 1976 and 1998, especially in machinery-dominated tasks such as site work. A more recent effort to examine the relationship between material technology and construction productivity found that labor productivity improved at an annual compound rate of 0.47 percent between 1977 and 2004 (Grau et al., 2009).

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[10] The first methodology is based on outputs in which real costs, as measured by dollars per square foot for several building types and adjusted for enhancements in quality and content, are compared for the period 1966 to 2003. The second methodology constructs a model based on observable changes in labor productivity at the task level and changes in the costs of materials, tools, and equipment used at the job site (Haskell, 2004).

These contradictory findings about the direction of construction productivity stem primarily from (1) variations in the definitions and measures for productivity, (2) the level at which productivity is measured (industry, project, or task), and (3) the diversity of construction projects, their functions, and costs. One common point of agreement is that there is significant room for improvement in the costs, schedules, quality, and safety of construction projects of all types.

STATEMENT OF TASK

In 2008, the National Institute of Standards and Technology[11] requested that the National Research Council (NRC) appoint an ad hoc committee of experts to plan and conduct a workshop to identify and prioritize technologies, processes, and deployment activities that have the greatest potential to advance significantly the productivity and competitiveness of the capital facilities sector of the U.S. construction industry in the next 20 years. The *capital facilities sector* is defined as commercial (including high-rise and multifamily residential), industrial, and heavy construction (infrastructure) projects. The report, therefore, does not address single-family and low-rise residential projects, a sector of construction that produces a significant portion of the total construction put in place annually and which is predominantly composed of firms with fewer than 10 workers (CPWR, 2007).

The 10 members of the Committee on Advancing the Competitiveness and Productivity of the U.S. Construction Industry established by the NRC have expertise in the U.S. construction industry, construction methods and project delivery, construction research and materials, large-scale engineering, construction economics, global markets and competitiveness, innovative technologies, fabrication processes, information technology, project and supply chain management, and productivity measurement and performance metrics. They have extensive work experience in industry, government, and academia (Appendix A presents biosketches of the committee members).

The committee held its first meeting in Washington, D.C., on July 17 and 18, 2008. Its second meeting, which included a 2-day workshop with other industry experts, was held on November 19-20, 2008, in Washington, D.C. (Appendix B provides the workshop agenda and list of participants). In preparation for the workshop, the committee commissioned three white papers by leading industry researchers: “An International Perspective on Construction Competitiveness and Productivity,” by Carl Haas (presented in Appendix C); “Technical Change and Its Impact on Construction Productivity,” by Paul M. Goodrum (presented in Appendix D); and “Creating and Cultivating the Next Generation of Construction Professionals,” by Jeffrey S. Russell (presented in Appendix E). The committee’s third meeting was held on February 3, 2009, in Irvine, California.

The committee’s conclusions and recommendations are based on its three meetings, including the workshop; on published materials, including the white papers that it commissioned; on several conference calls among committee members and staff; and on the expertise of its members.

Chapter 2 addresses four obstacles to improving productivity that are most relevant to the committee’s task: limited use of automated equipment and information technologies; attracting and retaining skilled workers and recent graduates; lack of performance measures; and a lack of research. Chapter 3 identifies five activities that the committee believes have the potential to create breakthrough improvements in construction efficiency and competitiveness in the next 2 to 10 years. Chapter 4 presents the committee’s recommendations for implementing these activities in order to improve efficiency and competitiveness of the capital facilities sector of the U.S. construction industry.

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[11] NIST’s mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. Additional information is available at http://www.nist.gov. Accessed September 15, 2008.

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Obstacles to Improving Construction Productivity

Improving the productivity of the U.S. construction industry is a long-standing issue and the subject of numerous studies. The 1983 report of the Business Roundtable entitled *More Construction for the Money* (BRT, 1983) identified an array of obstacles hindering productivity:

- Adversarial relationships between owners and contractors, management and labor, union and open-shop workers, business and government;
- The lack of accurate information about the industry, its projects, and its labor supply;
- Poor safety performance;
- Undertrained foremen and poor job-site management;
- A lack of training and education for the workforce;
- Disinterest in adopting new technologies and a slow pace of innovation;
- The lack of management systems;
- Collective bargaining agreements and labor practices; and
- Government regulations, including building code administration.

The same Business Roundtable report presented 225 recommendations for overcoming the identified obstacles and for saving at least $10 billion annually (1983 dollars) (BRT, 1983). The majority of recommendations involved improving various aspects of project management, including planning, communications, supervision, and personnel and manpower practices. The report also concluded:

> Only if the owners who pay the bills are willing to take the extra pains and pay the often small cost of more sensitive methods will they reap the benefit of more construction for their dollars. (BRT, 1983, p. 14)

A 1986 report of the National Research Council (NRC) entitled *Construction Productivity: Proposed Actions by the Federal Government to Promote Increased Efficiency in Construction*, concluded that research and development (R&D)[1] "can help improve productivity, and that construction-related R&D investments have been inadequate in the United States" (NRC, 1986, p. 55).

In 1995, the National Science and Technology Council (NSTC) published a report entitled *Construction and Building: Federal Research and Development in Support of the U.S. Construction Industry.* The authors envisioned a "competitive U.S. industry producing high quality, efficient, sustainable, and hazard resistant constructed facilities" (NSTC, 1995, p. 2). They posited that by making technologies and best practices available for general use by the construction industry, it would be possible to construct better facilities and improve the health and safety of the construction workforce. Five of that report's proposed goals were as follows:

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[1] The term *R&D* included investigations and studies dealing with technology, management, administration, cost control, and other nontechnical subjects (NRC, 1986, p. 55).

- Fifty percent reduction in delivery time;
- Fifty percent reduction in operation, maintenance, and energy costs;
- Fifty percent less waste and pollution;
- Fifty percent more durability and flexibility; and
- Fifty percent reduction in construction work illnesses and injuries (NSTC, 1995).

Some of the obstacles to improved productivity identified in the 1983 Business Roundtable report and listed above persist, while others have been mitigated through changes in the operating environment. A key message of the present report is that advances in available and emerging technologies offer significant opportunities to improve construction efficiency substantially in the 21st century and to help meet other national challenges, such as environmental sustainability.

Chapter 2 focuses on four long-standing obstacles to construction productivity that are most relevant to the task of the NRC's Committee on Advancing the Competitiveness and Productivity of the U.S. Construction Industry: limited use of automated equipment and information technologies, attracting and retaining skilled workers and recent graduates, the lack of effective performance measures, and a lack of research.

LIMITED USE OF AUTOMATED EQUIPMENT AND INFORMATION TECHNOLOGIES

Automated Equipment

Manufacturing and other industries have realized significant improvements in productivity through automation and greater use of information technologies. Seeking to apply these lessons to construction, large Japanese construction companies invested significant resources to automate and integrate some construction-related tasks in the 1980s and 1990s. They attempted to completely automate and integrate processes and technology, using modularization, just-in-time delivery, robotics, rigid supply chain management, and innovations in connections and assembly methods (in Appendix C, see the subsection entitled "Japan"). Integrated automatic systems composed of numerous robots and other automated components were used to construct steel and reinforced-concrete high-rise buildings, among other tasks. In this Japanese experience, the costs of buying and using some of these technologies were much higher than the costs of using existing practices. As a consequence, robotics and other types of automated systems were not adopted by the industry and are used infrequently.

In the United States, the construction industry still relies heavily on manual methods of placement and assembly. The lack of automated technologies can be attributed to a range of factors, including:

- Building codes that allow little room for experimentation or innovation in construction technologies;
- The unsuitability of conventional manufacturing processes for construction materials;
- The operating environment of construction projects (exposure to rain, wind, debris, dust, and so on), which is hostile to automated machinery;
- Conventional design practices;
- Significantly smaller product batch sizes as compared with those of industries such as manufacturing;
- The high investment up front and maintenance costs of automated equipment; and
- Increased labor costs for operators and maintenance crews of automated equipment.

Despite these obstacles, some advances have been made in construction equipment, in materials-handling systems, and in the development of secondary components, such as windows, or the in-factory production of prefabricated structures. Examples of the types of activities for which available, automated equipment and other technologies can be used on construction projects include the following:

- *Excavation and earthmoving operations.* "Stakeless" earthmoving refers to the use of automated construction equipment (e.g., bulldozers) that can be remotely operated and can use global positioning systems (GPS) and onboard computer technologies. Such equipment can be effective in the excavation and compaction of soils and in paving, because such work areas are often exposed and spread out. Some studies estimate that automated construction equipment can reduce costs and improve productivity by 50 percent for excavation and earthmoving tasks (Purdue University, 2009). Such technologies are being used by large contractors.
- *Trenchless technologies***.** These include a large family of methods used for installing and rehabilitating underground utility systems with minimal surface disruption and destruction resulting from excavation.
- *The placement and finishing of concrete and masonry*. Programmable pumps, automated horizontal distributors, and conveyor systems can be effective in the conveyance of concrete. Once the concrete is in place, a variety of technologies are available to perform vibrating, leveling, screeding, cleaning, cutting, and finishing activities. Mobile bricklaying and robotic masonry block installation machines can provide accurate and efficient placement of masonry units, minimizing common risks to worker safety and health while maintaining production.
- *Fabrication and erection of structural steel*. Remotely controlled handling of structural steel provides accurate and efficient movement of steel into place. When welds are needed, automated systems are available to produce high-quality welds at an efficient pace for some types of construction.
- *Fabrication and installation of concrete and steel pipe*. Directional boring equipment is available for installing underground utilities without digging a trench. When large diameter concrete pipe is to be placed, automated pipe-laying systems are available to reduce greatly the exposure of workers to trench cave-ins. Orbital welding allows for the efficient and accurate welding of pipe, resulting in better quality and fewer unsatisfactory welds.
- *Painting and coatings*. Automated technologies can be used to apply paint and coatings to work spaces and areas that may be inaccessible to workers. Such equipment can lessen workers' exposure to unsafe work conditions and hazardous materials and concurrently improve the quality of the application.
- *Finishes.* Wallboard, prefabricated partitions, millwork, and other finish materials can often be manipulated and installed using automated equipment. Such equipment allows for accurate and efficient installation without exposing workers to heavy lifting and ergonomic impacts.
- *Site inspection and surveying.* Remotely controlled site inspection and surveying equipment can provide accurate information about work spaces and areas that are often inaccessible to workers, such as bridge decks and framing, confined spaces, and deep excavations. In addition to enhancing worker safety, these technologies can provide more accurate information about site conditions, such as the inside of pipes and containment structures.

To date, available automated equipment, prefabricated components, and other innovations have been used primarily by large construction companies on industrial and infrastructure projects. Their widespread use by contractors for commercial projects has been hampered by a number of factors, including the costs to own, lease, or operate automated equipment; the limited availability of some automated equipment; and conventional design practices that typically do not consider the use of automated equipment during preproject planning.

Information Technologies

Major industries other than construction have improved their productivity through the use of information technologies. These include modeling techniques and processes that integrate design, production, and operations activities (interoperability). In the automotive industry, for example, designers first develop virtual models and digital databases for vehicles, complex projects that involve numerous interrelated systems, a variety of materials, and a range of designers, engineers, suppliers, and constructors. Virtual models are used to identify potential design and engineering problems and to fix those problems before any actual product assembly takes place. The virtual models are directly linked to databases containing “intelligent” information (i.e., data that will change in response to changes in the virtual models). Some of the benefits of these models are better data for real-time decision making, improved design quality, shorter delivery times, and the reduction or elimination of rework after assembly has begun (Jones, 2009).

A variety of software applications and information technologies have been developed to support interoperability (also called Building Information Modeling, BIM) within the construction industry. Among these are the following:

- *Virtual design models.* These models are used to visualize and plan for architectural, structural, mechanical, and site components. Three-dimensional virtual models can be used to detect potential design omissions so that they can be fixed before actual construction begins. This is important because the total costs of a project and the time to delivery can increase significantly when design errors or omissions must be fixed in the field.
- *Energy models.* These models are used to optimize the design for heating, cooling, ventilation, and lighting within a building.
- *Construction and scheduling models.* These models provide for the efficient sequencing of project-related activities, work crews, equipment, materials, and supplies.
- *Cost estimating models.* These models can be linked to various building components, offering the opportunity for consideration of the cost implications of using different materials, equipment, and construction techniques in the planning stage. They can also be used in a later phase of a project to respond to changing conditions. For example, if a project is running over budget, such a model could be used to determine whether less expensive materials or other components could be substituted to save money.
- *Ingress and egress models.* These models allow a designer to populate a building virtually in order to plan for the most efficient activity flows, use of space, equipment placement, and evacuations during emergencies.
- *Supply chain management technologies.* Examples include radio-frequency identification (RFID) tags to track materials as they leave suppliers’ premises or to locate them on-site.
- *Laser scanning*. Laser scanning for existing structures is used to create virtual models that can be used for life-cycle management.

BIM has been used for industrial projects for some time. A growing number of architectural and engineering firms are developing interoperable applications for other types of projects. However, the use of BIM applications varies significantly among architects, engineers, general contractors, and subcontractors (Jones, 2009). The applications and technologies are only rarely integrated across all phases of a project, and thus their benefits are not fully optimized. In addition, barriers remain in developing fully operable systems, including legal issues, data-storage capacity, and the ability to search thousands of data items quickly to support real-time decision making. The lack of interoperability within the capital facilities sector of the construction industry has been estimated to result in $15.8 billion in inefficiencies and lost opportunities every year (NIST, 2004).

ATTRACTING AND RETAINING SKILLED WORKERS AND RECENT GRADUATES

The typical image of the construction workforce is that of people working in the field on a construction project: equipment operators; concrete workers, ironworkers; carpenters, electricians, drywall installers, masons, and other craftspersons; project managers and foremen; and manual laborers. However, the planning, design, construction, and operation of capital facilities and infrastructure also involve many skills and disciplines not typically thought of as applying to “construction work”: planners, architects, engineers, interior designers, furnishing and materials suppliers, and project owners.

Attracting and retaining skilled craftspersons and foremen, engineers, and project managers are long-standing issues within the construction industry. The challenge of workforce recruitment is rooted in the image of the industry: To the casual observer, construction work appears to be physically exhausting, low-tech, dangerous, and tedious (BRT, 1983).

The construction industry is, in fact, one of the most dangerous industries for workers in the United States, with the fourth-highest rate of fatalities in 2005 (after agriculture, mining, and transportation) and the second-highest rate of nonfatal injuries and illnesses (after transportation) (CPWR, 2007).[2] In 2007, the death rate of construction workers from work-related causes was nearly three times that of full-time workers in other industries. In 2005, construction workers experienced about 76 percent more days away from work owing to injuries or illnesses than did workers in other industries (NRC, 2009).

Nonetheless, these numbers represent significant improvements in construction safety. Between 1992 and 2005, construction-related fatalities declined by more than 22 percent overall. The rate of injuries and illness also appears to have dropped significantly, possibly by a factor of two, although measurements are difficult because of the segmented nature of the industry. The driving force behind these improvements were project owners that demanded improvements of their contractors and changed the culture from one which accepted that “Construction is inherently dangerous—accidents happen” to one in which there is a belief that “Zero accidents are achievable” (NRC, 2009). The owners’ efforts were aided by improved equipment and research conducted by the National Institute for Occupational Safety and Health and others (NRC, 2009).

The low-tech image of the construction industry is a deterrent to the recruitment and retention of skilled workers and of recent graduates in engineering and project management who are essential to the successful development of capital facilities projects (see the discussion in Appendix E). A shortage of skilled workers in construction is particularly problematic for the future. The U.S. Department of Labor’s Bureau of Labor Statistics (BLS) has projected that 780,000 new construction jobs will be created between 2006 and 2016 (BLS, 2007), a pace of about 1 percent per year.[3] The demand for construction workers will be driven in part by demands for energy, transportation, clean drinking water, and safe wastewater removal, and for new buildings to support commerce, education, recreation, and a growing population. By 2030, the U.S. population is projected to grow by 30 million people (U.S. DOC, 2009), all of whom will require shelter, workplaces, schools, and the services provided by infrastructure systems: power, water, connectivity, and mobility. Unless enough skilled workers and recent graduates can be attracted to and retained by the construction industry, or unless new labor-saving technologies are used by a majority of large firms, it will be difficult for U.S. companies to meet future demands for construction projects efficiently.

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[2] Hazards for construction workers include working at heights, in excavations and tunnels, on highways, and in confined spaces; exposure to high levels of noise, to chemicals, and to high-voltage electric lines; and the use of power tools and heavy equipment. Significant health risks include hearing loss, silicosis, musculoskeletal disorders, skin diseases, and health effects associated with exposures to lead, asphalt fumes, and welding fumes (NRC, 2009).

[3] This compares with declines of 1.1 percent per year for jobs in manufacturing and 0.6 percent per year for utilities, and increases of 0.7 percent and 0.4 percent per year for wholesale and retail trade, respectively (BLS, 2007).

LACK OF EFFECTIVE PERFORMANCE MEASURES

Metrics and performance measures are enablers of innovation for industries and for individual companies. The importance of metrics to improved productivity is captured in the often-repeated phrase “You can’t improve what you don’t measure.” One method used by industries to measure changes in productivity and efficiency is to set benchmarks by collecting data for various facilities, processes, and practices.

In the automotive industry, for example, an annual report by Harbour Associates measures various automotive plants using statistical sampling techniques. The resulting statistics and metrics are made available to all automobile manufacturers so that they can compare the efficiency of their plants and processes with the efficiency of their competitors and see where they need to improve. Through this benchmarking program, General Motors, for instance, was able to cut the number of hours that it took to produce a vehicle by 30 percent between 1998 and 2006. Similar levels of improvement have been achieved at other companies. The Harbour report has become a source of performance measures and benchmarks for vehicle manufacturers around the world.

Construction firms do not have a single source of metrics for comparing the efficiency of their projects and processes, or for assessing their competitive position. Various data are gathered by a number of public- and private-sector organizations to measure construction productivity at the industry, project, and task levels. However, the definitions and measures for productivity vary. Some of the conflicting findings about the direction of construction productivity among industry-level, project-level, and task-level data may also be related to the accuracy of industry measures, in particular to the inflation indexes used to measure industry real output (see the section entitled “Introduction” in Appendix D).

As noted in Chapter 1, there is no single, official index or measure for the productivity of the construction industry. Factors that contribute to this situation include the lack of adequate data, the lack of consensus on appropriate measurement techniques, and the lack of consensus on the value of these measures. The BLS, for example, bases productivity measures for many industries on labor productivity as the ratio of the value of output produced for sale to labor hours worked. Although data for the labor hours worked in construction are available, the BLS does not produce productivity measures for construction because there is no consensus on how to determine the output for sale (e.g., square feet of office space, number of residential units, miles of road paved).

Productivity-related data for construction are also collected by the U.S. Census Bureau, which conducts an economic census every 5 years. The census includes data for *value of construction work* (defined as value of construction produced for sale) and *value added by industry* (defined as value of construction minus the costs related to subcontracts and materials used). The U.S. Census Bureau also publishes the monthly *Construction Reports Series C30*, which contains several measures of construction, including the *value of construction put in place* (defined as a measure of the value of construction installed or erected at the site during a given period) by type of construction (e.g., commercial, industrial). Using these two federal databases to measure industry-level productivity is difficult because the BLS data are categorized using the North American Industry Classification System (NAICS), but the U.S. Census Bureau’s data are not.

Project-level metrics can be used to measure how an individual project compares with other, similar projects (e.g., other school buildings, other oil refineries, other power plants) in terms of total cost, delivery time, labor hours, or other factors. Project-level data are a function of individual components (e.g., materials, systems), processes (e.g., type of contract, type of project delivery system), and tasks. Some project owners and contractors collect this level of data, but the information is not always shared with competitors, making it difficult to establish benchmarks for the entire industry.

One venue where project-level information is shared is the Construction Industry Institute (CII). CII collects project-level data from its member companies as part of its benchmarking and metrics program. Participating CII members have access to that database, which they can use to benchmark their projects against other companies (the data are “scrubbed” to delete company and project names). CII allows nonmember companies access to these data at a nominal fee. Similarly, the private-sector firm

Independent Project Analysis (IPA) collects proprietary, project-level data that can be used by clients willing to pay for it.

Task-level metrics are leading indicators and are commonly used by contractors and subcontractors who must evaluate the efficiency of their workforces on a daily or weekly basis and make adjustments so that problems on active projects can be detected and corrected quickly. Tasks refer to specific construction-related activities, such as the placement of concrete or the installation of mechanical systems. Most task-level metrics include explicit measures of output for specific tasks and the labor hours required to complete the task. CII also collects task-level data for participating firms. These metrics are collected for actual projects and undergo validation checks to improve their accuracy. Such data are available to nonmember companies for a fee.

Estimation manuals containing task-related data are published for sale by the R.S. Means Company. These manuals often focus on how much of a given output is produced by a work crew in an 8-hour period. The estimates are based on data collected for construction projects in various cities across the country and are not considered to be as accurate as task-level data collected by individual construction firms (see the discussion in Appendix C). Owners, contractors, and subcontractors are most likely to use these estimation manuals when they do not already have data based on their own projects.

LACK OF RESEARCH

The U.S. construction industry does not have an industry-wide research agenda that identifies or prioritizes research areas with the most potential for improving its productivity, its competitiveness, or its efficiency. This lack is in contrast to the case in other developed countries. South Korea, for instance, has a national technology research program focusing on construction automation. The European Union has several construction management and technology initiatives under way with the purpose of driving innovation. Sweden, Japan, Canada, and the United Kingdom also have major ongoing initiatives for construction-related research (see Appendix C). Whether these strategies will result in a greater share of the global market is not yet known, but if successful, they will likely make foreign construction firms more competitive with U.S. firms when bidding for both domestic and international projects.

Estimates of the total amount of money being invested in construction-related research in the United States are difficult to come by owing to the fragmentation of construction-related research. Basic and applied research are being conducted by a few large owners, a few large construction companies, construction suppliers, equipment manufacturers, universities, professional societies and industry organizations (e.g., CII, the Construction Users Roundtable), and some government agencies (e.g., National Institute of Standards and Technology, the Department of Defense, the National Institute for Occupational Safety and Health and the National Science Foundation). A 1994 study reported that all key construction industry stakeholders combined invested in R&D at a rate that was equal to 0.5 percent of the value of construction put-in-place (CERF, 1994). This would translate to about $5.5 billion in 2005. To put this amount in perspective, private-sector investments in R&D for manufacturing, an industry roughly 2.5 times the size of construction, were 25 times higher, at nearly $143 billion, in 2006 (NSF, 2008).

The level and fragmentation of construction research funding also means that few organizations can single-handedly take on research projects that involve more than a few million dollars. The lack of an industry-wide strategy to coordinate and prioritize research activities quite likely means that those research dollars and resources that *are* available are being suboptimized.

3

Opportunities for Breakthrough Improvements in the U.S. Construction Industry

As pointed out in Chapter 1, the commercial, industrial, and heavy construction sectors are stratified and differ from each other in terms of the characteristics of project owners, their sophistication, and their involvement in the construction process; the complexity of the projects; the source and magnitude of financial capital; required labor skills; the use of specialty equipment and materials; design and engineering processes; and knowledge and other factors. Nonetheless, these sectors also share common issues and obstacles to improving construction productivity, including the following:

- A diverse and fragmented set of stakeholders: owners, users, designers, builders, suppliers, manufacturers, operators, regulators, manual laborers, and specialty trade contractors, including plumbers, electricians, masons, carpenters, and roofers;
- Segmented processes: planning, financing, design, engineering, procurement, construction, operations, and maintenance. Each process is typically performed sequentially and each involves different groups of stakeholders, shifting responsibilities, and shifting levels of financial risk, which in turn often leads to adversarial relationships, disputes, and claims;
- The image of the industry—work that is cyclical, low-tech, physically exhausting, and unsafe—which makes it difficult to attract and retain skilled workers and recent graduates;
- The one-of-a-kind, built-on-site nature of most construction projects;
- Variation in the standards, processes, materials, skills, and technologies required by different types of construction projects;
- Variation in the building codes, permitting processes, and construction-related regulations propagated by states and localities;
- The lack of an industry-wide strategy to improve construction efficiency;
- The lack of effective performance measures for construction-related tasks, projects, and the industry as a whole; and
- The lack of an industry-wide research agenda and levels of funding for research that are inadequate.

In an industry of thousands of small establishments, an array of stakeholders, dynamic processes, diverse products, and no overall strategy or research agenda, three major issues arise:

1. Identifying the technologies, processes, materials, or other actions that can result in the greatest benefits to the industry as a whole;
2. Determining who should be responsible and accountable for driving change and improving productivity; and
3. Mitigating the risks to owners, clients, contractors, and suppliers from using innovative technologies, materials, and processes.

This chapter identifies and discusses the activities that could result in breakthrough improvements in efficiency and competitiveness for the construction industry and activities for mitigating the innovation-related risks to stakeholders.

IDENTIFICATION OF ACTIVITIES THAT COULD LEAD TO BREAKTHROUGH IMPROVEMENTS

As indicated in Chapter 1, the specific task of the Committee on Advancing the Competitiveness and Productivity of the U. S. Construction Industry was to plan and conduct a workshop to identify and prioritize technologies, processes, and deployment activities which have the greatest potential to significantly advance the productivity and competitiveness of the capital facilities sector of the U.S. construction industry in the next 20 years.

Because the concept of *productivity* can be difficult to define, measure, and communicate, the committee determined that it would focus on ways to improve the *efficiency* of the capital facilities sector. It defines *efficiency improvements* as ways to cut waste in time, costs, materials, energy, skills, and labor. Studies focusing on efficiency within the construction industry have documented 25 to 50 percent waste in coordinating labor and in managing, moving, and installing materials (Tulacz and Armistead, 2007); losses of $15.6 billion per year due to the lack of interoperability[1] (NIST, 2004); and transactional costs of $4 billion to $12 billion per year for resolving disputes and claims associated with construction projects. The committee believes that improving efficiency will also improve overall productivity and help individual construction firms produce more environmentally sustainable projects and become more competitive.

To help determine which activities offer the greatest potential for resulting in breakthrough improvements, the committee first identified the attributes that would characterize an efficient capital facilities sector of the U.S. construction industry:

- Production of quality products that meet owners’ and the nation’s needs;
- Competitiveness in the global marketplace;
- Well-integrated processes, supply chains, and work flows;
- Promotion of sustainability through the efficient use of time, materials, skills, and dollars;
- Attractiveness to a diverse, well-trained, knowledgeable, professional, skilled labor force able to work collaboratively to meet owners’ and clients’ objectives;
- Ability to adapt to new conditions and to deploy new technologies effectively;
- Use of best practices to reduce rework and delivery time, and to improve job-site safety and project quality; and
- Measurement of performance to enable innovation and improvements in products and processes.

The committee and the industry experts who participated in the 2-day workshop conducted by the committee identified many actions that could be taken to move toward an efficient capital facilities sector. The committee narrowed these possibilities down to five interrelated activities that it believes have significant potential to lead to breakthrough improvements in efficiency and competitiveness for capital facilities construction in 2 to 10 years, in contrast to 20 years, as follows:

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[1] *Interoperability* is the ability to manage and communicate electronic data among owners, clients, contractors, and suppliers, and across a project’s design, engineering, operations, project management, construction, financial, and legal units.

1. Widespread deployment and use of interoperable technology applications, also called Building Information Modeling (BIM).
2. Improved job-site efficiency through more effective interfacing of people, processes, materials, equipment, and information.
3. Greater use of prefabrication, preassembly, modularization, and off-site fabrication techniques and processes.
4. Innovative, widespread use of demonstration installations.
5. Effective performance measurement to drive efficiency and support innovation.

Discussed individually in the major sections below, the five activities are interrelated, and the implementation of each will enable that of the others. For example, the widespread deployment of interoperable technologies will help to improve the supply chain management that is essential to the improvement of job-site efficiency and the greater use of preassembled components. Similarly, greater use of demonstration installations will help to mitigate the risk associated with new technologies, materials, and processes. Effective performance measures will help document which innovations result in improved efficiency and productivity and will help to build a “business case” for using such innovations throughout the industry. It cannot be stressed too strongly that finding ways to attract and retain skilled workers and recent graduates will be essential to achieving success.

The committee believes that implementing these five activities for capital facilities and infrastructure will help to achieve the following:

- Overcome fragmentation by requiring greater collaboration up front among project stakeholders;
- Lead to more efficient use and better integration of people, processes, materials, and equipment through all phases of a construction project; and
- Create more useful and more accurate information for the development of performance measures that can facilitate innovation in technologies and materials and improvement in products and processes.

WIDESPREAD DEPLOYMENT AND USE OF INTEROPERABLE TECHNOLOGY APPLICATIONS

Interoperability is the ability to manage and communicate electronic data among a project’s owners, clients, contractors, and suppliers, and across a company’s design, engineering, operations, project management, financial, and legal units. As noted in Chapter 2, a range of modeling, virtual design, and other technologies for construction-related processes are already available and are often referred to as Building Information Modeling. Such models have been used for industrial projects for some years, and they are now being applied to some commercial projects.

To support the deployment of interoperable technologies, the consortium named FIATECH[2] has developed an industry road map. Similarly, the buildingSMART Alliance of the National Institute of Building Sciences (NIBS)[3] is developing open, national standards for data input and analysis. And the

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[2] FIATECH is a consortium of industries and companies whose objective is to make a step-change improvement in the design, engineering, construction, and maintenance of large capital assets. Additional information is available at http://www.fiatech.org. Accessed February 4, 2009.

[3] NIBS was authorized by the U.S. Congress in the Housing and Community Development Act of 1974 (Public Law 93-383). The institute’s public interest mission is to serve the nation by supporting advances in building science and technology to improve the built environment. Additional information is available at http://www.nibs.org. Accessed February 4, 2009.

American Institute of Architects (AIA)[4] has developed an *Integrated Project Delivery Guide* to help owners, designers, and builders use interoperable techniques.

Thus, the committee believes that many of the pieces needed to deploy interoperable technologies throughout the capital facilities sector of the construction industry already exist or are in development. With a concerted effort, those challenges that remain—for example, data storage and retrieval, application development, legal constraints, the development of intelligent searching capabilities—can be solved in 2 to 5 years.

Interoperability is more than the automation of current work processes—that is, more than just doing the same things that are done at present only faster. Interoperable technologies and applications change work processes and the relationships among project owners, clients, contractors, and subcontractors. Effective use of these technologies and applications requires collaborative planning up front among owners, designers, and contractors. Collaboration in the early stages of planning, in turn, can improve the integration of what are now fragmented processes, help fix problems in the “virtual” phase before significant resources have been invested in physical structures, and lead to less rework in the field and less waste of materials, labor, and time.

The linking of virtual models to intelligent databases is especially important because the design and construction of a single capital facility or infrastructure project typically involves hundreds or even thousands of documents—drawings, physical models, plans, details of mechanical systems, contracts, budgets, construction specifications, building codes, product descriptions, and others. Digital databases provide a platform for improving design quality, reducing errors and omissions, and reducing costs. Having a common set of real-time information accessible to project owners, contractors, subcontractors, project managers, and other involved parties saves time, improves communication, and reduces errors caused by conflicting information in individual documents or applications. Such databases also provide long-term benefits: The “as-built” information related to a completed project can provide valuable data for operating and maintaining it for 30 or more years.

Through more collaborative processes and an emphasis on planning up front, interoperable technology applications can help to improve the quality and speed of project-related decision making; integrate processes, supply chains, and work flow sequencing; improve data accuracy and reduce the time spent on data entry; and reduce design and engineering conflicts and the subsequent need for rework.

IMPROVED JOB-SITE EFFICIENCY THROUGH MORE EFFECTIVE INTERFACING OF PEOPLE, PROCESSES, MATERIALS, EQUIPMENT, AND INFORMATION

The job site for a large construction project is a dynamic place, involving numerous contractors, subcontractors, tradespeople, and laborers, all of whom require equipment, materials, and supplies to complete their tasks. Managing these activities and demands to achieve the maximum efficiency from the required resources is difficult and typically not done well.

The difficulty of attracting and retaining experienced project foremen, project managers, engineers, and skilled tradespeople to construction is a well-documented issue that may be exacerbated in the future. Shortages of trained and educated workers could prove to be a significant obstacle not only to improved construction productivity but also to national efforts focused on infrastructure renewal, environmental sustainability, and global climate change.

Greater use of automated equipment at the job site offers an opportunity to conduct some construction-related tasks more efficiently, with fewer people, as long as those people are adequately trained. To date, a primary obstacle to more widespread use of automated equipment is the segmentation of planning, design, procurement, and construction processes: The improved productivity benefits that could result from the effective use of automated equipment will be fully realized only through

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[4] The AIA is the leading professional membership association for licensed architects, emerging professionals, and allied partners. Additional information is available at http://www.aia.org. Accessed February 4, 2009.

FIGURE 3.1 Examples of poorly managed job sites. SOURCE: Thomas (2008).

collaborative planning up front that involves the project owner, designers, contractors, and subcontractors. The Construction Industry Institute (CII) has developed a checklist for the use of automated equipment in the design process that would help overcome this obstacle (Purdue University, 2009).

Time, money, and resources are wasted on a project in situations such as these:

- A project is poorly managed and its workers must wait around for the tools, supplies, materials or equipment, or instructions needed to do their jobs;
- Work crews' schedules conflict;
- Work crews are not on-site at the appropriate time;
- Work areas are overcrowded; and
- Materials, supplies, and equipment are stored haphazardly, cannot be easily located, and must be moved several times (Figure 3.1).

Greater use of information technologies at the job site for supply chain management and other uses could significantly cut waste related to time, materials, and labor and improve the quality of projects. Relevant technologies in widespread use include radio-frequency identification (RFID) tags that can be used for the tracking of materials, and personal digital assistants (PDAs) that project managers and others can use to input data from the field into a common digital database. Technologies are also available to help with more efficient procurement of materials and supplies in order to improve supply management and delivery and to eliminate the need for some on-site storage.

Having real-time project information available to owners, contractors and subcontractors, and tradespeople at the job site could expedite and improve on-site decision making and work sequencing and foster collaborative partnerships. Technologies such as shareware sites (e.g., file transfer protocol shareware), PDAs, and others can be used to collect data developed during construction in order to manage tasks, capture changes, and meet reporting requirements. When organized and used correctly, such technologies can significantly improve job-site efficiency and execution in the field and expedite problem resolution so that projects can continue to progress.

Improved project and job-site management through the effective use of technologies requires well-trained, educated workers who can work collaboratively and communicate effectively and who possess technical knowledge. Traditionally, construction firms have recruited engineering graduates for design and project management positions. As described in Appendix E (see the section entitled "Educational Preparation for the Engineering Professional of Tomorrow"), the National Academy of Engineering, the American Society of Civil Engineers (ASCE), and other organizations have called for major changes in engineering curriculums to provide engineers with the opportunity to develop the skills required to work effectively in the 21st-century operating environment. However, engineers with communication and collaboration skills will likely be in demand by many industries in addition to construction. Construction firms will thus need to compete with other employers and industries whose images and opportunities may be perceived to be superior.

To meet the needs of the construction industry better, some colleges and universities have established programs in construction management and related issues. The ASCE has established a task force to define, recognize, and incorporate engineering paraprofessionals as an important part of civil engineering.[5] And a number of professional societies and construction firms have established mentoring, internship, and awards programs to stimulate the interest of high school students in pursuing a career in construction (in Appendix E, see the section entitled “Recruiting Tomorrow’s Workforce”). All of these initiatives hold promise for creating a professional workforce with the skills to use effectively information technologies and automated equipment that can improve job-site efficiency.

GREATER USE OF PREFABRICATION, PREASSEMBLY, MODULARIZATION, AND OFF-SITE FABRICATION TECHNIQUES AND PROCESSES

Construction workers typically are exposed to high levels of noise, dust and airborne particles, adverse weather conditions, and other factors that can cause fatigue and injuries and thereby reduce efficiency and productivity. New types of equipment can make an activity physically easier to perform, easier to control, more precise, and safer for construction workers. Similarly, changes in materials can reduce the weight of construction components, which in turn can make them easier to handle, move, and install. Manufacturing building components off-site provides for more controlled conditions and allows for improved quality and precision in the fabrication of the component.

Prefabrication, preassembly, modularization, and off-site fabrication involve the assembly or fabrication of building systems and/or components at off-site locations and plants. Once completed, the systems or components are shipped to a construction job site for installation at the appropriate time. One study that examined the relationship between changes in material technology and construction productivity based on 100 construction-related tasks found the following:

- Labor productivity for the same activity increased by 30 percent where lighter materials were used; and
- Labor productivity also improved when construction activities were performed using materials that were easier to install or were pre-fabricated (Goodrum et al., 2009).

Prefabrication and related techniques allow for the following:

- More controlled conditions for weather, quality control, improved supervision of labor, easier access to tools, and fewer material deliveries (CII, 2002).
- Fewer job-site environmental impacts because of reductions in material waste, air and water pollution, dust and noise, and overall energy costs, although prefabrication and related technologies may also entail higher transportation costs and energy costs at off-site locations;
- Compressed project schedules that result from changing the sequencing of work flow (e.g., allowing for the assembly of components off-site while foundations are being poured on-site; allowing for the assembly of components off-site while permits are being processed);
- Fewer conflicts in work crew scheduling and better sequencing of craftspersons;

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[5] ASCE defines *engineering paraprofessional* (EPP) as a position supporting a licensed engineer (LE). The EPP works under the responsible charge of an LE but may exert a high level of judgment in the performance of his or her work. EPPs comprehend and can apply knowledge of engineering principles in the solution of broadly defined problems. EPPs are generally engineering technologists, but engineers, engineer interns, and professional engineers can also provide engineering paraprofessional services. Additional information is contained in Appendix E, in the section entitled “A Greater Role for Paraprofessionals.”

FIGURE 3.2 Example of a prefabricated exterior paneling system. SOURCE: Thomas (2008).

- Reduced requirements for on-site materials storage, and fewer losses or misplacements of materials; and
- Increased worker safety through reduced exposures to inclement weather, temperature extremes, and ongoing or hazardous operations; better working conditions (e.g., components traditionally constructed on-site at heights or in confined spaces can be fabricated off-site and then hoisted into place using cranes) (CURT, 2007).

Prefabrication and related techniques are commonly used in the construction of industrial projects, but they are also used, if less frequently, for commercial and infrastructure projects. Best practices for the use of these technologies have been developed by CII. The committee believes that greater use and deployment of these techniques (if used appropriately) can result in lower project costs, shorter schedules, improved quality, more efficient use of labor and materials, and improved worker safety (Figure 3.2).

INNOVATIVE, WIDESPREAD USE OF DEMONSTRATION INSTALLATIONS

Although automated equipment, prefabricated components, virtual models, information technologies, and other innovations are available, deploying them throughout the capital facilities sector is difficult. Until such innovations have been proven to be “mature,” their use entails new risks that many project owners and contractors are not willing to accept.[6]

Demonstration installations can be an effective approach for mitigating the risks related to using innovative processes, technologies, or products. Demonstration installations provide an environment for testing and verifying the effectiveness and the maturity of new processes, technologies, and materials. Such installations can take a variety of forms: field testing on a job site; construction-related seminars, training, conferences; and scientific laboratories with sophisticated equipment and standardized testing and reporting protocols.

In a broad sense, a demonstration installation is a research and development (R&D) tool that represents one way for the construction industry to address particular problems. For example, an owner or

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[6] A forthcoming report titled *Enhancing Innovation of the EPC Industry: A White Paper* focuses on the mind-set, resources, processes, and operating environments of engineering-procurement-construction (EPC) organizations and their effect on attitudes toward innovation. The report describes two elements required to assist EPC organizations in advancing innovation: (1) an innovation maturity index aimed at the readiness of companies to adopt innovations, and (2) an economic model demonstrating the value of innovation investment (CII, forthcoming).

a contractor who has developed a more efficient way to complete a task could stage a field demonstration for other contractors at the job site. If the demonstration proved effective, other contractors could immediately adopt that method or process (e.g., on-site, vendor-managed supplies).

More elaborate demonstrations may be necessary for the adoption of high-cost, high-risk technologies. For example, robotic devices from different manufacturers could be evaluated in a laboratory where they are required to perform the same operation. Construction processes or equipment could be evaluated in a testbed in which the same operators use different tools to ascertain their efficiency, reliability, and ease of use for a given task.

Federal entities such as the National Aeronautics and Space Administration, the Department of Defense, and scientific laboratories have developed "technology readiness indexes" to evaluate the maturity of high-risk, high-cost, untested technologies for deployment. *Technology readiness indexes* are systematic measurement systems to support the assessment of the maturity of a particular technology and the consistent comparison of maturity among different types of technology (Mankins, 1995).

Typically, for a technology to be considered mature it must have been applied in a prototype, tested in a relevant or operational environment, and found to have performed adequately for the intended application. This sequence implies the need for a way to measure maturity and for a process to ensure that only sufficiently mature technologies are employed. It also provides a basis for an independent, objective evaluation of a new technology.

Box 3.1 provides an example of the definitions for technology readiness levels for one technology readiness index. The committee believes that the development of a similar type of tool for evaluating high-risk, high-cost, or high-impact construction-related technologies could also expedite the deployment of innovations by verifying their maturity and readiness for use by construction firms.

EFFECTIVE PERFORMANCE MEASUREMENT TO DRIVE EFFICIENCY AND SUPPORT INNOVATION

Performance measures are enablers of innovation and of corrective actions throughout a project's life cycle. They can help companies and organizations understand how processes or practices led to success or failure, improvements or inefficiencies, and how to use that knowledge to improve products, processes, and the outcomes of active projects. The nature of construction projects and the industry itself calls for lagging, current, and leading performance indicators at the industry, project, and task levels, respectively, as described below.

Factors in determining how and by whom performance measures should be developed include (1) the availability, time-sensitivity, and accuracy of the data required for developing effective measures; (2) the purposes for which the measures are to be used; and (3) the beneficiaries of their use.

- *Industry-level measures* are needed to determine whether the productivity of the construction industry as a whole is improving or declining over time. Lagging indicators can be used to track industry trends for several years to help identify the root causes of improvement or decline. Information related to root causes in turn can be used to develop industry-wide strategies for improvement, including the improvement of policies, procedures, practices, and research. Industry-level measures can also be used to track the impact of innovations, such as the greater use of prefabricated components, interoperable technologies, and automated equipment.

BOX 3.1
Example of Definitions of Technology Readiness Levels (TRLs) for a Technology Readiness Index

TRL 1—Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

TRL 2—Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL 3—Analytical and experimental critical function and/or characteristic proof-of concept: Proof-of-concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

TRL 4—Component/subsystem validation in laboratory environment: Stand-alone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5—System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

TRL 6—System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

TRL 7—System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

TRL 8—Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space): End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

TRL 9—Actual system "mission proven" through successful mission operations (ground or space): Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

SOURCE: Los Alamos National Laboratory (2009).

Industry-level statistics and measures are of greatest interest and value to federal and other government agencies (e.g., the Department of Commerce, the Department of Labor), to policy makers, and to research-oriented organizations in government, academia, and the private sector. Because these are lagging indicators that are not highly time sensitive, their value to individual project owners and contractors is limited.

At the international level, industry-wide measures could be important in determining the competitiveness of the U.S. construction industry with those in the United Kingdom, Canada, South Korea, or other developed countries. Information about international benchmarking programs and issues related to the development of effective industry-level metrics for different countries are outlined in Appendix C.

- *Project-level measures* are needed to contribute to the understanding of how an individual project compares with other similar projects (e.g., other school buildings, other oil refineries) in terms of total cost, schedule, cost changes, labor hours, and other factors. Such current measures are of greatest interest to owners of multiple projects and to large contractors who are seeking to reduce the costs and delivery time of projects, to improve worker safety, or to initiate some other change in construction-related processes and practices.

Project-level data are a function of individual components (e.g., materials, systems), processes (e.g., type of contract, type of project delivery system), and tasks. Developing effective project-level data is challenging because no two projects are exactly the same, if only because they are located at different sites. Significant variations among project types are the rule. School buildings, for example, differ by the type of school (e.g., elementary, secondary, or high school), by the number of students and teachers, and by the type of the amenities (e.g., gymnasiums, kitchens). For some types of projects, metrics based on total facility cost per square foot or on total installed cost are used. Nonetheless, care must be taken in determining which project parameters should be measured so as to provide the greatest value to individual firms and the industry as a whole.

- *Task-level measures* are leading indicators that are commonly used by contractors and subcontractors that need to evaluate the efficiency of their workforces on a daily or weekly basis so that problems on active projects can be detected and corrected quickly. As noted in Chapter 2, task-level data are collected by contractors, by CII, and by the R.S. Means Company.

4

Implementing Activities for Breakthrough Improvements: Recommended Actions

Implementing the five interrelated activities identified in Chapter 3 by the committee as opportunities for achieving breakthrough improvements in efficiency and competitiveness for capital facilities construction will require a strategic, collaborative, evidence-based approach. It will need to be strategic because no single group of stakeholders or individual organization can drive change through the entire capital facilities sector. The large corporations and government agencies that regularly invest in capital facilities and infrastructure will benefit most directly from improvements in the industry, and they will need to take a leading role if breakthrough improvements are to be achieved.

The approach to implementing the five activities will need to be collaborative in order to overcome fragmentation among stakeholder groups, construction processes, and construction practices if interoperable technologies and prefabricated components are to be used effectively, if job-site efficiency is to be improved, and if appropriate demonstration installations are to be identified and used. Collaboration will also help mitigate the risks and spread the costs and benefits of innovation. Evidence-based best practices and effective performance measures will be needed in order to make a compelling business case for the adoption of new processes and technologies throughout the capital facilities sector.

Many of the ingredients needed for a strategic, collaborative, evidence-based approach are already in place. In some cases, additional research and development will be necessary to fully and effectively implement the identified activities that could result in breakthrough improvements in the next 2 to 10 years.

DRIVING CHANGE STRATEGICALLY THROUGH COLLABORATION

Those owners that regularly invest in capital facilities and infrastructure—large corporations and government agencies—are in the best position to drive change in the capital facilities sector. They have a significant influence on the construction market and on some of the largest and most professional construction firms. Because they are contracting and paying for capital facilities, such owners can facilitate innovation in processes, technologies, and behaviors through contract provisions, incentives, and contractor selection processes. These owners will also realize the greatest, most direct benefits from improvements in construction efficiency—higher-quality, more-sustainable buildings and infrastructure, produced at lower costs and in less time.

Effective implementation of contracts that require the use of innovative technologies or practices or the training of workers will require that owners work closely and collaboratively with their contractors to allocate the risks, costs, and benefits of innovation appropriately: Shifting all of the risk to contractors would undermine collaboration and lead to adversarial relationships.

Widespread deployment of interoperable technologies, automated equipment, and prefabricated components will also require more effective planning up front. This in turn will require owners to work closely and collaboratively with general contractors, subcontractors, and designers.

An owner-driven strategy has been effective in past initiatives. As noted in Chapter 2, when owners began taking an active role in construction worker safety, they established objectives, measured progress toward those objectives, and greatly reduced injuries and fatalities on their job sites (BRT, 1997).

Improvements in construction productivity could be driven in a similar fashion. Collectively, large private-sector owners and government entities could set goals and objectives for efficiency improvements (e.g., the National Science and Technology Council's national construction goals, [NSTC, 1995]), establish metrics, monitor progress, and share best practices that can lead to improvement throughout the capital facilities sector.

However, these owners cannot drive change without the collaboration and support of large contractors, subcontractors, equipment manufacturers, standards-setting organizations, and researchers. A critical mass of these stakeholders will be needed to develop methods collaboratively to share the risks, costs, and rewards of more efficient projects and processes.

The committee believes that the critical mass of stakeholders needed to achieve breakthrough improvements can be assembled through a coalition of professional industry and government organizations. Such organizations include the Construction Users Roundtable (CURT), Associated General Contractors of America (AGC), Construction Industry Institute (CII), Associated Builders and Contractors (ABC), American Council of Engineering Companies (ACEC), American Institute of Architects (AIA), National Academy of Construction (NAC), National Institute of Standards and Technology (NIST) in the Department of Commerce, and the National Science Foundation (NSF).

CURT, an independent, not-for-profit organization, describes itself as the "owners' voice to the construction industry" (CURT, 2009). Its membership includes not only owners (private-sector companies and several federal government agencies, including the U.S. Army Corps of Engineers, the General Services Administration, and the Architect of the Capitol) but also associate members (contractors and professional or trade associations, including the Association of Union Contractors). CURT facilitates discussion among many of the largest companies and organizations in the United States. The owner organizations in CURT can influence the efficiency of the construction industry (and improve their own projects) by demanding improvement and monitoring progress through metrics.

The AGC is a construction trade association representing all facets of commercial construction. This trade association collaborates with owner organizations and other construction stakeholders to "further the ever-changing agenda of commercial construction contractors, improve job site safety, expand the use of cutting-edge technologies and techniques and strengthen the dialogue between contractors and owners" (AGC, 2009).

The CII, a research unit of the University of Texas at Austin, is a consortium of more than 100 leading owners, engineering and construction contractors, and suppliers from both the public and private sectors (CII, 2009). These organizations have joined together to enhance the business effectiveness and sustainability of the capital facility life cycle through CII research, related initiatives, and industry alliances. CII funds evidenced-based research to develop best practices for the construction industry and has conducted its research through more than 40 universities throughout North America.

The ABC is a national association representing 25,000 merit shop construction and construction-related firms in 79 chapters across the United States. ABC's membership represents all specialties within the U.S. construction industry and is composed primarily of firms that perform work in the industrial and commercial sectors of the industry.

The ACEC numbers more than 5,500 private-sector engineering firms throughout the country. The ACEC's member firms range in size from a single registered professional engineer to corporations employing thousands of professionals. Combined, these firms employ thousands of engineers, architects, land surveyors, scientists, and other specialists and are responsible for more than $200 billion of private and public works annually (ACEC, 2009).

The AIA is the leading trade association representing architects.

The NAC is an honorific organization of industry leaders recognized for making outstanding contributions year after year to the U.S. engineering and construction industry. NAC members promote the industry's advancement through service and strategic initiatives.

Evidence-based research and standards will be needed to fully implement and deploy the committee's five priority activities and other construction-related innovations. Some research and standards are being developed through FIATECH, the National Institute of Building Sciences (NIBS), and some private-sector companies. Two federal agencies positioned to take a leading role in producing evidence-based research are NIST and NSF.

The mission of NIST is to "promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life" (NIST, 2009). NIST conducts research in the areas of building materials, computer-integrated construction practices, fire science and fire safety engineering, and structural, mechanical, and environmental engineering. Its research products include measurements and test methods, performance criteria, and technical data that support innovations by industry and are incorporated into building and fire standards and codes. With its laboratories, NIST is in a position to sponsor the testing and evaluation of high-cost, high-risk, and high-impact construction-related technologies.

NSF, an independent federal agency, was established "to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense. . . ." (NSF, 2009). NSF is the only federal agency whose mission includes support for all fields of fundamental science and engineering (except for medical sciences) and whose research is integrated with education and training (NSF, 2009).

Each of these professional industry and government organizations has an important role to play, and a stake in, improving the competitiveness and efficiency of the capital facilities sector of the construction industry. Together, they comprise a critical mass of key stakeholders. They also provide the venues required for the collaborative activities necessary to change existing processes and practices and, in some cases, the resources and facilities required to conduct industry-related research.

These organizations also have access to the industry media (e.g., trade journals such as *Engineering News Record*) and academic journals, which reach hundreds of thousands of construction professionals each month. The media could be used to disseminate research results and evidence-based information about best practices, new technologies, and innovations in construction.

The committee believes that as these owners, contractors, and researchers effectively use innovative technologies, they will improve their own efficiency and competitiveness. And as these owners, contractors, and researchers disseminate the results of their efforts through trade and academic journals, presentations, and best practices, smaller firms that wish to remain competitive can follow their example. In this way it will be possible to effect widespread change throughout the capital facilities sector of the construction industry.

RECOMMENDATIONS FOR MOVING FORWARD

The committee is not in a position to mandate action by leading construction firms or professional organizations, but it can suggest a path forward. The committee believes that the sponsor of this study, the National Institute of Standards and Technology, is well positioned to work with key construction-related organizations in the public and private sectors to develop a collaborative strategy for improving the productivity of the capital facilities sector. NIST regularly works with a wide range of construction stakeholders, including owners, contractors, and researchers from industry, academia, and government, to support the development of construction-related standards and technologies. NIST also has sophisticated testing facilities that can be used for evaluating innovative technologies, demonstrating their capacity for improving effectiveness and productivity, and verifying their readiness for deployment on a widespread basis.

The committee identified the five interrelated activities that it believes have significant potential to advance the competitiveness and efficiency of the capital facilities sector within 2 to 10 years. To expedite the deployment of these activities on a widespread basis, the committee makes the following recommendations:

Recommendation 1: The National Institute of Standards and Technology should work with industry leaders to bring together a critical mass of construction industry stakeholders to develop a collaborative strategy for advancing the competitiveness and efficiency of the capital facilities sector of the U.S. construction industry. The collaborative strategy should identify actions needed to fully implement and deploy interoperable technology applications, job-site efficiencies, off-site fabrication processes, demonstration installations, and effective performance measures.

NIST is uniquely positioned to work with public- and private-sector owners, contractors, researchers, and standards-setting organizations. The committee recommends that NIST convene a series of meetings involving representatives of the Construction Users Roundtable, Associated General Contractors of America, the Construction Industry Institute, the Association of Builders and Contractors, the American Council of Engineering Companies, the National Academy of Construction, the American Institute of Architects, the National Science Foundation, and other government organizations. The purpose of the meetings should be to develop a collaborative strategy for fully implementing the five activities identified by the committee that could lead to breakthrough improvements in efficiency and competitiveness for the capital facilities sector of the U.S. construction industry. In some cases, this will entail finding ways to deploy automated equipment, information technologies, and prefabricated components more effectively. In other cases it will require identifying the additional research and resources needed to fully implement these activities to achieve breakthrough improvements.

Because implementation of the five activities would require a workforce that has the education and training to use new technologies and collaborative processes effectively, the strategy for implementing them should also address how to attract and retain skilled workers and recent graduates to the industry. Finally, the strategy should address how to effectively disseminate best practices and other information throughout the capital facilities sector.

Recommendation 2: The National Institute of Standards and Technology should take the lead in developing a "technology readiness index" similar to indexes developed by the National Aeronautics and Space Administration and the Department of Defense for high-risk, high-cost, high-impact construction-related innovations. Such an index could help mitigate the risks of using new technologies, products, and processes by verifying their readiness to be deployed on a widespread basis.

A technology readiness index is most appropriate for evaluating the maturity of high-cost, high-risk, and high-impact technologies. Such an index could be used to provide a common understanding of the status of a technology and its level of risk. It could also be used to help make decisions about funding for additional research and development or for deploying the technology into widespread practice.

Recommendation 3: The National Institute of Standards and Technology should work with the Bureau of Labor Statistics, the U.S. Census Bureau, and construction industry groups to develop effective industry-level measures for tracking the productivity of the construction industry and to enable improved efficiency and competitiveness.

With its stated mission of measurement science and its resources, NIST is the organization best positioned to take the leading role in developing industry-level measures for construction. Collaboration by NIST with the Bureau of Labor Statistics, the U.S. Census Bureau, and construction industry organizations will be required in order to develop industry-level measures that help identify trends in construction industry productivity. Industry organizations can help NIST and others to determine which types of data can reasonably be collected and validated for this purpose.

Developing measures that can be used to measure efficiency in different segments of the capital facilities sector—commercial, industrial, heavy construction/infrastructure—as well as a single index for the industry may also be desirable. Consideration should also be given to differentiating the data collected by region in order to capture regional differences in the costs of labor, equipment, and materials, and in climate. In collaboration with other government organizations, NIST should also determine whether there is value in developing measures that would be comparable to construction productivity measures used in other developed countries.

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Appendixes

A

Biosketches of Committee Members

Theodore C. Kennedy, *Chair*, was elected to the National Academy of Engineering in 1999 for leadership and innovation in advancing the nation's construction industry. He is a member of the National Research Council's Board on Infrastructure and the Constructed Environment. Mr. Kennedy is the cofounder of BE&K, Inc., a privately held international design-build firm that provides engineering, construction, and maintenance for process-oriented industries and commercial real estate projects. BE&K companies design and build for a variety of industries, including pulp and paper, chemical, oil and gas, steel, power, pharmaceutical, and food processing. BE&K is consistently listed as one of *Fortune* magazine's Top 100 Companies to Work For, and BE&K and its subsidiaries have won numerous awards for excellence, innovation, and programs that support its workers and communities. Mr. Kennedy served as the chairman of the national board of directors of INROADS, Inc., and is a member of numerous other boards. He currently serves as chair of the Alabama's A+ College Ready Board and in that capacity is spearheading a statewide initiative to establish advanced placement programs in Alabama's public schools. He is a former president of Associated Builders and Contractors and former chair of the Construction Industry Institute. He has received numerous awards, including the Distinguished Alumnus Award from Duke University, the Walter A. Nashert Constructor Award, the President's Award from the National Association of Women in Construction, and the Contractor of the Year award from Associated Builders and Contractors. Mr. Kennedy has a B.S. in civil engineering from Duke University.

Parviz Daneshgari is the president of MCA, Inc., a firm providing services focused on implementing process and product development, waste reduction, and productivity improvements. At MCA, Inc., Dr. Daneshgari has provided supply chain consulting services to national and international companies in the automotive, medical, insurance, banking, and construction industries. Other projects include developing a standard format for calculating sizes and shares of the construction industry, large cities construction market characteristics, and lean production principles. Dr. Daneshgari is an adjunct professor for the University of Michigan-Dearborn and for Oakland University. He holds an M.B.A. from Wayne State University; a Ph.D. and an M.S. in mechanical engineering from the University of Karlsruhe, Germany; and a B.S. in mechanical engineering and a B.S. in civil engineering from Northwestern University, Illinois.

Patricia D. Galloway is the chief executive officer of Pegasus-Global Holdings, Inc., an international management consulting firm. Dr. Galloway was the first woman to serve as president of the American Society of Civil Engineers (ASCE) in the organization's 154-year history, her proudest accomplishment, enabling her to serve as a role model for young women engineers. She is currently the vice chair of the National Science Board, a presidential appointment with Senate confirmation; her term ends in 2012. Dr. Galloway is also a member of the Eastern Washington Governor's Advisory Council. She is a licensed professional engineer in 14 U.S. states, in Canada, and in Australia and is a certified project management professional. Having traveled to nearly 100 countries, Dr. Galloway is known for her experience and expertise in global engineering and construction. She also lectures around the world on topics such as leadership, globalization, risk management, engineering education, and women in engineering. She is an elected member of the National Academy of Construction and the Pan American Academy of

Engineering, for which she serves on the board of directors. Dr. Galloway is also an elected member of the American Arbitration Association Board of Directors. She received a Distinguished Engineering Alumna award from Purdue University in 1992. In addition to having lectured in numerous venues around the world, Dr. Galloway has served as a cohost to the Discovery Channel program “Modern Engineering Marvels.” She holds a Ph.D. in infrastructure systems engineering (civil) from Kochi University of Technology in Japan, an M.B.A. from the New York Institute of Technology, and a bachelor’s degree in civil engineering, specializing in structural design and construction management, from Purdue University. She is the author of *The 21st Century Engineer: A Proposal for Engineering Education Reform*, published by ASCE Press, and has authored more than 150 articles and papers. Dr. Galloway is currently a blog writer for *Engineering News Record*, discussing current issues in the construction industry.

James O. Jirsa is the Janet S. Cockrell Centennial Chair in Engineering in the Department of Civil Engineering at the University of Texas at Austin. Dr. Jirsa was elected to the National Academy of Engineering in 1988 for significant contributions to research on the behavior and design of structural reinforced concrete. He is a former chair of the National Research Council’s Board on Infrastructure and the Constructed Environment. Dr. Jirsa has been on the faculty of the Department of Civil Engineering of the University of Texas at Austin since 1972 and has served as department chair since 1996. Dr. Jirsa has held the Janet S. Cockrell Centennial Chair in Engineering since 1988. He was named to the Phil M. Ferguson Professorship in 1984 and served as director of the Ferguson Structural Engineering Laboratory from 1985 to 1988. Prior to his move to Austin, Dr. Jirsa taught at Rice University and the University of Nebraska, where he received his B.S. degree in civil engineering. He has graduate degrees from the University of Illinois at Urbana-Champaign. Dr. Jirsa’s teaching and research specialization areas are the design, behavior, and durability of reinforced-concrete structures; earthquake engineering; and the repair and strengthening of structures. He is a registered professional engineer. Dr. Jirsa has received many honors and awards over the span of his career, beginning as a Fulbright Scholar in France in 1963-1964. More recently he received the Hocott Award for Research from the College of Engineering in 1994 and the Joe W. Kelly Award in 1997 from the American Concrete Institute, “in recognition of a creative career as a teacher, researcher, and author.” He is on the board of directors of the Earthquake Engineering Research Institute.

Behrokh Khoshnevis is a professor of industrial and systems engineering and civil and environmental engineering. He is the director of the Center for Rapid Automated Fabrication Technologies (CRAFT) and director of the Manufacturing Engineering Graduate Program at the University of Southern California. He is an expert in construction industry technologies and innovations. Dr. Khoshnevis is active in computer-aided design and computer-aided manufacturing; robotics and mechatronics-related research projects that include the development of novel solid free form, or rapid prototyping, processes; and autonomous mobile and modular robots for assembly applications on Earth and in space. He routinely conducts lectures and seminars on invention and technology development. He is a fellow of the Institute of Industrial Engineers, a fellow of the Society for Computer Simulation, and a senior member of the Society of Manufacturing Engineering. His automated construction invention, Contour Crafting, was selected in 2006 as one of top 25 best inventions by the National Inventors Hall of Fame and the History Channel’s “Modern Marvels” program.

Feniosky Peña-Mora was recently named dean of the Fu Foundation School of Engineering and Applied Science at Columbia University. Dr. Peña-Mora was previously an associate provost, Edward William and Jane Marr Gutgsell Endowed Professor in the Department of Civil and Environmental Engineering, as well as a center affiliate at the National Center for Supercomputing Applications and a faculty affiliate at the Beckman Institute at the University of Illinois at Urbana-Champaign. Dr. Peña-Mora earned a Master of Science degree in civil engineering and a Doctor of Science in civil engineering systems from the Massachusetts Institute of Technology (MIT) in 1991 and 1994, respectively. Before coming to the

University of Illinois in 2003, Dr. Peña-Mora worked at MIT as assistant professor and associate professor of information technology and project management in the Civil and Environmental Engineering Department. He has also served as a visiting professor at Loughborough University in Great Britain and at the Ecole Polytechnique Fédérale de Lausanne in Switzerland. He is an expert in change management, process integration, and large-scale civil engineering. Dr. Peña-Mora's research interests include change management, conflict resolution, and processes integration during the design and development of large-scale civil engineering systems. He is the author of more than 100 publications in refereed journals, conference proceedings, book chapters, and textbooks on computer-supported design, and on computer-supported engineering design and construction, as well as project control and management of large-scale engineering systems. He has held the position of chief information technology consultant on the Boston Central Artery/Third Harbor Tunnel Project, where he focused on information technology support for change management and process integration during the design and construction phases of this massive $14.6 billion, two-decade-long engineering endeavor.

Benedict Schwegler, Jr., is chief scientist at Walt Disney Imagineering Research and Development and a consulting professor at Stanford University. From hydrological modeling to four-dimensional software, from integrated infrastructure design to next-generation entertainment effects, Dr. Schwegler's mission is to invent, simulate, and deliver new technologies to improve the quality of the built environment. He has been a key executive for theme park and resort developments for the Walt Disney Company in the United States, Europe, Japan, and Hong Kong. He is a member of the Jet Propulsion Laboratory's Technical Divisions Advisory Board, a winner of the Henry R. Michel Award from the American Society of Civil Engineers, and a juror for the Sloan Prize for the best portrayal of science in a feature film at the Sundance Film Festival.

David A. Skiven is a facilities management consultant and frequent adviser to federal agencies including the U.S. Navy and the U.S. Air Force. He is also currently serving as co-director of the Engineering Society of Detroit Institute, a nonprofit organization dedicated to improving Michigan's economy. Mr. Skiven retired as the executive director of the General Motors Corporation Worldwide Facilities Group in 2007. The Worldwide Facilities Group was responsible for providing facilities management, utilities, construction, and environmental segments, allowing General Motors (GM) clients to focus on their core business, resulting in structural cost savings and improved utilization of assets. In 42 years at GM, Mr. Skiven worked in various engineering and plant operations, including as manager of Facilities and Future Programs–Manufacturing Engineering for the Saturn Corporation and as director of Plant Environment and the Environmental Energy Staff, before being appointed executive director of the Worldwide Facilities Group in 1993. Mr. Skiven has served as a member of the National Research Council's Board on Infrastructure and the Constructed Environment, on the board of directors of BioReaction, Inc., and on the Board of the Engineering Society of Detroit. Mr. Skiven has a B.S. degree in mechanical engineering from General Motors Institute and an M.S. degree from Wayne University. He is also a registered professional engineer.

Jorge A. Vanegas serves as dean of the College of Architecture at Texas A&M University (TAMU), holds a faculty appointment as a tenured professor in the Department of Architecture, and serves as director of the Center for Housing and Urban Development (CHUD). As dean, Dr. Vanegas oversees the operations of (1) four departments—Architecture; Construction Science; Landscape Architecture and Urban Planning; and Visualization; (2) five research centers—the Center for Health Systems and Design; Center for Heritage Conservation; CHUD; CRS Center for Leadership and Management in the Design and Construction Industry; and Hazard Reduction and Recovery Center; (3) the Architecture Ranch, a hands-on research/education demonstration facility on a 13-acre site and a 10,000-square-foot facility at TAMU's Riverside Campus; and (4) several study abroad programs. Dr. Vanegas has active research and education interests in sustainable urbanism, civil infrastructure systems, facilities, and housing; advanced strategies, tools, and methods for integrated capital asset delivery and management; and design/construction integration in the development and rehabilitation of facilities and civil infrastructure systems. He has been active in the research and educational deployment efforts of the Construction Industry Institute in constructability; the use of prefabrication, preassembly, modularization, and off-site construction; and innovative practices for cost-effective capital projects. Dr. Vanegas held prior academic appointments at the Georgia Institute of Technology from 1993 through 2005, and at Purdue University from 1988 to 1993. He received a B.S. in architecture from the Universidad de los Andes in 1979 and master's and Ph.D. degrees in civil engineering from Stanford University.

Norbert W. Young, Jr., is the president of McGraw-Hill Construction, a global source of construction industry information. At McGraw-Hill, Mr. Young is responsible for building relationships with owners, key design firms, and construction firms. He holds a Master of Architecture degree from the University of Pennsylvania. His professional affiliations include the American Institute of Architects, where he is a fellow; the Urban Land Institute; the Construction Specifications Institute; and the International Alliance for Interoperability, where he served as chair of the North American Board of Directors. He is a trustee of the National Building Museum and is former chair of the board of regents of the American Architectural Foundation. He is also a member of the Construction Users Roundtable, a national organization of more than 50 major owners focused on providing the "voice of the owner" to the design and construction industry. Prior to joining McGraw-Hill, Mr. Young was president of the Bovis Construction Group's Bovis Management Systems, where he was instrumental in creating an integrated approach to delivering preconstruction services. Mr. Young was also a partner at Toombs Development Company, where he managed all aspects of design and construction, and he spent 12 years as a practicing architect in Philadelphia.

B

Workshop Agenda and List of Participants

WORKSHOP AGENDA

- Identify the key opportunities for achieving breakthrough improvements in the productivity and competitiveness of the capital facilities sector of the U.S. construction industry.
- Identify and prioritize technologies, processes, and deployment activities with the greatest potential to achieve breakthrough improvements.

November 19, 2008

8:30 a.m.	Welcome/Introductions of the National Research Council Workshop Committee and Participants Theodore Kennedy, *Committee Chair*
9:00 a.m.	The Challenge: Achieving Breakthrough Improvements in Construction Productivity Shyam Sunder, Director, Building and Fire Research Laboratory, National Institute of Standards and Technology (NIST)
9:30 a.m.- 12:30 p.m.	Advancing Construction Productivity and Competitiveness: Issues and Opportunities
9:30 a.m.	Overview Theodore Kennedy, *Committee Chair*
9:40 a.m.	An International Perspective on Construction Productivity and Competitiveness Carl Haas, University of Waterloo
10:00 a.m.	Market Forecasts and Opportunities for the Capital Facilities Sector Hank M. Harris, President and Managing Director, FMI Management Consulting
10:20 a.m.	Break
10:40 a.m.	Breakthrough Technologies: 3D BIM and Lean Construction Alex Ivanikiw, Barton-Malow, and Michael Neville, Ghafari Associates
11:10 a.m.	Technical Change and Its Impact on Construction Productivity Paul Goodrum, University of Kentucky
11:30 a.m.	Improving Construction Labor Productivity on Mid-Sized Projects

H. Randolph Thomas, Penn State University

11:50 a.m. Creating and Cultivating the Next Generation of Construction Professionals
Jeffrey Russell, University of Wisconsin

12:10 p.m. Panel Discussion: Q&A with Participants; Identification of Additional Issues

12:30 p.m. Lunch

1:30 p.m. Breakout Session Objective: Identify the key opportunities for breakthrough improvements in the productivity and competitiveness of the capital facilities sector.

What opportunities are presented by:

- Technologies/materials/automation?
- Processes and practices: management, project delivery, legal, regulatory, safety, other?
- Workforce: designers, engineers, managers, skilled trades, labor, other?
- How might technologies, processes, workforce be used to overcome/lessen long-standing barriers to improving productivity (e.g., industry segmentation, lack of skilled labor, image of the industry)?
- What new opportunities/barriers do these crosscutting issues present? (E.g., If a different level/mix of skills is needed to deploy technologies more fully, how do you create them?)

3:30 p.m. Break

4:00 p.m. Plenary Session: reports from three breakout groups/Synthesis of Findings

5:00 p.m. Wrap-up

November 20, 2008

8:30 a.m. Review of Key Opportunities for Achieving Breakthrough Improvements Identified on Day One
Theodore Kennedy, *Committee Chair*

9: 00 a.m. Breakout Sessions: Prioritize Technologies, Processes, and Deployment Activities with the Greatest Potential to Achieve Breakthrough Improvements

Each group to focus on the following:

- What are realistic time frames for achieving results from each of the identified breakthroughs? 5-10 years? 10 years or longer?
- What additional research is needed to move promising innovations into practice?

- What measures will be needed to establish baselines and to measure improvements in productivity for the industry?
- Identify the key players and their roles in moving potential breakthroughs into practice

10:30 a.m.	Break
11:00 a.m.	Plenary Session: Review Results from three breakout sessions
12:00 noon	Lunch
1:00 p.m.	Plenary Session: Synthesize/Review Findings Regarding Prioritization of Breakthrough Technologies, Processes, and Deployment
2:30 p.m.	Wrap-up/Next Steps/Thank You
3:00 p.m.	Adjourn

WORKSHOP PARTICIPANTS

Planning Committee

Ted Kennedy, Co-Founder, BE&K Inc., *Committee Chair*
Parviz (Perry) Daneshgari, President, MCA, Inc
Patricia Galloway, Chief Executive Officer, Pegasus-Global Holdings, Inc.
James Jirsa, Janet S. Cockrell Centennial Chair in Engineering, University of Texas
Behrokh Khoshnevis, Professor, Epstein Dept. Industrial and Systems Engineering, University of Southern California
Feniosky Peña-Mora, Associate Provost for Institutional Programs, Department of Civil and Environmental Engineering, University of Illinois
Benedict Schwegler, Jr., Vice President and Chief Scientist, Walt Disney Imagineering Research and Development
David Skiven, Executive Director, General Motors Corp. Worldwide Facilities Group (retired)
Jorge Vanegas, Interim Dean, College of Architecture, Texas A&M University
Norbert Young, Jr., President, McGraw-Hill Construction Group

Participants

Barbara Balboni, Senior Engineer, RS Means Company
Virgil Barton, Vice President, Quality Management, The Shaw Group, Inc.
Susan Bucci, Manufacturing and Construction Division, U.S. Census Bureau
David Butry, Office of Applied Economics, Building and Fire Research Laboratory, National Institute of Standards and Technology
Stephen L. Cabano, President and Chief Operating Officer, Pathfinder, LLC
Robert Chapman, Director, Office of Applied Economics, Building and Fire Research Laboratory, National Institute of Standards and Technology
Frank Congelio, Section of Nondurable Goods, Bureau of Labor Statistics
Wayne Crew, Executive Director, Construction Industry Institute
Don Cooley, Director, Construction Services, CH2M Hill

Ken Dunn, Director of Operations, Hill International
Charles Eastman, Architecture and Computing, Georgia Institute of Technology
Lincoln Forbes, President, Construction Division, Institute of Industrial Engineers
Jesus de la Garza, Vecellio Professor of Civil and Environmental Engineering, Virginia Tech
G. Edward Gibson, Construction Engineering and Management, University of Alabama
Paul Goodrum, College of Engineering, University of Kentucky
Allison Huang, Office of Applied Economics, Building and Fire Research Laboratory, National Institute of Standards and Technology
Carl Haas, Canada Research Chair in Construction and Management of Sustainable Infrastructure, University of Waterloo
Michael Haller, Walbridge Aldinger Company
Makarand Hastak, Professor and Head, Construction Engineering and Management, Purdue University
Alex Ivanikiw, Senior Vice President, Barton Malow
Nazeeh Kiblawi, President, Truland Systems Corporation
John Kunz, Director, Center for Integrated Facility Engineering, Stanford University
Paul Lally, Chief, Investment Branch, Bureau of Economic Analysis
Egon Larsen, Global Construction Manager, Air Products and Chemicals Inc.
David McKinney, Alabama Power
David Mongan, President, Whitney, Bailey, Cox & Magnani
Randall Monk, Independent Project Analysis
Michael Neville, Vice President, Ghafari Associates
Marvin Oey, Director, Construction Institute, American Society of Civil Engineers
Richard Offenbacher, Senior Vice President, Graybar
Mark Palmer, Computer Integrated Building Processes Group, Building and Fire Research Laboratory, National Institute of Standards and Technology
Joseph Pecoraro, Parsons Corporation
Richard Platner, Associate Director, CPWR: The Center for Research and Training
Hank Harris, President and Managing Director, FMI Management Consulting
Jeffrey Russell, Civil and Environmental Engineering, University of Wisconsin-Madison
Daniel Sansbury, Construction Indicator Programs, Manufacturing and Construction Division, U.S. Census Bureau
Mirek Skibniewski, Editor-in-Chief, Automation in Construction, University of Maryland
Lucio Soibelman, Information Technologies for Construction, Carnegie Mellon University
Dana K. “Deke” Smith, Executive Director, Building Smart Alliance, National Institute of Building Sciences
Shyam Sunder, Director, Building and Fire Research Laboratory, National Institute of Standards and Technology
H. Randolph Thomas, Civil and Environmental Engineering, Penn State University
Steve Thomas, Associate Director, Construction Industry Institute
Jan Tuchman, Editor-in-Chief, Engineering News Record
Lisa Usher, Industry Productivity Statistics, Bureau of Labor Statistics

C

An International Perspective on Construction Competitiveness and Productivity

Carl Haas, P.E., P. Eng., Ph.D.
Canada Research Chair and Professor in Civil and Environmental Engineering
University of Waterloo, Ontario, Canada

Abstract This paper synthesizes some of the information that exists around international construction industry productivity and competitiveness metrics as well as innovation strategies in order to help inform strategic planning for improving the U.S. construction industry. It focuses on comparing Canada, South Korea, Japan, the United Kingdom, the European Union, Sweden, and the United States. Information was acquired from the literature, the Internet, reports, and consultations with international experts. International benchmarking and metrics efforts are reviewed, and principles are developed for conducting metrics comparisons between programs. Some productivity metrics for different nations are compared. Then, the remainder of the paper is focused on a description and comparison of innovation and improvement strategies. It is observed that a high productivity level for a nation probably does not impede that nation from improving even more at a high rate. Innovations are being shared almost immediately internationally by way of academic and business links partially facilitated by the Internet. And, since innovative ideas are quickly shared, what differs from nation to nation is emphasis.

INTRODUCTION

Advancing the competitiveness and productivity of the U.S. construction industry is a tremendous challenge. In approaching this challenge it is useful to consider an international perspective. Many studies have been conducted that compare productivity between nations or regions within nations. Fewer studies compare the competitiveness of construction industries between nations, and even fewer studies compare innovation strategies. To generate an international perspective on construction competitiveness and productivity, a synthesis of what information does exist is required. A review of specific national innovation strategies will also shed some light on what is perhaps one of the key drivers of competitive advantage between nations.

The objective of this paper therefore is to synthesize some of the information that exists around international construction industry productivity and competitiveness metrics as well as innovation strategies in order to help inform strategic planning for improving the U.S. construction industry. The focus is on economically advanced countries, because evidence exists that the construction industries in less affluent countries are generally much less productive and less competitive from an exporting perspective. Countries and regions referenced in this paper include Canada, South Korea, Japan, the United Kingdom (UK), the European Union (EU), Sweden, and the United States.

Information for this paper was acquired from the literature, the Internet, reports, and consultations with international experts. Consultations occurred in person, over the phone, and on the Internet with experts around the world in the weeks leading up to the Workshop on Advancing the Competitiveness and Productivity of the U.S. Construction Industry of the National Research Council's Board on

Infrastructure and the Constructed Environment. Those who provided information and influenced the thoughts in this paper are included in an acknowledgments section at the end of the paper. In terms of methodology, it is important to keep a particular paradox in mind. While distinctive national, legal, cultural and infrastructure characteristics certainly exist, the paradigm of competition among nations may have to be partially relaxed considering the reality of our highly integrated and "flat" (Friedman, 2005) world, in which knowledge moves quickly and experience is mobile, thus rendering borders less significant and differences between countries less distinct. At the same time, the socioeconomic dynamics and characteristics of "mega-regions" (Florida et al., 2007) may be more distinctive than those related to national boundaries. For example, data show that variations in productivity among regions of a country can be greater than [those] between the countries themselves (Harrison, 2007).

The structure of this paper reflects the objectives and scope described above. International benchmarking and metrics efforts are reviewed, and principles are developed for conducting metrics comparisons between programs. Then some productivity metrics for various nations are compared. The remainder of the paper is focused mostly on a description and comparison of innovation and improvement strategies, briefly preceded by a discussion of innovation theory as related to the construction industry. Finally, some observations based on the preceding synthesis are made.

BACKGROUND

Concepts of productivity, performance, competitiveness, and metrics have evolved over time and differently in different countries, although it appears that they may be converging. In this section, this evolution is briefly reviewed. Perspectives on the process of innovation in construction are then reviewed.

Productivity, Performance, Competitiveness, and Metrics

Dozens of studies and publications on construction benchmarking and metrics exist. A few are particularly relevant to issues surrounding international comparisons, including Costa et al. (2006); Meade et al., (2006); Sawhney et al. (2004); Walsh and Sawhney (2007); Harrison (2007); Flanagan et al. (2007); Rao et al. (2004); and Momaya and Selby (1998).

Harrison compares construction productivity in Canada with that of 20 other nations, focusing particularly on the United States (Harrison, 2007). He provides an excellent review of deflators based on cost of inputs and price of outputs and points out their relative advantages and disadvantages in a clear and concise way. It is noted that evidence of task and activity productivity gains contrasts with estimates of industry declines for the United States. Failing to incorporate quality-based deflators may decrease productivity estimates unfairly. Harrison follows with discussions of model price indexes and how construction productivity is estimated in Canada and concludes with a critique of possible sources of measurement error. Harrison (2007) should be read as a primer by anyone who is interested in measuring construction productivity in North America.

Costa et al. (2006) discuss benchmarking programs in the construction industry in Brazil, Chile, the United Kingdom, and the United States (Costa et al., 2006). They analyze the benchmarking initiatives in these four countries, which include the following: (1) Key Performance Indicators (KPIs) in the United Kingdom; (2) the National Benchmarking System for the Chilean Construction Industry (NBS-Chile); (3) the Construction Industry Institute Benchmarking and Metrics program (CII BM&M) in the United States; and (4) the Performance Measurement for Benchmarking program in the Brazilian Construction Industry (SISIND-NET Project). Three main issues were analyzed for each benchmarking initiative: (1) type of benchmarking, (2) scope of the performance measurement system, and (3) implementation of the initiatives.

Meade et al. (2006) summarize benchmarking efforts in the United Kingdom, the United States, Canada, and Japan. This is with the intent of placing the efforts of the Canadian Construction Innovation

Council (CCIC) in the context of other national-level efforts. CCIC focused on performance benchmarking rather than on productivity. Recently, Fayek et al. (2008) report on the new Performance and Productivity Benchmarking program initiated by the Construction Sector Council (CSC) in Canada that is focused on the human resource elements that affect construction productivity. Also in Canada, the Industrial Research Assistance Program (IRAP) of the Canadian National Research Council (CNRC) has initiated a program of research focused on the effect of technological innovation on construction productivity. This group can be likened to the National Institute of Standards and Technology (NIST) in the United States.

Flanagan has for many years pioneered an approach to comparison of construction internationally involving "competitiveness" rather than more prosaic measures such as labor productivity, or cost and schedule growth (Flanagan et al., 2007). He says that, "competitiveness may be described as something that is multi-defined, multi-measured, multi-layered, dependent, relative, dynamic and process related." Metrics categories for competitiveness include factors conditions, demands conditions, government, industry characteristics, firm strategy and management, and human resources. This approach has gained more and earlier credibility in the EU than in North America and Asia. In a study funded by the Swedish construction industry, the following competitive factors were compared among Finland, Sweden, and the United Kingdom: profitability, predictability, relationships, innovation, applicants to construction-related courses, wages, health and safety, business ethics, environmental performance, and extent of whole-life planning (Flanagan et al., 2005).

Abdel-Wahab et al. (2008) have published an article on the impact of training on construction productivity in the United Kingdom. They find that construction productivity, measured in gross value added (GVA) per worker, has generally been flat from 1995 to 2006. Review of their graphs indicates that it increases during periods of stable employment and decreases during periods of rapid employment growth. The authors conclude that organizational and management practices have influenced productivity more than training. Most importantly is that quality or value of the workforce (human capital) is measured by percent of National Vocational Qualifications (NVQs) and by participation rates in training. Sloan Center and Construction Industry Institute (CII) research has focused on formal apprenticeship training certifications as a measure of human capital as well, and on training rates as a practice metric.

The International Council for Research and Innovation in Building and Construction (CIB TG61) group builds on the concepts described in all of the preceding paragraphs to focus on macroeconomics for construction.[1] The group is led by Professor Les Ruddock of the Research Institute for the Built and Human Environment at the University of Salford in the United Kingdom. The group holds annual meetings and workshops, and its scope includes, among other items, international benchmarking of construction. The director of CIB, which is headquartered in the Netherlands, is Dr. Wim Bakens. Table C.1 summarizes and compares the efforts described in the preceding paragraphs.

MEASURING PERFORMANCE

Metrics and innovation in construction are closely intertwined. Evaluating the impact of particular innovations and of progress in construction requires metrics. An approach to comparing international benchmarking and metrics programs is developed in this section, and then a few of those programs are compared.

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[1] Information about the International Council for Research and Innovation in Building and Construction may be found at its Web site (http://www.cibworld.nl/website/).

TABLE C.1 Studies Involving Comparison of International Construction Benchmarking and Metrics

Measures	Researchers	Countries
Performance and productivity	Costa et al. (2006)	Brazil, Chile, United Kingdom, and United States
Performance	Meade et al. (2006)	Canada, United Kingdom, Japan, and United States
Productivity	Walsh and Sawhney (2007)	Many countries
Productivity	Harrison (2007)	Canada and United States, then many countries
Productivity and competitiveness	Flanagan et al. (2007)	Australia, Canada, Finland, France, Italy, Japan, Netherlands, United States, and West Germany
Productivity	Rao et al. (2004)	Canada and United States
Competitiveness	CIB TG61	Various
Competitiveness	Momaya and Selby (1998)	Canada, Japan, and United States

Principles for Comparing Construction Benchmarks and Metrics

Construction project management and engineering researchers and experts have for decades been trying to create standards to enable fully integrated and automated processes and practices. A very early effort by Charles M. Eastman published in the now-defunct *AIA Journal* described a working prototype "Building Description System," according to Jerry Laiserin in his introduction to the *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors* (Eastman et al., 2008). Now there is a Building Information Model (BIM) for buildings, International Organization for Standardization (ISO) 15926 for industrial construction projects, BrIM for Bridge Information Modeling, CIM for City Information Modeling, and several other related "standards." The purpose is to enable (1) interoperability, (2) integration, (3) sharing, and (4) information transfer.

Where standards do not exist at all, achieving the above functions requires that translation and transformation routines be developed. Even when such standards are defined, and where existing applications (such as computer-aided design [CAD] or data analysis programs) are too expensive to completely rebuild immediately, enabling the above functions between different applications may require staged development, including the following:

1. Establishing *interoperability* with file sharing via standard formats,
2. Developing real-time *intra-operations* between applications, and
3. Creating independent data and information *persistence* between applications.

Similar issues exist for comparing international construction metrics. In this case, the information model consists of metrics definitions which, much like the industry foundation classes (IFCs) that make up BIMs, may include detailed building assembly definitions. These definitions make up building indexes such as those described in a report on the Web site of the Bureau of Labor Statistics (BLS)[2] entitled *Producer Price Index Introduced for the Nonresidential Building Construction Sector—NAICS 236221*, and which are defined in the Statistics Canada[3] disaggregated building construction price indexes. CII has its own related hierarchical set of definitions referenced in following sections of this paper. They might be termed a hierarchical set of "work packages." The result is that at the national level

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[2] See http://www.bls.gov.

[3] Statistics Canada is Canada's national statistical agency. Additional information available at http://www.statcan.gc.ca/start-debut-eng.html.

in the United States and other counties, productivity metrics data can be shared and integrated nationally but not internationally, since these standards differ among countries. Within the industrial construction sector, the use of the CII standards allows the CII's member companies and the members of the Construction Owners Association of Alberta (COAA) to integrate and share data, but the data cannot be shared between this sector and the national agencies whose standards differ yet again. The World Bank has recently established its own set of standard work packages for comparing construction labor productivity between countries for its purchasing power parity (PPP) program, but these have not yet been officially released and may not be released soon.

Beyond work package definitions for adjustment indexes and productivity metrics, performance and practice metrics definitions also differ between national benchmarking and metrics programs. Translating between some performance and practice metrics may be almost impossible in practice; however, for key performance metrics such as cost and schedule growth it may be possible by coincidence or forethought.

In some cases, the above-referenced and other construction benchmarking and metrics standards exist for different industry sectors, different countries, and at different levels of aggregation and for different purposes, and yet they overlap in many ways. Just as there is an effort within FIATECH[4] to "harmonize" the BIM, ISO 15926, and other standards, such an effort may be required in the international construction benchmarking and metrics domain.

In summary, there are essentially five dimensions that define the information space across which construction metrics must be compared, and for which purpose transformations may be required:

1. *Performance* (including productivity, schedule, cost, safety, competitiveness, and so on);
2. *Work package* (precisely defined and hierarchically aggregated scopes of work);
3. *Practice* (including project management practices, training, automation, and so on);
4. *Environment* (project complexity, labor market, weather, and so on); and
5. *Time* (frequency, phase, and duration).

Three of these dimensions are illustrated in Figure C.1.

The key issues then, for the purpose of enabling future international comparisons, are to what extent there is a desire to adopt existing standards versus the extent to which there is a desire to engage in harmonization, translation, and transformation exercises.

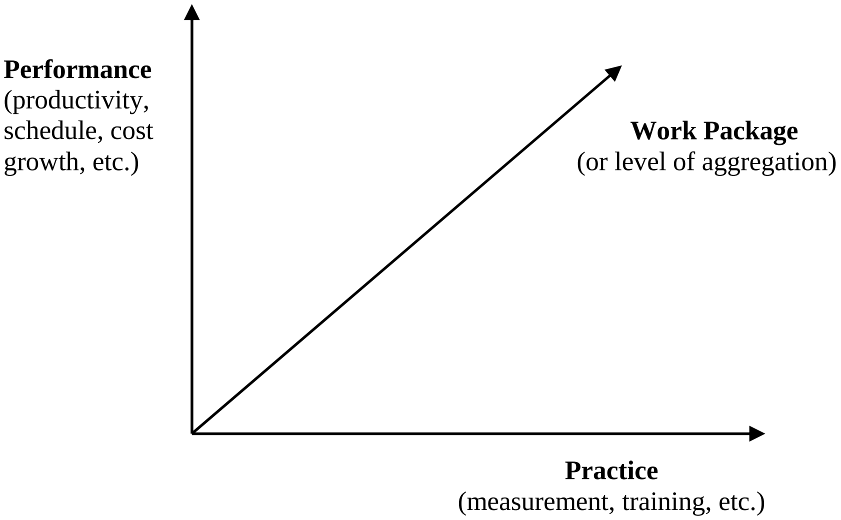

FIGURE C.1 Three dimensions for construction metrics comparisons.

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[4] Additional information is available at http://www.fiatech.org.

Comparison of National Construction Benchmarking and Metrics Programs

Many construction benchmarking and metrics programs exist in several countries. These are in addition to national-level productivity tracking efforts such as Statistics Canada and the BLS in the United States as well as international productivity tracking efforts such as those of the World Bank and the Groningen Growth and Development Centre. Costa et al. (2006) have done an excellent comparison of these efforts in the United Kingdom, the United States, Chile, and Brazil. Here, their summary comparisons are modified and extended on the basis of the analysis of the additional sources of information referenced in the "background" section of this paper. Table C.2 compares two major U.S. construction benchmarking and metrics programs. Table C.3 is adapted from the Costa et al. (2006) comparison of four programs by adding three more programs and editing the original table. Table C.3 describes and compares seven international programs in terms of leading and lagging measures. In addition, the evaluation by Costa et al. (2006) of the programs in the United Kingdom, Chile, the United States, and Brazil identified several positives and challenges as common to those experiences. Generally positively received were online software for users, users' groups or clubs, annual training, annual reports, and visits to sites. Common challenges that were noted were (1) the lack of a link between the benchmarking program and practice improvement programs and project management functions, (2) too much focus on lagging indicators, and (3) keeping the companies committed for the long term.

It must be noted that at least one private organization exists that focuses on international benchmarking and metrics in the industrial construction sector. Independent Project Analysis (IPA) is a private, international construction benchmarking and metrics corporation founded in 1987 and headquartered in the United States. IPA consults on project evaluation and project system benchmarking. Its Web site claims about 140 project and research analysis professionals at seven offices on five continents who serve hundreds of clients. The clients primarily include large oil companies, chemical producers, pharmaceutical companies, minerals and mining companies, and consumer products manufacturers. IPA's data and methods are proprietary.[5]

TABLE C.2 Comparison of Two Major U.S. Construction Benchmarking and Metrics Programs

Construction Industry Institute (CII)	Bureau of Labor Statistics (BLS)
• Construction productivity metrics system (CPMS) • Mostly industrial sector • Hours per unit of work • Hierarchical and detailed work structure • Do not adjust with input cost indexes • Focused on industrial sector	• Introducing new output price indexes • Measured in materials per unit cost and in installation-cost per unit of a building assembly • A typical BLS building assembly corresponds to second or third tier of CPMS, and while they do not appear identical on an initial review, this should be investigated more thoroughly.

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[5] Additional information is available at http://www.ipaglobal.com/inside%20pages/About_IPA/index.html.

TABLE C.3 Comparison of International Construction Benchmarking and Metrics Programs

Scope of Measures	Lagging Measures	Leading Measures
KPI (United Kingdom)	Client satisfaction Defects Predictability cost Predictability time Profitability Safety Productivity	
CDT (Chile)	Cost deviation by project Deviation of construction due date Change in amount contracted Rate of subcontracting Cost client Efficiency of direct labor Accident rate Risk rate	Effectiveness of planning Urgent orders Productivity performance
CII Benchmarking and Metrics (U.S.)	Project cost growth Project budget factor Project schedule growth Project schedule factor Total project duration Change cost factor Recordable incident rate Lost workday case incident rate Hours per unit output (labor productivity)	Total field rework factor phase cost Factor phase cost growth (owner data only) Phase duration factor Construction phase duration Project health index Automation Integration CII best practices such as Project Definition Rating Index
SISIND-NET (Brazil)	Cost deviation Time deviation Degree of client satisfaction (user) Degree of client satisfaction (owner) Average time for selling unit Contracting index Ratio between number of accidents and total man-hour input Nonconformity index in unit delivery	Percentage of plan completed Construction site best practice Supplier performance (subcontractors, material suppliers, and designers) Number of nonconforming audits Degree of employee satisfaction Rate of training courses Rate of employees trained
CCIC (Canada)	Cost predictability Cost in use Cost per unit Time predictability Quality Safety Scope growth Innovation Sustainability	
CSC/CBR (Canada)	CCIC measures Hours per unit output (labor productivity)	Best practices Automation (Information Technology) Integration (Information Technology) Training rate Certification rate
World Bank	Hours per construction component (labor productivity)	

SOURCE: Adapted from Costa et al. (2006).

Role of Levels of Aggregation in Comparing Benchmarking and Metrics Programs

Levels of aggregation for construction work packaging for productivity benchmarking were mentioned above in relation to dimensions for benchmarking and metrics comparisons (Figure C.1). Aggregation can enable international comparisons or make it more difficult if such systems do not harmonize. Chapman and Butry (2008) suggest three levels for measurement of construction productivity:

1. Task (e.g., on-grade concrete slab)
2. Project (e.g., building)
3. Industry (e.g., nonresidential building construction sector)

Park et al. (2005) describe the CII system, which has three tiers below the project level:

1. Element (e.g., carbon steel small bore piping)
2. Subcategory (e.g., small bore piping)
3. Category (e.g., piping)

Meade et al. (2006) suggest five levels for measurement of construction project performance:

1. Task
2. Project
3. Organization
4. Industry
5. National economy

To this, one might add trading blocks such as the EU, economic tiers such as developed and developing world, and even megacity regions. Harmonizing levels of aggregation among systems is required for effective comparison. This has not been attempted in any deliberate manner yet.

Role of Adjustment Indexes in Comparing Benchmarking and Metrics Programs

One purpose of adjustment indexes is to adjust input and output numbers so that productivity calculations can be compared over time and between industry sectors and countries. Therefore, adjustment indexes are important to understand for the purpose of this paper. In fact the reason that the United States has not tracked the productivity of the construction industry until recently is that it did not have a good output price index. Harrison (2007) describes the following index types:

- Input price indexes (e.g., *Engineering News Record* building and construction cost indexes)
- Output price indexes (see Table C.4)
  —Disaggregate
  —Aggregate
- Quality indexes
- Hedonic indexes
- Wage rate indexes
- Industrial product indexes

Comparison of National Construction Productivity Analyses

Harrison (2007) calculates U.S. construction productivity at the national level based on the National Economic Accounts and Industry Economic Accounts of the Bureau of Economic Analysis (BEA). He estimates that between 1961 and 2005, construction productivity in the United States declined at 1.44 percent annually. He notes that construction labor productivity growth was positive for Canada in the same period (Table C.5), but he also points out that within Canada, the construction labor productivity growth rates vary substantially from province to province, by as much as 2 percent per year, and compared to Canada's average construction labor productivity, rates vary by as much as plus 18 percent and minus 33 percent depending on the province. Harrison (2007) also points out that underestimates of output quality (via deflators) may shave almost half a percent per year from the true construction productivity growth rate in Canada in the past two decades. Teicholz (2001) estimates a compound decline in the United States of 0.48 percent annually between 1964 and 1996 based on BLS and U.S. Department of Commerce data. His estimates vary slightly based on period. Goodrum et al. (2002) estimate a compound improvement in the United States of labor productivity of between 0.80 percent and 1.80 percent annually between 1976 and 1998, based on task level data from three sets of estimating manuals and 200 tasks. Clearly, uses of different sources of data, periods of analysis, levels of aggregation, and price indexes used as deflators make international comparisons difficult when measurements of only the two countries discussed vary so widely. Skepticism of any measurement system is therefore in order.

At the industry level, Chapman and Butry (2008) suggest continuing the BLS practice of using the North American Industry Classification System (NAICS) as a basis on which to assess U.S. construction productivity in the future. The BLS does keep labor statistics, but owing to output measurement problems it does not track construction industry productivity. However, the U.S. Census Bureau's Economic Census includes the value of construction work in terms of value added, every five years by NAICS code, so according to Chapman and Butry (2008) it is possible to generate industry-level metrics for each construction industry NAICS code, and they suggest a method for doing this. Harrison (2007), however, points out that Statistics Canada does not use the NAICS to estimate construction-sector productivity. Gross output for construction in Canada's System of National Accounts is based on types of construction rather than industrial class. Thus, comparing Canada's estimates at the national and sector levels to U.S. estimates of productivity may be problematic, if the NAICS is used in the United States.

A paper that analyzes the general business-sector labor productivity gap between the United States and Canada shows that Canada lags the United States by a factor of 0.82 to 1.00; however, construction stands out as an exception (Rao et al., 2004). Data selected from the paper for the United States and Canada are presented in Table C.6. Construction is one of the few industries in which Canadian capital intensity is close to the United States. Generally it lags substantially.

Additional sources of data exist that compare productivity and productivity growth rates across a large number of countries with advanced economies (Table C.7). It does not appear that any conclusions can be drawn based on those data concerning the relationship between growth rate and absolute level of productivity. Or, put more positively, it appears that having a high productivity level may not impede a country from improving even more at a high rate.

TABLE C.4 Comparison of Canadian and U.S. Construction Price Indexes

Indexes	Canada	United States
Hedonic		Census single-family houses under construction index (CSFHUCI)
Aggregated	New housing price index (NHPI)	
Disaggregated	Apartment building construction price index (ABCPI) Nonresidential building construction price indexes (NRBCPI); (warehouse, shopping center, school, office, light factory)	New warehouse building construction (2005) New school building construction (2006) New office building construction (2007) New manufacturing and industrial building construction (2008) Nonresidential electrical contractors (2008) Nonresidential plumbing, heating, and air-conditioning contractors (2008) Nonresidential roofing contractors (2008) Nonresidential concrete contractors (2008)

SOURCE: Adapted from Harrison (2007).

TABLE C.5 Some Comparisons of U.S. and Canadian Construction Productivity Growth Rates from Various Sources and Over Different Periods

Source of Estimate	Data Dimension	Canada	United States
Harrison (2007)	Construction labor productivity improvement rates (1961 to 2006) for Canada and (1961 to 2005) for United States	1.09%[a]	−1.44%[b]
Harrison (2007)	Construction labor productivity improvement rates per period for Canada	1.8% (1961 to 1981) 0.53% (1981 to 2006)	
Harrison (2007)	Construction labor productivity growth rates (1979 to 2003)	0.40%[c]	−0.84%[c]
Teicholz (2000)	Construction labor productivity growth rate (1964 to 2000)		−0.72%[d]
Goodrum et al. (2002)	Construction labor productivity growth rate (1976 to 1998)		0.80-1.80%[e]

[a] Based on Statistics Canada Labour Force Survey and System of National Accounts data.
[b] From the Bureau of Economic Analysis National Economic Accounts and Industry Economic Accounts.
[c] From Groningen Growth and Development Centre, 60-Industry Database.
[d] From Bureau of Labor Statistics and U.S. Department of Commerce data.
[e] Based on data from R.S. Means, Richardson, and Dodge estimating manuals.

TABLE C.6 Construction Productivity Comparisons Between Canada and the United States, 1997, 1999, and 2001

Data Dimension (United States = 1.00)	1997	1999	2001
Relative multifactor productivity in Canada	1.15	1.19	1.28
Relative labor productivity in Canada	1.15	1.20	1.29
Relative capital intensity in Canada	1.00	1.04	1.04

SOURCE: Data from Rao et al. (2004)

TABLE C.7 Construction Productivity Comparisons Among Countries

Country	Relative Productivity in the Construction Sector from the Swedish Construction Federation (United States = 100)	International Labor Productivity Growth Rates in Construction Industry, 1979 to 2003 Groningen Centre Data (Harrison, 2007)
Belgium	62	1.63
Finland	39	0.71
France	41	1.68
Greece	19	0.68
Ireland	48	1.64
Italy	38	0.95
Norway	56	1.40
Spain	44	1.54
Sweden	76	0.79
United Kingdom	20	1.92
United States	100	−0.84
Canada	120[a]	0.40
South Korea		2.56
Austria		2.43
Portugal		1.78
Australia		1.33
Denmark		1.24
Netherlands		1.21
Japan		−0.06
Germany		−0.06

[a] From Rao et al. (2004).

CHANGES AND INNOVATIONS

While commonalities exist, construction industry change and innovation strategies vary significantly among different countries. Comparing different countries' approaches through a set of change and innovation metrics would be desirable but is beyond the scope of this paper. Instead, an anecdotal summary of the highlights of change and innovation management approaches, as well as particularly interesting innovations, is provided for several countries in the following subsections. However, first this summary is placed in context with a brief discussion of innovation in construction.

Innovation in Construction

The construction industry has been characterized by its slow adoption of innovations, although it has been observed by some that the rate of adoption has been accelerating internationally in the past 10 years. In most of the nations reviewed in this paper, numerous impediments to innovation adoption are typically claimed, including the following:

- Human and institutional resistance to change;
- The perception of unacceptable additional project risk associated with innovations;
- Fragmentation of the industry nationally, resulting in lack of a financial mass required to pursue innovation, maintain intellectual property ownership, and manage knowledge effectively;
- Unique products that defy the easy adoption of mass manufacturing principles and innovations;
- A unique combination of delivery method, design standards, and legal structure for every project; and
- A focus on the short project construction phase for an economic planning horizon rather than on overall life-cycle costs.

Potential solutions to these problems have been proposed, including the following:

- Sustaining the effort and staying focused;
- New business models for sharing risk, such as vendors who market innovation as a service;
- Shared learning frameworks within trusted networks;
- Better design of innovations; and
- Pursuing explicit innovation deployment procedures and programs.

A tremendous amount of academic research has been done in the area of innovation in the construction industry. Many papers related to this subject were published in the 1970s, 1980s, and 1990s in construction research journals (for example, by Abernathy and Utterback, 1978; Carr and Maloney, 1983; Carr and Lane, 1999; Tatum, 1989; Slaughter, 1993, 1998). Recent work by Chinowsky for CII also offers some insight into the construction innovation life cycle.

Although considerable strides have been made in terms of the application of a number of these innovations over the past 20 years, the adoption and acceptance of new ideas, methods, processes, and equipment are considered to happen at a snail's pace in the construction industry compared with other industries. Several organizations have tried to tackle this problem, with varying degrees of success, including for example the Civil Engineering Research Foundation(CERF) and FIATECH. However, the overall lack of success in accelerating the adoption of innovation in the industry continues to be disappointing.

Organizations such as FIATECH, NIST, CERF, and some of the successful university-based construction research programs might be considered models of how to proceed from a government or university point of view. Specific companies are also considered innovative in the industry. Something might be learned by visiting one of the large Japanese construction company research laboratories, such as Shimizu. Shimizu is extremely innovative, but it is not necessarily competitive beyond the Japanese environment. Arup is an example of a European-based construction company that is extremely innovative. While innovation cultures may exist in some companies, it is hard to identify countries whose construction industries could be considered particularly innovative. Still, it is clear that a few regions and countries have made or are making immense efforts to change this situation. South Korea is a particularly apt example.

South Korea

South Korea, like many economically advanced nations, has a government-sponsored national construction research laboratory. In this case it is the Korea Institute of Construction Technology (KICT). With close to 600 personnel and with a scope that includes construction, structures, water resources, building science, and roads and transportation, it is similar in function to a combination of the Federal Highway Administration and NIST in the United States. Its mission includes coordinating research and development (R&D) in construction technology in South Korea and acting as a center for knowledge and information on construction technology.

The Korea Institute of Construction Engineering and Management (KICEM) is a leading professional membership society of construction engineering and management professionals and corporations in South Korea with more than 3,000 members. KICEM focuses on construction-, engineering-, and management-related research projects, knowledge transfer, and consulting. University professors, researchers, and experts from industry have been involved in these projects.

South Korea has a vibrant university-based national construction technology research program. Many of the professors leading this research acquired their graduate degrees from U.S. research institutions and are now leading world-class research programs. Given the level of professional distinction, the profile of the national laboratories, and the activity and quality level of the academic researchers, it is clear that construction engineering and management have a high degree of prestige in South Korea. Following are examples of current, university-based research projects and associated funding levels:

1. Construction Automation Research Projects and CALS/EC Research Projects
    - Microelectromechanical systems-based Wireless Vibration Sensor for Tunnel Construction and Maintenance (2004 to 2009)
    - Next-generation Construction Supply Chain Management System (2006 to 2009)
2. Technology Fusion Research Projects
    - Intelligent Earthwork Robots (2006 to 2011)—approximately $12 million U.S. dollars (USD) funding level
    - Automated Construction System in Korea (2006 to 2011)—approximately $12 million USD funding level
    - Virtual Construction (2006 to 2011)—approximately $16 million USD funding level

Japan

Japan's construction technology reputation rose to prominence in the late 1980s and early 1990s with its leadership in construction robotics and automated high-rise construction systems such as Taisei corporation's T-Up^{TM} system, Obayashi corporation's ABC^{TM} system, and Shimizu corporation's SMART^{TM} system (Haas et al., 1995). These were attempts at the complete automation and integration of processes and technology, including modularization, just-in-time delivery, use of robotics, rigid supply chain management, and innovations in connections and assembly methods. Most construction technology and management research in Japan occurs in the laboratories of its seven largest construction firms, which dominate the domestic market, and is mandated to some extent by the government as an investment of part of these firms' income. While these automated systems were fully implemented and deployed (in the case of the SMART system, at least three high-rises were built using this technology), the labor savings that were expected did not completely materialize. All told, these R&D and deployment efforts, which were coordinated by Japan's Ministry of International Trade and Industry, represented a level of effort of many hundreds of millions of dollars at that time. From a business point of view, these programs would likely be considered failures, as they resulted in virtually no new international business for the large Japanese construction firms based on these technology developments. While some useful technologies were salvaged from these efforts, the reaction to the experience as a whole has been severe. A visit to Shimizu's corporate Web site indicates a focus on sustainability and earthquake engineering but virtually nothing on automation.

It is possible that the Japanese were simply ahead of their time. For example, "stakeless" earthmoving in the United States has been adopted at an extremely rapid pace, owing to its potential to reduce costs and improve productivity by approximately 50 percent. (Stakeless earthmoving is construction robotics by another name.) Modularization is enjoying tremendous popularity now in North America, and supply chain management has become a recent focus of many firms on the basis of the capabilities created by radio-frequency identification (RFID) tags, Global Positioning Systems, and wireless communications.

The European Union

Europe currently has several major EU-wide construction management and technology development efforts. Each is driving innovation in a number of key areas.

ENCORD is the European Network of Construction Companies for Research and Development.[6] According to the ENCORD position and strategy paper (2009), ENCORD is a network of construction industry decision makers and executives involved in R&D issues. The paper states: "ENCORD currently has 20 members with head offices in 9 European countries and operations worldwide. All members are major European contractors and suppliers of construction material, and are strongly devoted to R&D for increased competitiveness and growth. ENCORD's main objective is to be Europe's forum for the promotion of industry-led research, development and innovation in the construction sector" (ENCORD, 2009, p. 2). ENCORD's priorities for action include these:

- Sustainable construction,
- Lean construction,
- Virtual construction and information and communications technology (ICT),
- Transport infrastructure,
- Health and safety,
- Knowledge management,
- Implementation of research activities, and
- A carbon disclosure project.

The European Construction Sector has developed a European Construction Technology Platform (ECTP) based on input from more than 600 industry partners as part of its strategic research agenda for achieving a sustainable and competitive construction sector by 2030 (ECTP, 2005).[7] ECTP's strategic priorities include these:

- Meeting Client/User Requirements
    1. Healthy, Safe and Accessible Indoor Environment for All
    2. A New Image of Cities
    3. Efficient Use of Underground City Space
    4. Mobility and Supply Through Efficient Networks

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[6] See http://www.encord.org.
[7] See http://www.ectp.org.

- Becoming Sustainable
    1. Reduce Resource Consumption (energy, water, materials)
    2. Reduce Environmental and Man-Made Impacts
    3. Sustainable Management of Transport and Utilities Networks
    4. A Living Cultural Heritage for an Attractive Europe
    5. Improve Safety and Security
- Transformation of the Construction Sector
    1. A New Client-driven, Knowledge-based Construction Process
    2. ICT and Automation
    3. High Added-value Construction Materials
    4. Attractive Workplaces

The European Construction Sector intends to carry out its agenda by (1) removing barriers to innovation, (2) developing a single European construction market, (3) implementing the research, (4) supporting training and education, and (5) linking with other industry Technology Platforms. The main deliverable to date appears to be a proposal for the creation of a Joint Technology Initiative (JTI) on Energy Efficient Buildings—E2B JTI. Its overall objective "is to deliver, implement and optimise building and district concepts that have the technical, economic and societal potential to drastically cut the energy consumption and reduce CO_2 emissions due to existing and new buildings at the overall scale of the European Union."[8] This JTI will be financed equally by at least nine industry members and the European Commission. For other JTIs, apparently EU member states may contribute funding as well.

Assuming that these broad visions and joint initiatives represent the views and commitment of the leaders in the European construction industry, they must be considered innovations in the sense that they represent an attempt to collaborate and combine resources to become more competitive as individual corporations and internationally as an industry. However, it is impossible at this point to determine if they have had significant impact.

The United Kingdom

Construction innovation in the United Kingdom is impacted by some unique drivers. The United Kingdom has experienced a massive influx of Eastern European construction workers and a substantial commercial and residential building boom (only now grinding to a halt). As noted by Professor Patricia Carrillo,[9] the UK government has also been pushing hard on innovation and supporting joint industry-and-government-funded research through various schemes. She points out the importance of the Latham Report (1994), the Egan Report (Strategic Forum for Construction [1998]), and its follow-up report (Strategic Forum for Construction [2002]), which forced the UK construction industry to look seriously at how they work together and how to improve performance. She says that the Fairclough Report (2002) adopted another approach: "It basically said that we are not very good at learning and innovation and we need to think more strategically about how we do R&D if we want to keep ahead of the pack." Her observation is that these efforts combined "to make the industry more productive and professional."

Professor Edum-Fotwe, an expert in the UK construction industry, made several observations:[10]

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[8] Available at http://www.ectp.org/default.asp.

[9] E-mail correspondence from Professor Patricia Carrillo, University of Loughborough, United Kingdom, October 10, 2008.

[10] Telephone interview with Professor F. Edum-Fotwe, University of Loughborough, United Kingdom, October 7, 2008.

1. The delay period for acceptance of innovation has been shrinking radically in the past several years.
2. Computing power and data overload are facilitating the return of parametric data analysis, last popular in the 1960s. Perhaps this is driving data mining as well.
3. Institutions such as the University of Loughborough, which have significant construction engineering and project management educational and research programs, are developing graduates with a much broader range of skills, including management and leadership skills, than in the past.
4. Large UK construction firms are operating in a strategic and sophisticated manner.
5. Innovations in the UK construction industry may have been more at the management end of the spectrum than the technology or engineering end.

Professor Alistair Gibb has pointed out the ascendance of prefabrication in the United Kingdom, closely paralleling the North American experience, due to its significant labor productivity advantage over on-site fabrication.[11] Nonetheless, he notes that labor in the United Kingdom is not dominated by trade unions and that there has been a significant increase in multi-skilling in the United Kingdom in the past two decades.

Perhaps some of the most significant shapers of the UK industry in the past two decades were initiatives led by Professor McCaffer at the University of Loughborough, including the establishment of the European Construction Institute (ECI). Established in 1990, ECI's mission is to develop and maintain a sustainable, performance-based culture across the industry. It includes more than 60 organizations from the private and public sectors, representing the spectrum of the construction industry across Europe. Its member companies meet at conferences, workshops, seminars, and master classes organized by ECI, and it has produced more than 70 major reports dealing with project best practices that have helped innovative companies to move ahead.

Sweden

According to its Web site,[12] the Swedish Construction Federation (BI) (Sveriges Byggindustrier) represents the interests of the construction industry in Sweden. BI is the trade and employers' association of the private construction companies. Among its 3,000 member companies, there are about 20 groups with more than 100 employees. One of its companies, Skanska, is one of the top 10 constructors in the world. BI is noted in construction research circles for its active involvement internationally, led by its research director, Pär Åhman. (BI funded the study providing the data for Table C-7 in this paper.) Sweden's construction industry is also known for the high level of pay for its craft labor and the high level of independence afforded construction crews in Sweden. Sweden is an example of a small country that achieves global competitiveness in select industries, partly through the explicit policy and support of its government.

Canada

Canada has an economy several times larger than Sweden's but 10 times smaller than the U.S. economy. Although it looks similar to that of the United States, it is significantly different in many ways. For example, the proportion of the construction workforce in the United States that is organized is about 17 percent. It is well over 40 percent in Canada (varying widely by region). In Canada, craft training is generally jointly financed by employers, the provincial governments, and the workers themselves in

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[11] E-mail correspondence from Professor Alistair Gibb, University of Loughborough, United Kingdom, October, 8, 2008.

[12] See http://www.bygg.org/in_english.asp.

formal government-legislated apprenticeship programs that span open- and union-shop sectors. Canada has a construction engineering and project management research community that is very well connected and coordinated. It includes more than two dozen university professors and their programs, as well as government laboratories such as the Canadian National Research Council's Institute for Research in Construction (IRC), which is the leading construction research agency in Canada. IRC focuses on developing innovative solutions for the country's largest industry. Its capabilities are very similar to those of NIST's Building and Fire Research Laboratory.

Canada has also had several industry-led construction research groups, including, for example:

- Canadian Construction Institute,
- Canadian Construction Innovation Council,
- The Construction Owners Association of Alberta, and
- The Construction Sector Council.

In addition, Canada has a national policy of matching industry funding for research with government funding, in order to leverage such efforts. The Natural Sciences and Engineering Research Council Collaborative Research and Development Grant program and the Ontario Centres of Excellence program are two such programs. It is unclear what the impact of the preceding programs and environment has had on Canada's construction industry productivity and competitiveness. Other than such programs, it is also not clear that Canada has been more innovative than the United States has been.

United States

Relatively little discussion is required of the United States, since most readers will be familiar with its approach to change and innovation in construction. There is no central authority in the United States for the construction industry or for construction research, unlike the U.S. transportation, health, and other industries of comparable size. Innovation and change are driven by the pressure of open competition and are aided by some coordinated research programs, including the Construction Industry Institute; NIST's Building and Fire Research Laboratory; the National Science Foundation (NSF) programs; state department of transportation research programs, which often include infrastructure construction research elements; FIATECH; subcontractors associations; CPWR: The Center for Construction Research and Training; and others. FIATECH has proposed a technology road map that is widely admired, but underfunded. CII and a group of researchers have twice proposed visions for construction productivity improvement and innovation to be funded as a collaborative Engineering Research Center (ERC) among NSF, CII, and several universities (Figure C.2). These multimillion-dollar ERC proposals have failed to be funded.

FINAL OBSERVATIONS

In the preceding sections, international benchmarking and metrics efforts were reviewed, and productivity metrics for different nations were compared. The remainder of the paper focused mostly on a description and comparison of innovation and improvement strategies, preceded by a discussion of innovation theory. Not enough data exist to make any firm conclusions, but some observations may be hazarded:

1. A high productivity level for a nation probably does not impede that nation from improving even more at a high rate.
2. Innovations are being shared almost immediately internationally by means of academic and business links, partially facilitated by the Internet.

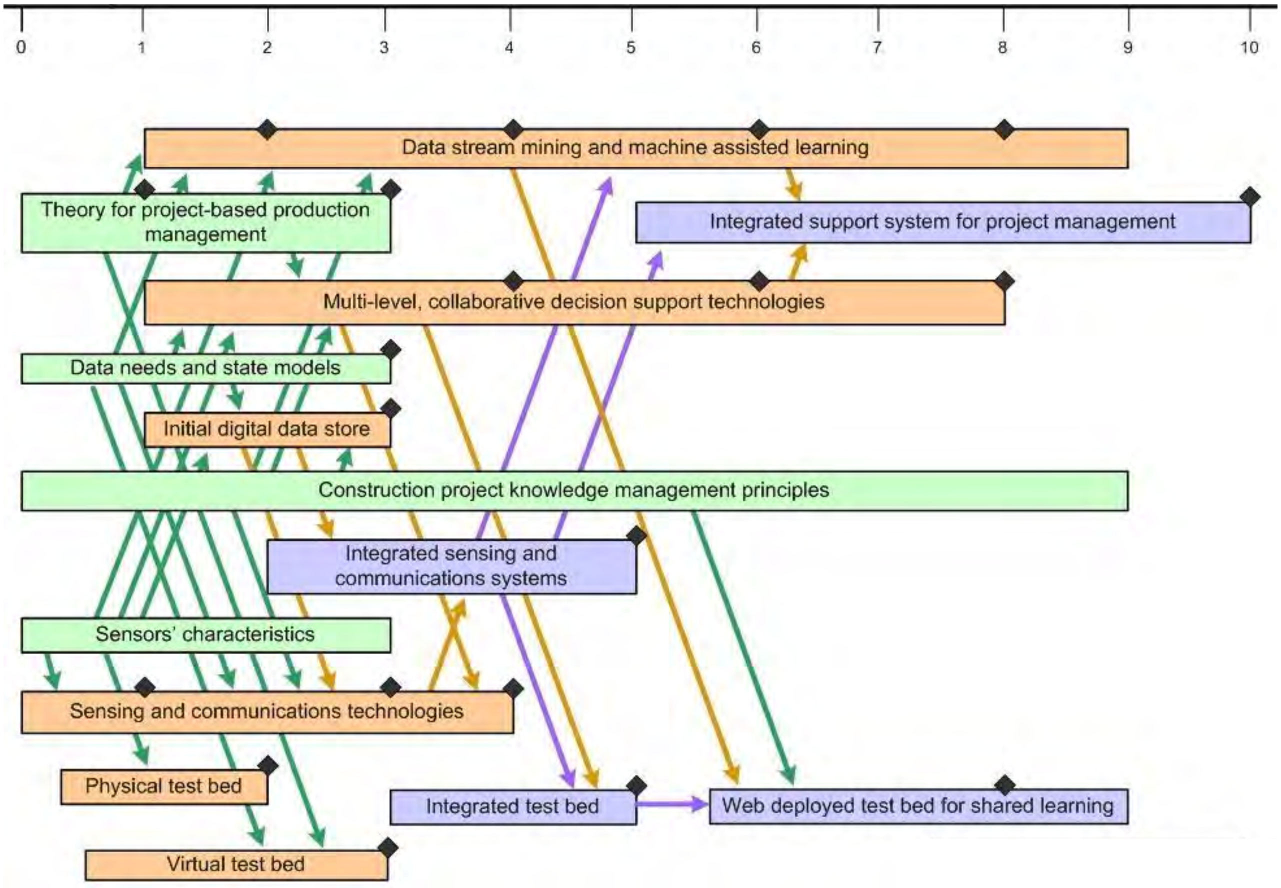

FIGURE C.2 Vision for the proposed Engineering Research Center for Collaboration, Control, and Communication in Construction (C5). SOURCE: Adapted from material in an unfunded proposal.

3. Since innovative ideas are quickly shared, what differs among nations is emphasis.

4. At the leadership level, the Europeans tend to focus on sustainability and customer satisfaction as related to competitiveness rather than on more prosaic concerns such as labor productivity. To pursue these, they have developed visionary research programs, and while their productivity in construction is increasing at a high rate, in an absolute sense it is still significantly lower than that of the United States.

5. The Japanese have radically reduced their emphasis on automation and are focusing instead on sustainability, green buildings, and earthquake engineering. The structure of their industry is still highly hierarchical, and most contracts are still negotiated.

6. The South Koreans are moving aggressively and are investing many 10s of millions of dollars into construction technology research in a very coordinated program that tends to merge the U.S. and EU topic areas.

7. The United Kingdom has a less organized workforce and more innovative project management structures than those of the United States, and it is focused on competitiveness more than on labor productivity.

8. On an international scale, some experts and economists have observed that such productivity in construction (particularly labor productivity) tends to correlate with gross national product per person

and with wage rates. Perhaps, higher prevailing wage rates force investment in capital and technology, thus improving at least labor productivity.

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D

Technical Change and Its Impact on Construction Productivity

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Abstract Over time, technology has changed many construction processes. It may be debatable whether the construction industry has leveraged technology to its fullest, but there is little doubt that where technology has had an impact, there has also been significant improvement in construction productivity. This paper examines characteristics of technical change among construction equipment, materials, and information systems and among construction activities and processes. Understanding how distinct characteristics among construction equipment, materials, and information systems are related to improvements in construction labor productivity may help aid the development of future innovations. Much research is needed, however, to lead to an understanding of how technical change has improved the quality characteristics of the construction industry's output and the potential impact that this has on the industry's productivity measures.

INTRODUCTION

From the perspective of a casual observer, the U.S. construction industry can appear to be less technically progressive than other U.S. industrial sectors. The industry is perceived to involve primarily tedious, dirty, and physically exhausting work. As a testament to this perception, a popular career guide recently ranked the occupation of a construction worker (laborer) as 244th out of a possible 250 career choices (Krantz, 2002). Technological improvements have dramatically changed the process of construction over the past couple of decades as well as the quality of construction output. Unfortunately, the industry measures both outcomes poorly. The perceived lack of technological change is a primary argument supporting the belief that construction productivity has been declining since the 1960s (Rosefielde and Mills, 1979), which influences workforce strategies, research programs, and industry perceptions, and it is based on a number of productivity studies using industrial, macroeconomic data (Stokes, 1981; BRT, 1983; Allen, 1985).

As a whole, the United States has enjoyed almost continuous productivity growth for the past several decades and especially strong growth in the past decade. In a relatively recent research effort, Triplett and Bosworth (2004) identified that much of the nation's productivity growth could be attributed to improved production of information technology (IT), increased use of IT, increased competition due to globalization, and changes in workplace practices and firm organizations. However, Triplett and Bosworth (2004) also point out that construction bucked this trend by experiencing negative productivity growth during the time period of their analyses, 1995 to 2001.

However, other studies have produced contradictory data. Research conducted through the Sloan Center for Construction Industry Studies at the University of Texas at Austin examined labor and partial factor productivity trends using microeconomic data for 200 construction activities as part of a larger effort to analyze the relationship between equipment technology and construction productivity (Goodrum et al., 2002). The results indicated widespread improvement in construction labor productivity across multiple construction divisions ranging from 0.2 percent to 2.8 percent per year between 1976 and 1998, especially in machinery-dominated divisions such as site work. Similar improvement was observed in partial factor productivity among the 200 construction activities. In a more recent effort to examine the relationship between material technology and construction productivity, the average percentage change in the labor productivity of an additionally sampled 100 activities was found to have an annual improvement compound rate of 0.47 percent between 1977 and 2004 (Goodrum et al., 2009). In addition to these measured improvements, there is anecdotal evidence shared among some industry practitioners that construction productivity has actually improved (Bernstein, 2003; Tuchman, 2004; Harrison, 2007).

The potential reasons explaining the discrepancy between macro and micro measures of construction productivity are numerous, with most of the focus on issues relating to the accuracy of industry measures, particularly on the inflation indexes used to measure industry real output. The concerns range from overreliance on the use of proxy inflation indexes to deflate construction expenditures (Pieper, 1990), to the use of input cost inflation indexes instead of the preferred output price indexes (Dacy, 1965; Gordon, 1968; and Pieper, 1990), and the challenge of measuring the change in the quality of industry output (Rosefielde and Mills, 1979; Pieper, 1990; Gullickson and Harper, 2002).

One alternative to using industry data to measure construction productivity is to use micro productivity data, which are typically reported in units of physical output per unit of input among construction activities. However, activity productivity data suffer their own measurement issues. In previous studies in which the writer has used activity productivity data (Goodrum et al., 2002; Goodrum and Haas, 2002, 2004; and Goodrum et al., 2009), the primary source of activity data has been commercial estimation manuals, which are often used by construction industry professionals for estimating the cost of a project. Previous studies have sampled 100 to 200 construction activities for the purposes of analyses, but the assumption that the measured changes in productivity among the observed activities actually reflect change throughout all of the construction industry has largely rested on sample size only. Weighting discrete activities to reflect their frequency of occurrence in the industry could help resolve this in part, but previous efforts by the writer have not attempted this. In addition, estimation manuals typically collect their data from contractors in multiple cities throughout the United States, but the methodology—precisely how the data are collected, the survey forms used, and the frequency at which both output and cost data are updated for every activity—is not documented in the public domain. Finally, contractors who submit information for the estimation manuals know that they are not required to construct a project using their own estimations, and this tends to create inflated estimates of construction costs (Pieper, 1989). Regardless, the annually published manuals are sold in volume for commercial use to a multitude of construction contractors, owner companies, and governmental agencies, all of which use the estimation manuals to predict project performance.

Outside of commercial estimation manuals, there are relatively few sources of other micro productivity measures in the construction industry. One source is the Construction Industry Institute (CII) through its Benchmarking and Metrics (BM&M) program. Primarily focused on the industrial construction sector, the BM&M program aims to measure and assess capital project performance and find the best practices among similar projects. The BM&M data set is intended to allow participating companies to compare performance on their projects with similar projects and to help companies identify practices that may improve their respective projects. The database currently includes 86 projects, providing information about field practices and labor productivity. The field practices include different aspects of job-site management systems, such as materials management, constructability, and automation and integration of project systems, among others. The database collected activity productivity data on a variety of construction tasks among seven trades. The BM&M productivity metrics were identified through the use of literature reviews, documentation from owner and contractor organizations, and a series of workshops with industry experts. Details on its methods of data collection and standard accounts have been well documented elsewhere (Park et al., 2005).

The combination of the commercial estimation manuals and the CII BM&M database affords an opportunity to examine the relationship between construction productivity and technical change at a microlevel, which is the general focus of the discussion that follows. The paper examines the relationship between technical change and construction productivity in three sections based on the primary components of construction technology: equipment, material, and information technology. Each section examines previous research both by the writer and by other researchers. Using data from commercial estimation manuals, the sections addressing research on equipment and material technology examine the longitudinal relationship between the respective change in these technologies and corresponding changes in productivity. Considering the relatively new implementation of information systems in construction, the paper compares the use of automation and integration information technologies and reported levels of productivity across multiple projects using data from the CII BM&M database. Together, these sections present a comprehensive perspective regarding the relationship between technology and productivity in the construction industry.

EQUIPMENT TECHNOLOGY

Koch and Moavenzadeh (1979) completed one of the first research efforts that focused on the relationship between technology and construction productivity by examining the change in equipment and unit labor costs for various road construction activities over three time periods: the 1920s, 1950s, and 1970s. Controlling for inflation, Koch and Moavenzadeh noted how unit costs had continuously dropped over all three time periods. Figure D.1 shows an example of Koch and Moavenzadeh's analyses involving the change in unit costs of excavation and hauling material over a 100-meter distance. They found that unit costs using the equipment technology from the 1970s were consistently the lowest in all three time periods, despite finding dramatic increases in labor and equipment costs through the 1930s, 1950s, to the 1970s. Koch and Moavenzadeh believed that these increases were offset by increased efficiency due to advancement in equipment technology. They found that increased usage and advancements in equipment technology were two primary causal agents. Furthermore, the capital costs of many activities increased while the relative labor costs declined reflecting an increase in the use of technology (Koch and Moavenzadeh, 1979). In addition, the rate of productivity improvements appeared to decline over time, with most improvements occurring from the 1930s to the 1950s when machine power innovations were introduced.

Koch and Moavenzadeh (1979) did note that the greatest changes in technology and improvement in efficiency occurred from the 1930s to the 1950s. In the 1930s, "Small capacity, unpowered equipment operated largely by unskilled laborers with horses or mules as a source of power and a few skilled men acting in a supervisory role was most common" (Rossow, 1977). By the 1950s, equipment became powered and larger in capacity and was operated mostly by skilled laborers, with occasional help from unskilled assistants. The equipment technology transitions by the 1970s were not as great and can be seen in Figure D.1 in the smaller improvements in unit costs from the 1950s to the 1970s. By the 1970s, the changes primarily involved equipment that had become more powerful and larger in capacity, with only a few new types of equipment (Rossow, 1977). Although hydraulics had advanced controls of machinery, Rossow (1977) did not discuss advancements in machinery control as being significant.

In a more recent research effort, Allmon et al. (2000) examined the impact of technology as well as real wages on productivity through a case study analysis of six construction activities. Using cost and output data from the *R.S. Means Building Construction Cost Data*, productivity was found to have increased in all six activities between 1976 and 1998. The study also found that some of the greatest increases in productivity were directly connected with the introduction of new, more technically advanced equipment. The study concluded that many of the improvements in productivity could be attributed to changes in technology. However, the research did not measure technology intensity, nor did it address the different types of changes in equipment technology and their relative importance with respect to productivity. It did, however, provide groundwork for a more thorough statistical analysis, which research by Goodrum and Haas (2002) addressed.

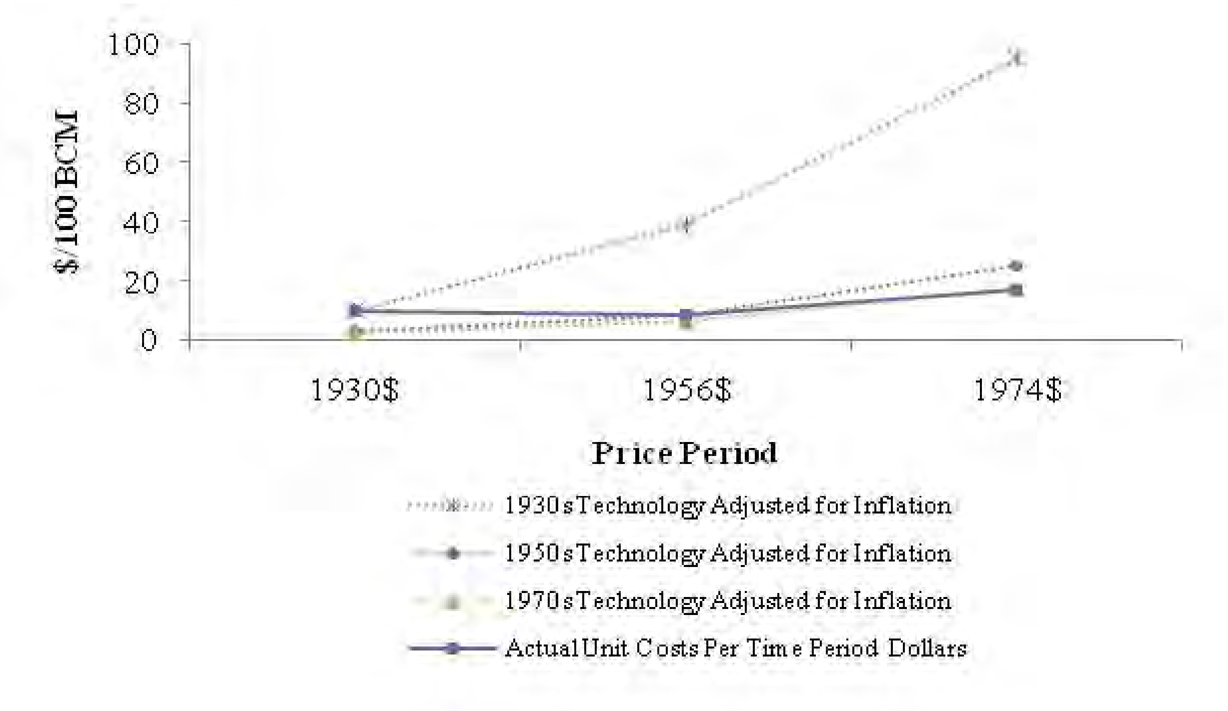

FIGURE D.1 Unit costs of hauling of each technology period for excavation/hauling at 100 meters at prices of 1930, 1956, and 1974. NOTE: BCM, bank cubic meter. SOURCE: Rossow (1977).

Goodrum and Haas (2002) examined the influence of equipment technology on construction productivity through a series of longitudinal studies that examined the changes that had occurred in the equipment technology and productivity of 200 construction activities between 1976 and 1998. Data were collected for years 1976 and 1998 on 200 construction activities from the *R.S. Means Building Construction Cost Data* (Means Company, Inc., various years), *Richardson's Process Plant Construction Estimating Standards* (Richardson Engineering Services, various years), and *F.W. Dodge Unit Cost Books* (McGraw-Hill Inc., various years).

One of the challenges in analyzing productivity statistically is that each construction activity has a different unit of measurement. For example, a concrete placement activity's multifactor productivity may be measured in cubic yards of concrete placed per unit cost, while structural steel placement may be measured in linear feet of steel placed per unit cost. Using relative instead of absolute values is one way to solve this issue. Thus, the percentage change in productivity from 1976 and 1998 was used by Goodrum and Haas (2002).

Expected physical output and crew formation data from the estimation manuals were used to calculate each activity's labor productivity (Equation D.1). Expected physical output, labor input cost, and equipment input cost data from the estimation manuals were also used to calculate each activity's partial factor productivity (Equation D.2).

$$\text{Labor Productivity, Year X} = \frac{\text{Expected Physical Output (Units)}}{\text{Workhour Requirements (Hrs)}} \qquad \text{D.1}$$

$$\text{Partial Factor Productivity, Year X} = \frac{\text{Expected Physical Output (Units)}}{\text{Labor Cost (1990\$) + Equipment Cost (1990\$)}} \qquad \text{D.2}$$

Input costs in partial factor productivity were deflated to 1990 dollars using the Construction Cost Index (CCI) from *Engineering News Record*. Note that Equations D.1 and D.2 assume that physical output measures do not change in quality. This is based on the assumption that changes in quality would be minimal, since the research examined construction activities that had not changed in scope between 1976 and 1998.

Next, the percentage change in labor and partial factor productivity from 1976 to 1998 was measured for each activity using equations D.3 and D.4:

$$\text{\% Change in Labor Productivity, '76-'98} = \left(\frac{\text{Labor Productivity, '98} - \text{Labor Productivity, '76}}{\text{Labor Productivity, '76}} \right) \cdot 100 \qquad \text{D.3}$$

$$\text{\% Change in Multifactor Productivity, '76-'98} = \left(\frac{\text{Partial Factor Productivity, '98} - \text{Multifactor Productivity, '76}}{\text{Multifactor Productivity, '76}} \right) \cdot 100 \qquad \text{D.4}$$

Note, there is a weakness in using just two points in time to measure the change in productivity, since the results can be affected by the choice of the two years. Particularly, it is noted that 1976 was a year of stagflation and excess capacity in the United States. It is expected that fluctuations in the change in productivity would occur in a year-by-year analysis. However, by examining the changes in productivity over a 22-year time period, the research was designed to focus on the long-term trends in construction productivity.

The average change in labor and partial factor productivity of the activities overall for each data source is shown in Table D.1. All three manuals indicate that labor and partial factor productivity increased from 1976 to 1998. The *R.S. Means* manual reveals a 0.8 percent compounded annual rate of improvement in labor productivity, *Richardson* a 1.2 percent increase, and *Dodge* a 1.8 percent increase. For partial factor productivity, *Means* shows a 0.7 percent increase, *Richardson* a 0.7 percent increase, and *Dodge* a 2.9 percent increase. The different estimates of productivity improvement are partially a reflection of the different distribution of types of construction activities in different divisions for each manual.

Next, activities were grouped by Construction Specification Institute (CSI) Masterformat construction division, and the compounded annual rate of change in labor and partial factor productivity was calculated for each division (see Table D.2). It is clear from this sample that different sectors of the construction industry experienced varying degrees of change in productivity. On average, site-work activities experienced the greatest improvement in labor and partial factor productivity. Electrical activities, moisture-thermal protection, and woods and plastic activities experienced the smallest improvements in labor and partial factor productivity. Further research is required to determine the reasons for the differences in productivity change by division.

TABLE D.1 Estimates of Labor and Partial Factor Productivity Trends (1976 to 1998), by Data Source

Data Source	Activity Sample Size	Labor Productivity: Compounded Annual Rate (total change)	Partial Factor Productivity: Compounded Annual Rate (total change)
Means Building Construction Cost Data	100	+0.8% (19.1%)	+0.7% (17.4%)
Richardson Process Plant Construction Estimating Standards	50	+1.2% (30.2%)	+0.7% (18.1%)
Dodge Unit Cost Books	50	+1.8% (48.6%)	+2.9% (88.5%)

TABLE D.2 Compounded Annual Rate of Change in Labor and Partial Factor Productivity for Activities, by Construction Division, from 1976 to 1998

Construction Division	Change in Labor Productivity 1976-1998 Compound Annual Rate (total change)	Change in Multifactor Productivity 1976-1998 Compound Annual Rate (total change)
Sitework	+2.8% (83.5%)	+2.4% (66.9%)
Doors and windows	+1.6% (43.1%)	+1.8% (47.8%)
Metals	+1.5% (25.6%)	+1.0% (25.1%)
Finishes	+1.2% (29.1%)	+1.6% (37.5%)
Masonry	+1.2% (28.8%)	+0.8% (25.0%)
Concrete	+1.1% (26.3%)	+1.4% (34.4%)
Mechanical	+1.0% (25.3%)	+1.4% (35.1%)
Wood and plastic	+0.3% (7.7%)	+0.4% (17.5%)
Moisture and thermal protection	+0.2% (4.7%)	+0.6% 14.9%)
Electrical	+0.0% (0.2%)	+0.8% (18.6%)

SOURCE: R.S. Means, Richardson, and F.W. Dodge estimation manuals.

To begin examining how the changes shown in Tables D.1 and D.2 are related to simultaneous improvements in equipment technology, five factors were identified (defined below) that characterize significant changes in equipment technology related to improvement of the productivity of construction activities:

- *Amplification of human energy*—Amplification of human energy involves technology designed to make an activity physically easier to perform. In its simplest terms, this amplification can be regarded as the shift in energy requirements from human to machine and causing an increase in machine output (e.g., revolutions per minute, horsepower). As examples, welding machines increased wattage output, and powder-actuated systems offered greater depth penetration for installing studs in metal decking. Further, most site-work machinery offered increased horsepower output (e.g., front-end loaders, dump trucks, backhoes, bulldozers, graders, asphalt pavers, and scrapers).
- *Level of control*—Level of control relates to advances in machinery and hand tools that transfer control from the human to the machine. Welding machines in the metals division, for instance, are now equipped with remote-controlled amperage adjusters, and powder-actuated systems have semiautomatic loading capabilities. The pneumatic nail gun has replaced the handheld hammer in the wood and plastic division as well as in formwork installation in the concrete division.
- *Functional range*—Changes in equipment's functional range expand a tool's or machine's range of capabilities. Through advances in hydraulic controls and microprocessors, machinery for site work now offers more control precision and a greater reach with booms and buckets.
- *Information processing*—Over time, construction equipment has been designed to provide greater and more accurate information regarding internal and external processes. Almost all of the advances in information processing occurred in heavy machinery with the development and improvement in engine performance monitoring and self-diagnosis systems.
- *Ergonomics*—Ergonomics involves technology that helps the human operator to best cope with the work environment (Oborne, 1987). Construction workers are exposed to high noise levels, dust, weather, and other external factors, which can cause worker fatigue and thereby reduce efficiency.

Advances in construction equipment technology have addressed these concerns. For example, operator stations on heavy machinery have been designed to provide a quieter environment with less vibration. Hand tools have been designed with molded grips to better fit in a worker's hand for greater comfort.

The activities that experienced improvement in the above equipment technology traits experienced more improvements in labor and partial factor productivity than those activities that did not, and this finding was statistically significant in a series of analysis of variance (ANOVA) results (Table D.3). Activities experiencing an improvement in energy, control, functional range, and information processing had at least twice as great an improvement in labor and partial factor productivity as the improvement of activities experiencing no improvement in the technology factors.

Ergonomics was not statistically significant in any of the ANOVA results. Although it is widely believed that alleviating the physical stresses of the workplace would allow operators to be more productive, this relationship was not seen in the quantitative analyses. Perhaps ergonomic changes reduce insurance costs through a reduction in workers' compensation and health insurance claims, but this study did not measure the insurance costs by activity.

Previous research included regression models of the equipment technology characteristics on changes in both labor and partial factor productivity (Goodrum and Haas, 2002, 2004). The models used a series of technology measures, including changes in capital-to-labor costs for each activity. In addition, the research developed an equipment technology index, which is detailed in Goodrum and Haas (2004) but can be briefly described as a scoring system based on the five equipment technology characteristics considering each activity's hand tools and machinery. Furthermore, the regression models examined a series of dichotomous variables to estimate the influence of the five equipment technology factors (energy, control, functional range, information processing, and ergonomics); however, only equipment technology control proved to be statistically significant in both regressions, with function being only marginally significant (p-value = 0.12) in the regression on labor productivity. The remaining factors of energy, information processing, and ergonomics were found to be statistically insignificant.

Several lessons are gained from the regressions in Table D.4. First, an increase in the change in the capital-to-labor ratio was observed, with significant increases in labor and partial factor productivity, although the relation was weaker between the capital-to-labor ratio and partial factor productivity. Second, the technology regressions explain significantly more of the variability of the change in labor productivity versus the change in factor productivity as seen by the difference in the R-squared values for both models. Both occurrences demonstrate an expected labor-saving bias of technical change. Third, the regression models indicate that changes in the level of control have the strongest relation, which changes both partial factor and labor productivity among the five identified equipment technology characteristics. Finally, the R-squared values might be considered low in comparison to those factors from other statistical studies. However, when considering the multitude of other factors that influence job-site productivity performance (e.g., skilled labor, quality of design documents, and weather), the ability of equipment technology alone to explain as much of the variability in productivity as shown in Table D.4 (especially in labor productivity) should be considered significant.

TABLE D.3 Analysis of Variance (ANOVA) of Change in Construction Productivity and Change in Equipment Technology Characteristics

	Change in Labor Productivity			Change in Partial Factor Productivity		
Equipment Technology Characteristic	No Change in Equipment Technology Characteristic	Change in Equipment Technology Characteristic	*F*-value	No Change in Equipment Technology Characteristic	Change in Equipment Technology Characteristic	*F*-value
Energy	3.6% (49)	39.8% (151)	11.84*	−4.8% (49)	18.9% (151)	5.38*
Control	14.9% (101)	46.6% (99)	10.45*	−1.1% (101)	27.6%(99)	10.94*
Functional range	13.5% (106)	51.8% (94)	18.21*	3.1% (106)	24.5% (94)	5.90*
Information processing	21.0% (144)	56.4% (56)	12.31*	6.8% (144)	29.3% (56)	5.25*
Ergonomics	26.4% (91)	34.8% (109)	0.81	8.0% (91)	17.4% (109)	1.09

NOTE: Numbers in parentheses represent sample size.
*Denotes significance at 0.05.

TABLE D.4 Regression of the Equipment Technology Index (ETI), Capital-to-Labor Ratio (K/L), and Dichotomous Variables on Percent Change in Labor Productivity

Dependent Variable: Percent Change in Labor Productivity;
Independent Variable as Indicated by Column Heading

Eqn.	Constant	K/L	$(K/L)^2$	ETI	ETI^2	Control	Function	F	R^2	Adj. R^2
A	5.23 (0.66)	131.74 (6.88)	110.39 (3.09)	−18.53 (−2.03)	6.60 (3.08)	19.43 (2.21)	14.51 (1.55)	19.08	0.37	0.35

Dependent Variable: Percent Change in Partial Factor Productivity;
Independent Variable as Indicated by Column Heading

Eqn.	Constant	K/L	$(K/L)^2$	ETI	ETI^2	Control		F	R^2	Adj. R^2
B	6.36 (0.67)	66.76 (2.79)	86.63 (2.04)	−19.23 (−1.80)	6.18 (2.32)	26.08 (2.47)		7.83	0.17	0.15

NOTE: *t*-values shown in parenthesis; N= 200 activities.

MATERIAL TECHNOLOGY

Other research has examined the relation between changes in material technology and construction productivity. These analyses examined how changes in material technology have influenced labor and partial factor productivity in the U.S. construction industry between 1977 and 2004, using methods of longitudinal analyses at the construction activity level similar to those used for the examination of equipment technology. However, this time, the analyses involved a smaller sample size of 100 construction activities (Goodrum et al., 2009). For these sets of analyses, labor productivity is defined as before (Equation D.1), but partial factor is redefined by Equation D.5 by replacing the equipment with the material input cost in the denominator.

$$\text{Partial factor productivity, year } X = \frac{\text{Expected physical output (units)}}{\text{Labor cost (1990\$) + material cost (1990\$)}} \qquad \text{D.5}$$

To achieve a critical understanding of the impact of material technology on construction performance, the researchers developed a metric based on a combination of literature review and industry interviews that were used to quantify the changes in material technology between 1977 and 2004. The metric was composed of five material factors that are briefly described below but are detailed elsewhere (Goodrum et al., 2009).

- *Reduction in unit weight*—The obvious productivity benefits of reduced material weight include ease of handling and transporting by craft labor, although lighter materials have other benefits related to structural design and space requirements.
- *Strength*—Technological advancements, especially with new admixtures and design of concrete mixtures, have increased unit strength of materials.
- *Curability*—Several material advancements have reduced the amount of time required for a material to cure and reach its desired strength (e.g., concrete) and/or dryness (e.g., paint).
- *Installation flexibility*—Installation flexibility refers to the environmental conditions under which a material can be installed. For example, extreme temperatures or moisture can have significant impacts on the installation of material. Technological advancements, such as epoxy coating, waterproofing, and cold-weather admixtures, have improved the durability of materials and allowed their installation in extremely moist and cold conditions.
- *Modularization*—Modularization relates to the amount of material customization performed on-site prior to installation. Prefabrication of individual components is included in this factor. The purpose of including this factor is to measure the benefits of “customizing” materials in a controlled environment under ideal conditions before actual installation.

Similar to the finding from the equipment technology analyses, the activities that experienced improvement in the above material technology traits experienced more improvements in labor and partial factor productivity than those activities that did not (Table D.5). In particular, activities experiencing an improvement in curability, installation, and modularity consistently experienced substantially greater improvement in labor and partial factor productivity. The differences among these three factors were also statistically significant above the 95 percent confidence level. In regard to the change in the unit weight and strength of the materials, the analyses found that a statistically significant relationship did exist among reduction in the unit weight of material and improvement in labor productivity, but the relationship was below the 95 percent confidence level in regard to partial factor productivity. Improvement in the unit strength of material was not found to be significant with either labor or partial factor productivity. One reason for the lack of statistical significance involving change in the strength of materials is that this change was more likely intended to allow structures to withstand higher loads rather than to expedite the process of construction.

Paralleling the analyses on equipment technology, previous research also developed a series of regression models to examine the relationship between changes in material technology and construction productivity (Goodrum et al., 2009). Due to the smaller sample size (100 activities), the regression models were simplified by not including the capital-to-labor ratio as was done for the equipment technology regressions. A material technology index was developed based on a scoring system of the five material technology characteristics and is described in detail elsewhere (Goodrum et al., 2009). The regression models examined a series of dichotomous variables for the five material technology factors of strength, weight, curability, installation flexibility, and modularization. Not all of the material technology factors were found to be significant; thus only three of the factors are included in the regression models as shown in Table D.6, which shows separate regressions for labor and partial factor productivity. As shown in the regression equation for labor productivity (Table D.6, Equation A), the material technology factor weight produced statistically significant effects on labor productivity above the 95 percent confidence level. This factor, along with the material technology index (MTI), explained 17 percent of the total variation in labor productivity according to the adjusted coefficient of determination. Activities with a decrease in the unit weight of construction materials experienced a 31.0 percent increase in labor productivity compared to other activities that did not experience a change in unit weight. The regression models for partial factor productivity are shown in Table D. 6, Equation B. The material technology variables of installation flexibility and modularization produced statistically significant effects, above the 95 percent confidence level, and these variables, along with the MTI, explained 48 percent of the total variation in partial factor productivity, according to the adjusted *R*-squared value.

It is noted that the material technology regressions had both a stronger substantial and statistical relationship with partial factor productivity than with labor productivity, which is surprising considering that technology overall typically has a labor-saving bias on production (Salter, 1966). Although the research did find evidence of declining material-to-labor cost ratios using industry data from the *Engineering News Record*, the exact cause for this decline remained inconclusive and warrants future research.

TABLE D.5 Analysis of Variance (ANOVA) of Change in Construction Productivity and Change in Material Technology Characteristics

	Change in Labor Productivity			Change in Factor Productivity		
Material Technology Characteristic	No Change in Material Technology Characteristic	Change in Material Technology Characteristic	*F*-value	No Change in Material Technology Characteristic	Change in Material Technology Characteristic	*F*-value
Unit weight	10.7% (92)	48.6% (8)	12.93*	13.3% (92)	37.1% (8)	3.03
Strength	13.8% (93)	39.0% (7)	0.63	14.7% (93)	31.1% (7)	1.75
Curability	8.9% (71)	24.4% (29)	5.34*	1.8% (71)	30.1% (29)	17.6*
Installation flexibility	8.7% (67)	23.1% (33)	4.95*	3.1% (67)	52.6% (33)	60.3*
Modularization	8.1% (71)	24.2% (29)	9.31*	1.7% (71)	42.6% (29)	34.9*

NOTE: Numbers in parentheses represent sample size.
*Denotes significance at 0.05.

TABLE D.6 Regression of the Material Technology Index (MTI) and Dichotomous Variables on Percent Change in Labor and Partial Factor Productivity

Dependent Variable: Percent Change in Labor Productivity;
Independent Variable as Indicated by Column Heading

Eq.	Constant	MTI	Weight	*F*	R^2	Adj. R^2
A	3.39 (0.91)	39.72 (−2.03)	30.96 (2.97)	11.64*	0.19	0.17

Dependent Variable: Percent Change in Partial Factor Productivity;
Independent Variable as Indicated by Column Heading

Eq.	Constant	MTI	Installation	Modularity	*F*	R^2	Adj. R^2
B	−10.65 (−3.28)	42.15 (2.40)	23.57 (3.30)	15.79 (2.44)	31.58*	0.50	0.48

* *t*-values shown in parenthesis; N= 100 activities.

INFORMATION TECHNOLOGY

Finally, prior research examined the relationship between the use of information technology and construction productivity. While previously related productivity research examined longitudinal changes in equipment and material technology, research on the relation of IT and construction productivity has taken more of a latitudinal approach considering the relatively short history of construction projects' use of IT. A number of research efforts have examined the impact of specific applications of IT and construction performance. Thomas et al. (2004) evaluated the relationship of design/information technology (D/IT) and construction project performance. The researchers measured the degree of D/IT usage specifically based on the use of four technologies: integrated database, electronic data interchange, three-dimensional computer-aided design modeling, and bar coding. Thomas et al. (2004) indicated that D/IT was positively related to project performance, especially cost and schedule. Grau et al. (2009) conducted an extensive field trial of an automated material tracking system for structural steel that integrated radio-frequency identification tags and the Global Positioning System and was able to tie the use of the system with improvement in steel labor productivity during the field trial efforts.

O'Connor and Yang (2004) conducted one of the first studies that examined the comprehensive use of IT on construction job sites and its relationship to project performance. The researchers developed an integration and automation (IA) index ranging from 0 to 10 according to the IA use level on a series of project work functions. The statistical analysis of O'Connor and Yang (2004) indicated that the schedule success–technology relationship was stronger than that for cost. El-mashaleh et al. (2006) found a similar quantitative result when they also examined the impact of IT on construction firm performance (especially cost and schedule). The method that they used to develop an IT index was similar to that in the research of O'Connor and Yang (2004). Their analysis showed that for every one unit increase in their IT index, construction firms experienced an increase of 5 percent and 3 percent in schedule performance and cost performance, respectively.

While these research efforts did identify a positive relationship between the use of IT and improvement in the cost and schedule performance in the construction industry, they did not link IT to actual productivity performance. As a result, recent research examined how the use of IT among different project work functions, such as supply management, communication systems, and cost and scheduling systems, is related to construction labor productivity (Zhai et al., 2009). For the purpose of the research, Zhai et al. (2009) adopted the following definitions of automation and integration, as developed by O'Connor and Yang (2004):

- *IT automation*—The use of an electronic or computerized tool by a human being in order to manipulate or produce a product. Hard automation, such as robotics, is not included in this definition.
- *IT integration*—The sharing of information between project participants or melding of information sourced from separate systems.

The data used in this research came from the CII's BM&M productivity database, described previously in this paper. Using data from the BM&M database that described the level of IT usage on specific project work functions as well as productivity measures on the same projects, Zhai et al. (2009) compared the level of IT usage on projects with the projects' respective labor productivity among four common trades: concrete, structural steel, electrical, and piping.

For the purposes of the study, the researchers measured labor productivity using the following equation:

$$\text{Labor Productivity} = \frac{\text{Actual Workhours}}{\text{Installed Quantity}} \tag{D.6}$$

It is important to note that a lower productivity number per Equation D.6 is better. To ensure company confidentiality and allow comparisons across different tasks and trades, the raw productivities were normalized using the Min-Max method (Han and Kamber, 2000) based on the following equation:

$$P_{norm} = \frac{P_{raw} - P_{raw\,\mathrm{min}}}{P_{raw\,\mathrm{max}} - P_{raw\,\mathrm{min}}}(P_{norm\,\mathrm{max}} - P_{norm\,\mathrm{min}}) + P_{norm\,\mathrm{min}} \qquad \text{D.7}$$

In Equation D.7, P_{norm} is the normalized productivity and, P_{raw} is the raw productivity measure; $P_{raw\mathrm{min}}$ and $P_{raw\mathrm{max}}$ are the minimum and maximum raw productivity values in the construction task; and $P_{norm\mathrm{min}}$ and $P_{norm\mathrm{max}}$ are the minimum and maximum normalized productivity values, equal to 1 and 10, respectively. The normalized productivity (Equation D.7) is consistent with the Equation D.6 measure of labor productivity; a lower value indicates better productivity.

Using methods developed by O'Connor and Yang (2004), automation and integration indexes were developed for each project based on the level of automation and integration achieved in 13 standard work functions. The range of each index is from 0 to 10. For purposes of the analysis, projects scoring 5 percent above the overall median among all sampled projects were classified as having a high level of automation or integration, and projects scoring 5 percent below the median were defined as having a low level of automation or integration. The projects falling within the 5 percent range were not used in the comparison between the two groups. In the automation-related analysis, four projects fell within this range, and in the integration-related analysis, nine projects fell within this range. The reason for using the median rather than the mean is that the automation and integration indexes did not have a perfectly normal distribution. The purposes of using such a 5 percent range below and above the median are to (1) create two groups with more distinct differences in automation and integration use levels, and (2) guarantee that the sample sizes are large enough to perform the statistical analyses.

Next, Zhai et al. (2009) examined the productivity among the four trades as well as the productivity among all trades using the normalized productivity measure. All-trades productivity is a combination of the four trade-specific normalized productivity data sets, which includes all of the normalized activity-productivity available in this research combined into one data set.

The results (Table D.7) indicate that automation usage is positively related to structural steel, electrical and all-trades productivity, and all of these relationships are significant at the 0.05 level. The results for the concrete and piping trades lack statistical significance although the relationships are positive.

As indicated in Table D.8, integration usage was positively related to concrete, structural steel, and all-trades productivity at a statistical significance level of 0.05. The relationship in the electrical trade was significant at the 0.15 level. Again, no statistically significant result was observed in the piping trade, although the relationship was positive. While both integration and automation are related with better productivity performance, these analyses suggest that integration has a relatively stronger impact with better labor productivity.

TABLE D.7 Results of *t*-test on Automation Index by Trade

	Normalized Productivity			Levene's Test for Equality of Variances		Equal Variances Assumed		Equal Variances Not Assumed	
Trade	High-level Automation	Low-level Automation	Difference	*F*	Sig.	*t*	Sig.	*t*	Sig.
Concrete	3.48 (33)	3.89 (37)	−0.40	4.98	0.03	−0.69	0.49	−0.70	0.49
Structural steel[a]	3.74 (40)	5.24 (24)	−1.50	16.91	0.00	−2.42	0.02	−2.14	0.04
Electrical[a]	3.65 (52)	5.21 (19)	−1.55	1.51	0.22	−2.04	0.05	−1.91	0.07
Piping	3.96 (53)	4.40 (37)	−0.45	3.97	0.05	−0.71	0.48	−0.69	0.50
All trades[a]	3.68 (178)	4.54 (117)	−0.86	20.62	0.00	−2.72	0.01	−2.58	0.01

NOTE: Numbers in parentheses are the sample sizes (activity productivities).
[a]Denotes significance at 0.05.

TABLE D.8 Results of *t*-test on Integration Index by Trade

	Normalized Productivity			Levene's Test for Equality of Variances		Equal Variances Assumed		Equal Variances Not Assumed	
Trade	High-level Integration	Low-level Integration	Difference	*F*	Sig.	*t*	Sig.	*t*	Sig.
Concrete[a]	2.91 (33)	4.71 (19)	−1.81	19.90	0.00	−3.12	0.00	−2.61	0.02
Structural steel[a]	3.48 (39)	5.30 (10)	−1.82	3.28	0.08	−2.58	0.01	−2.58	0.01
Electrical[b]	3.28 (48)	5.66 (8)	−2.38	8.15	0.01	−2.36	0.02	−1.73	0.12
Piping	3.82 (52)	5.02 (15)	−1.20	10.59	0.00	−1.39	0.17	−1.12	0.28
All trades[a]	3.37 (172)	5.06 (52)	−1.69	28.89	0.00	−4.41	0.00	−3.57	0.00

NOTE: Numbers in parentheses are the sample sizes (activity productivities).
[a] Denotes significance at 0.05.
[b] Denotes significance at 0.15.

The described *t*-test results were based on normalized productivity measures in order to preserve the confidentiality of the CII BM&M data and also to allow analysis across different tasks and trades, since the normalized productivity measures are dimensionless (Zhai et al., 2009). However, reporting the analyses using normalized productivity obscures the actual effects. To help clarify the results, the researchers calculated the means of raw productivity for the projects with high- and low-level technology use and then calculated the percentage difference using the following equation:

$$\textit{Percentage difference of productivity} = \frac{(\textit{Mean } P_{RawH} - \textit{Mean } P_{RawL})}{\textit{Mean } P_L} \times 100 \qquad \text{D.8}$$

where P_{RawH} denotes the raw productivity with high-level automation (or integration) index. Similarly, P_L denotes the raw productivity with low-level automation (or integration) index. As a reminder, raw productivity was measured on the basis of actual work hours per installed quantity, so the percentage difference of productivity indicates the approximate percentage of time saving per installed quantity when using a high versus a low level of technology usage (Table D.9).

TABLE D.9 Percentage Improvement in Raw Labor Productivity Measurements Considering Automation and Integration of Construction Industry Institute Work Functions

	Percent Improvement in Labor Productivity	
	Automation	Integration
All trades	30.9%	45.0%
Concrete	23.3%	56.4%
Structural steel	33.9%	41.5%
Electrical	30.3%	38.4%
Piping	36.4%	45.9%

Overall, the analyses in information technology show that construction labor productivity is positively correlated with the usage of automation and integration information systems on the sampled construction projects. The average time savings per installed quantity were observed to be 30.0 percent and 45.0 percent when using a high versus a low level of automation and integration, respectively. Another important finding in the research by Zhai et al. (2009) is that automation and integration uses have different significance in various trades. It is intriguing that piping was the one trade that showed no significant correlation between automation and integration technologies on a project and productivity basis. Further research is needed to examine this occurrence. Although it is possible that the results lack significance owing to sample size, it is also possible that current automation and integration technologies are indeed not helping the piping trade become more productive. In the case of the latter explanation, attempting to understand why current automation and integration technologies are not helping is warranted. Meanwhile, O’Connor and Yang (2004) found similar results in their effort using similar automation and integration indexes described herein. In particular, O’Connor and Yang (2004) found that integration information systems had a more significant impact on project performance compared to automation information systems, which mirrors the results presented herein. From the definition of the automation and integration use levels, it can be seen that automation is a prerequisite to integration, and integration is an enhancement of automation. Therefore, in hindsight, it was not unexpected to observe that integration has a more significant impact on labor productivity.

TECHNOLOGY AND ITS INFLUENCE ON CONSTRUCTION PRODUCTIVITY MEASURES

Thus far, the discussion has focused on the observed relationships between technical change and related changes in construction productivity. However, it is unlikely that the influence of technical change is restricted just to productivity performance. There is evidence that technical change is likely influencing the industry measures of construction output, and it is the writer’s opinion that this influence needs to be considered in construction inflation indexes to help develop reliable industry measures of construction productivity. As mentioned previously, other researchers have expressed concerns regarding the need to understand how changes in the quality of construction influence the measure of the industry’s real output (Rosefielde and Mills, 1979: Pieper 1990; Gullickson and Harper, 2002). Although quality has many different meanings—such as reduction in process defects and improvement in customer satisfaction—quality changes in the context of this discussion are changes in the features of the built project. Two construction sectors are addressed below in this section along these lines: the residential and the industrial sectors.

It is the writer's opinion that technology is significantly improving the quality of new homes by improvements in energy efficiency, fire protection, building security, and high-performance windows, to name a few examples. Preferably when deflating an industry's output in order to measure its productivity, output price indexes are used. However, in certain sectors of construction, input cost indices have been used instead, since output price indices do not exist for all sectors of construction (Dacy, 1965; Gordon, 1968; and Pieper, 1989). In the residential construction sector, which is also the industry's largest sector by volume, an output price index produced by the U.S. Census Bureau, called the Single-Family Houses Index, is used, but there are still concerns regarding the ability of the U.S. Census Bureau's index to capture changes in quality adequately (Pieper, 1990). At the root of the concern is the hedonic regression model used to estimate the price variables used in the Census Bureau's price index. The hedonic regression models are primarily based on a 1970s-style ranch home; thus, it is plausible that other characteristics resulting from technical advances of modern home structures that are significantly related with new home prices, but not included in the hedonic regression, may inflate the price variables due to omitted variable bias. If the price variables are overestimated, this effect could contribute to overestimating the Census Bureau's price index, which would underestimate the real output of the residential sector. While this effect is plausible, it has not been quantified. Further work in this area is justified in order to quantify the effects of omitted variable bias in the Census Bureau's Single-Family Houses Index and to determine if there actually is any discernable bias and what impact this may be having on the measures of the overall construction industry's output.

Overestimation of the Census Bureau's price index is especially true if there is extensive growth in the omitted quality characteristics. Preliminary data from current research by the writer as well as others (NAHBRC, 2001; Hassel et al., 2003) suggest that this may be the case. Research by Dyer and Goodrum (2008) is examining the effects of omitted variable bias in the Census Bureau's price index within one geographic area. The researchers have been quantifying the frequency of omitted quality characteristics of new homes in Bowling Green, Kentucky, by using sales data between 2002 and 2007 from the Multiple Listing Service, which tracks the prices of new homes sold along with many quality characteristics of new homes that are not currently measured in the existing price index models of the Census Bureau. Examples of omitted quality characteristics include (1) thermal windows, (2) floor coverings, (3) kitchen appliances, (4) whirlpool tubs, (5) walk-in closets, (6) smoke alarms, (7) tray/vaulted ceilings, (8) landscaping, (9) exterior lighting, and (10) structured cable wiring. The research intends to use the sales data and the housing characteristics to estimate the local price index using the Census Bureau's price index methods both with and without significant omitted significant quality characteristics in order to measure the effects of the omitted quality characteristics for this one locale. The models developed by Dyer and Goodrum may be applicable to other geographic regions in the United States in order to help develop a broader effort of understanding of the effects of omitted variable bias in the Census Bureau's price index on a national level.

While the research discussed above addresses concerns of the productivity measures in the residential sector, it does not address other concerns about how to improve productivity measures in other sectors of construction. Ultimately, different sectors will likely rely on varying methods owing to nuance differences in volume and heterogeneous output. For the sake of brevity, the writer offers one approach for measuring productivity specifically for the industrial sector. The U.S. industrial sector is characterized as having relatively fewer projects compared to other sectors, but the projects are also typically some of the largest in the United States with strategic implications for the nation's economy. For this reason, the writer proposes that work on developing reliable productivity measures is urgently warranted and proposes the use of a model price index, also known as an estimate price index, for doing so in the industrial sector. A model price index avoids the challenge of controlling for the change in quality of structures by holding constant a detailed specification for either an entire structure or different components of a structure. Individuals with experience in estimating construction prices are then asked to estimate the selling price of the model. This way, the price change can be observed while holding quality constant. Individuals can be asked to price the entire structure, which is called an aggregate approach, or to price only specific components, which is called the disaggregated approach. The aggregate model price index approach is typically preferred for relatively simple structures, like a single house. For more complicated structures, like an industrial facility, the disaggregated approach is favored (Mohammadian and Seymour, 1997).

For the industrial sector, the framework for a model price index exists through the Construction Industry Institute's model plant. The model plant was initially developed by CII in 1985 to represent a generic petrochemical facility (CII, 1986) and has been modified and updated through a series of related efforts since then. Its mock scope of work includes construction activities in the areas of civil, structural, electrical, mechanical, and architectural finishes. Since its development, the CII model plant data have been used to benchmark industry productivity (CII, 1988); to analyze the impact of multifunctional equipment (Guo and Tucker, 1993); to examine the schedule and manning impacts of utilizing a multiskilled work force (Burleson et al., 1998; and Gomar et al., 2002); and to examine the impact of alternative training strategies for a project's work force (Castaneda-Maza et al., 2005; Brandenburg, 2004; Pappas, 2004; and Srour et al., 2006).

The CII model plant would be useful in developing a model price index, but it needs to be updated, since it is still based on 1980s technical characteristics of a petrochemical facility. If it could be updated by including modern instrumentation and current specifications, it could be used to develop a disaggregated price index model in which different construction firms throughout North America could be used to price specific components of the index. Considering expected strong growth in the industry sector owing to anticipated energy projects, work in this area deserves attention.

CONCLUSION

From the perspective of an outside observer, it is easy to understand why it appears that technology has had little influence on construction productivity. It is arguable that the basic methods of construction have largely remained unchanged over the past several decades from the excavation of soil by mechanical means, to the placement of concrete, to structural-steel erection. However, there have been several significant changes within the processes of these methods. Changes in the energy, level of control, and functionality have made the equipment more productive. Changes in the ease of installation, curability, and modularity are characteristics of material technology that are significantly related to construction productivity improvements. Finally, information systems that support a project's functions and its work crews have become more integrated and automated, which have also improved construction productivity.

Looking forward, research is needed to examine how technology has changed the characteristics of construction output. This paper identifies two lines of research in this area: (1) an examination of how changes in the characteristics of new housing has influenced the accuracy of the Census Price Index, a major deflator used in the measure of construction output; and (2) an updating of the characteristics of the CII model plant, a hypothetical typical industrial project, for the purpose of developing a disaggregated price index model for the industrial construction sector. Doing so will help researchers and industry leaders understand whether productivity of the construction industry has actually declined or improved. More importantly, improving the accuracy of industry productivity measures will help develop effective industry strategies for improving the performance of the U.S. construction industry.

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Creating and Cultivating the Next Generation of Construction Professionals

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Abstract: In today's global marketplace, how does one compete? Whether the competitive arena is real estate development, Internet sales, or construction-related activity, today's world stage is greatly reduced in size from what it once was. Today, competitors are right around the corner, and new strategies are urgently needed to strongly position the U.S. construction industry for success now and in the future. The challenges are many, and among them is the need for more knowledgeable workers. In addition, the construction industry needs to elevate and enhance its educational programs to develop better-prepared professionals at all levels to respond to a complex, challenging world.

The purpose of this paper is to help improve the competitive profile of the U.S. construction and engineering industries through four strategies:

1. To describe a holistic, systems view of civil engineering education.
2. To articulate a new vision for civil engineering.
3. To discuss how educators are reforming engineering education.
4. To advocate greater inclusion of paraprofessionals and engineering technicians within the workforce.

The objectives of these four strategies are to enhance the recruitment potential of careers in the engineering and construction industries and to effectively prepare a new generation of engineers through educational reforms.

COMPETITION IN A GLOBAL MARKET

The U.S. construction industry faces challenges unlike those facing any other profession and unlike those at any other time in its history. It is challenge built of competition: competition among firms for projects; competition for available, yet dwindling natural resources; competition for talent to fill needed positions throughout the industry. It is unacceptable to adopt an attitude of "business as usual" in the face of such unrelenting, global competition.

Just how robust is competition in the construction sector? In the spring of 2008, *Forbes* (2008) announced its "Global 2000" list of public companies with the highest scores based on sales, profits, assets, and market value. In the words of the *Forbes* authors, today it is "one world, one gigantic marketplace."

Overall, U.S. companies still dominate the Global 2000 list, but with 61 fewer entries than in the prior year and 153 fewer than in 2004, as many U.S. firms failed to keep pace with global competitors. By comparison, Brazil, China, and India rapidly added companies to the list. As an example, India has 48 companies listed this year, compared to 27 in 2004.

In the list of construction companies identified as global top performers, U.S. firms are few and far between. The top-performing U.S.-based construction firm, according to *Forbes*, is Fluor Corporation, with $16.69 billion in annual sales. Yet, Fluor sits in 21st place on the global list, followed by five French-based firms, five firms based in Spain, and those in China, Germany, Ireland, Japan, Mexico, Sweden, and Switzerland.

In all, the *Forbes* report listed 78 top performers in the global capital construction sector. Of those, just 13 were U.S.-based companies (*Forbes,* 2008). Interestingly, the *Forbes* report contained no listings for companies in the "Engineering" industrial category. While this author believes that this is an omission, the undeniable point of the *Forbes* Global 2000 is this: one of the brutal facts facing the construction and engineering industries is formidable global competition.

Competition in construction is more than just among firms. It is also a fact of life, and increasingly so, in resource availability. Many natural resources that the construction industry depends on are increasingly limited or expensive. Oil, water, copper, and most other feedstocks vital to construction are experiencing price volatility, in part driven by fundamental shifts in long-term supply and demand. Traditionally, the means, methods, and fundamental premises of construction have been based on the assumption that all required resources will be abundant.

The industry is learning that this premise is changing rapidly, with potentially severe limits to growth. Issues revolving around resource availability and various environmental stressors are ubiquitous phenomena that are appearing in all economic systems, regardless of political ideology (Pearce and Turner, 1990). What is new is the rate at which modern societies consume resources. "Humankind has consumed more aluminum, copper, iron and steel, phosphate rock, diamonds, sulfur, coal, oil, natural gas, and even sand and gravel during the past century than all earlier centuries together. Moreover, the pace continues to accelerate, so that today the world annually produces and consumes nearly all mineral commodities at record rates" (Tilton, 2002).

Those of us in the engineering and construction industries must be prepared with a broader and deeper vision that embraces the challenges and complexities of our modern world. In the following sections of this paper, the author discusses the following topics:

- How the American Society of Civil Engineers (ASCE) views the global market and the civil engineer of 2025.
- How ASCE and other professional associations are modifying education and early-work experiences to build stronger, better-prepared professionals.
- How professional organizations and trade associations are striving to recruit young people into careers in engineering and construction.
- How to involve construction professionals.

VISION FOR THE FUTURE[1]

In June 2006, under the leadership of ASCE, a diverse group of civil engineering and other leaders, including international participants, gathered to articulate an aspirational global vision for the future of civil engineering at the Summit on the Future of the Civil Engineering Profession in 2025. Summit participants envisioned a different world for civil engineers in 2025. An ever-increasing global population that is shifting even more to urban areas will require widespread adoption of sustainability. Demands for energy, transportation, drinking water, clean air, and safe waste disposal will drive

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[1] Please note that much of the material in the section entitled "Vision for the Future" has been extracted from *The Vision of Civil Engineering in 2025* (ASCE, 2007).

environmental protection and infrastructure development. Society will face increased threats from natural events, accidents, and perhaps other causes such as terrorism.

Informed by the preceding, a global vision—*Vision 2025*—was published in 2007. It sees civil engineers entrusted by society to create a sustainable world and enhance the quality of life. Civil engineers will do this competently, collaboratively, and ethically as master builders, environmental stewards, innovators and integrators, managers of risk and uncertainty, and leaders in shaping public policy.

Summit organizers and participants intended that *Vision 2025* would guide policies, plans, processes, and progress within the civil engineering community and beyond, including around the globe. Individual civil engineers and leaders of civil engineering organizations should act to move the civil engineering profession toward the vision.

The summit of June 2006 produced a series of aspirational visions stimulated by participant views of the world of 2025. The resulting integrated global aspirational vision is as follows:

> Entrusted by society to create a sustainable world and enhance the global quality of life, civil engineers serve competently, collaboratively, and ethically as master:
>
> - Planners, designers, constructors, and operators of society’s economic and social engine, the built environment;
> - Stewards of the natural environment and its resources;
> - Innovators and integrators of ideas and technology across the public, private, and academic sectors;
> - Managers of risk and uncertainty caused by natural events, accidents, and other threats; and
> - Leaders in discussions and decisions shaping public environmental and infrastructure policy.
>
> (ASCE, 2006).

As used in the vision, “master” means to possess widely recognized and valued knowledge and skills and other attributes acquired as a result of education, experience, and achievement. Individuals within a profession who have these characteristics are willing and able to serve society by helping solve problems, helping shape solutions to contemporary problems, and helping prevent problems, creating a more viable future.

The Civil Engineer of 2025

The ASCE’s 2006 Summit on the Future of the Civil Engineering Profession in 2025 addressed this question: What could civil engineers be doing in 2025? Addressing this second question naturally led to describing the profile of the 2025 civil engineer, that is, the attributes possessed or exhibited by the individual civil engineer of 2025 consistent with the preceding aspirational vision for the profession.

“Attributes” may be defined as desirable knowledge, skills, and attitudes. As used here, knowledge is largely cognitive, as opposed to affective or psychomotor, and consists of theories, principles, and fundamentals. Examples are geometry, calculus, vectors, momentum, friction, stress and strain, fluid mechanics, energy, continuity, and variability.

In contrast, “skills” refer to the ability to do tasks. Examples are using a spreadsheet; continuous learning; problem solving; critical, global, integrative/system, and creative thinking; teamwork; communication; and self-assessment. Formal education is the primary source of knowledge as defined here, whereas skills are developed through formal education, focused training, and certain on-the-job experiences.

Attitudes reflect an individual’s values and determine how he or she “sees” the world, not in terms of sight, but in terms of perceiving, interpreting, and approaching. Examples of attitudes conducive to effective professional practice are commitment, curiosity, honesty, integrity, objectivity, optimism, sensitivity, thoroughness, and tolerance. The 2006 summit identified many and varied attributes, organized into the preceding knowledge, skills, and attitudes categories. The results are presented here.

- The civil engineer is *knowledgeable***.** He or she understands the theories, principles, and/or fundamentals of:

  —*Mathematics, physics, chemistry, biology, mechanics, and materials***,** which are the foundation of engineering;
  —*Design* of structures, facilities, and systems;
  —*Risk/uncertainty***,** such as risk identification, data-based and knowledge-based types, and probability and statistics;
  —*Sustainability***,** including social, economic, and physical dimensions;
  —*Public policy and administration***,** including elements such as the political process, laws and regulations, and funding mechanisms;
  —*Business basics*, such as legal forms of ownership, profit, income statements and balance sheets, decision or engineering economics, and marketing;
  —*Social sciences*, including economics, history, and sociology; and
  —*Ethical behavior*, including client confidentiality, codes of ethics within and outside of engineering societies, anticorruption and the differences between legal requirements and ethical expectations, and the profession's responsibility to hold paramount public health, safety, and welfare.

- The civil engineer is *skillful.* He or she knows how to do the following:

  —*Apply basic engineering* tools such as statistical analysis, computer models, design codes and standards, and project monitoring methods;
  —*Learn about, assess, and master new technology* to enhance individual and organizational effectiveness and efficiency;
  —*Communicate* with technical and nontechnical audiences, convincingly and with passion, by listening, speaking, writing, mathematics, and visuals;
  —*Collaborate* on intradisciplinary, cross-disciplinary, and multidisciplinary traditional and virtual teams;
  —*Manage t*asks, projects, and programs so as to provide expected deliverables while satisfying budget, schedule, and other constraints;
  —*Lead* by formulating and articulating environmental, infrastructure, and other improvements and build consensus by practicing inclusiveness, empathy, compassion, persuasiveness, patience, and critical thinking.

- The civil engineer embraces *attitudes* conducive to effective professional practice. He or she exhibits the following:

  —*Creativity and entrepreneurship* that lead to the proactive identification of possibilities and opportunities and taking action to develop them;
  —*Commitment* to ethics, personal and organizational goals, and worthy teams and organizations;
  —*Curiosity*, which is a basis for continued learning, fresh approaches, the development of new technology or innovative applications of existing technology, and new endeavors;
  —*Honesty and integrity*, that is, telling the truth and keeping one's word;
  —*Optimism* in the face of challenges and setbacks, recognizing the power inherent in vision, commitment, planning, persistence, flexibility, and teamwork;

—*Respect for and tolerance of* the rights, values, views, property, possessions, and sensitivities of others; and

—*Thoroughness and self-discipline* in keeping with the public health, safety, and welfare implications of most engineering projects and the high degree of interdependence within project teams and between such teams and their stakeholders.

Many of the preceding attributes are shared with other professions. Civil engineering's uniqueness is revealed in how the attributes enable the profession to do what it does and, more importantly, to become what it wants to be. This is inherent in the global aspirational vision.

Those of us who pursue our careers in engineering or construction know the power that lies in the profession—how a blending of technical skills with imagination, ingenuity, and maybe a little intuition can produce remarkable achievements in meeting the needs of society.

EDUCATIONAL PREPARATION FOR THE ENGINEERING PROFESSIONAL OF TOMORROW[2]

The National Academy of Engineering has defined attributes of 2020 engineers (NAE, 2004). Besides the traditional and essential strong analytic and communication abilities, additional needed attributes include practical ingenuity, creativity, business and management fundamentals, leadership ability, agility, resilience, and lifelong learning.

As a concrete example of what is being done to provide these new broader attributes, consider the 24 outcomes within the ASCE (2008b) Civil Engineering Body of Knowledge (BOK). In addition to maintaining or strengthening mathematics, natural sciences, and engineering sciences and achieving greater technical depth, the BOK explicitly and clearly calls for broader exposure to the humanities and social sciences and additional breadth of professional practice. This broader knowledge and these broader skills and attitudes are clearly defined. Furthermore, some of these outcomes have already been reflected in accreditation criteria. More importantly, some engineering programs are implementing the broader and deeper BOK based on its merits.

Most engineering students and engineer interns respond to what is expected and supported. By and large, the industry has, by virtue of traditional engineering education and the way it manages a graduate's early experience, expected too little, and practiced poor stewardship. The reform effort now under way in portions of the U.S. engineering profession is solving this problem by expecting and supporting much more, that is, by "raising that bar" during formal education and early experience.

Reformation of U.S. engineering education has been studied and discussed for decades. Seeley (2005) identifies "the main currents in various reform movements." He describes the gradual evolution of engineering education beginning with adoption of the Morrill Land Grant Act of 1862; that act established land grant schools that shifted the dominant pattern of "engineering education from shop floors to classrooms." He cites key studies, including the Wickenden report that recommended less hands-on specialization and more attention to mathematics and science (Wickenden, 1930). The Grinter report stressed the value of engineering science and led to much more fundamental research (Grinter, 1956). The controversial Walker report (1965), according to Seeley (2005), "proposed addressing overloaded curricula by instituting a generalized undergraduate degree and reserving specialization for the master's level."

While improvements have occurred in engineering education, they have been evolutionary, not revolutionary. These improvements fall short of reform. For example, at the end of his essay, Seeley (2005) offers this summary:

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[2] Please note that much of the material in the section entitled "Educational Preparation for the Engineering Professional of Tomorrow" has been extracted from the second edition of the American Society of Civil Engineer's Civil Engineering Body of Knowledge for the 21st Century (ASCE, 2008b).

> Despite these changes, however, many of the challenges facing engineering educators have remained remarkably consistent over time. The question of what to include in tight curricula, how long engineering education should last, how much specialization there should be at the undergraduate level, how to prepare students for careers that include both technical and managerial tracks, and how to meet the needs and expectations of society all seem timeless. (p. 125)

And, for about two centuries, engineering has, with very few exceptions, adhered to 4-year undergraduate education. This 4-year degree has continued to be recognized as the engineering professional degree in spite of decades of scientific and technological advances, increased environmental concern, growing threats of disasters, and rapid globalization.

The ASCE Board of Direction adopted, refined, and confirmed Policy Statement (PS) 465, Academic Prerequisites for Licensure and Professional Practice, which “supports the attainment of the Body of Knowledge (BOK) for entry into the practice of civil engineering at the professional level” (ASCE, 2007). The BOK is defined in the policy as “the necessary depth and breadth of knowledge, skills, and attitudes required of an individual entering the practice of civil engineering at the professional level in the 21st century.” Note that a more detailed description on the history of the adoption of PS 465 can be found in “ASCE Policy 465-A Means for Realizing the Aspirational Visions of Civil Engineering,” a paper presented at the American Society for Engineering Education conference in Pittsburgh, Pennsylvania, in June 2008.

Table E.1 introduces the 24 outcomes—4 foundational outcomes, 11 technical outcomes, and 9 professional outcomes—in the BOK. The outcomes are organized by three categories—foundational, technical, and professional—to further clarify the BOK.

The long-term effect of PS 465 is illustrated in Figure E.1 which compares today’s civil engineering professional track with tomorrow’s.

The preceding, relative to today’s approach, means that tomorrow’s civil engineer will achieve the following:

- Master more mathematics, natural sciences, and engineering science fundamentals;
- Maintain technical breadth;
- Acquire broader exposure to the humanities and social sciences;
- Gain additional professional practice breadth; and,
- Achieve greater technical depth—that is, specialization.

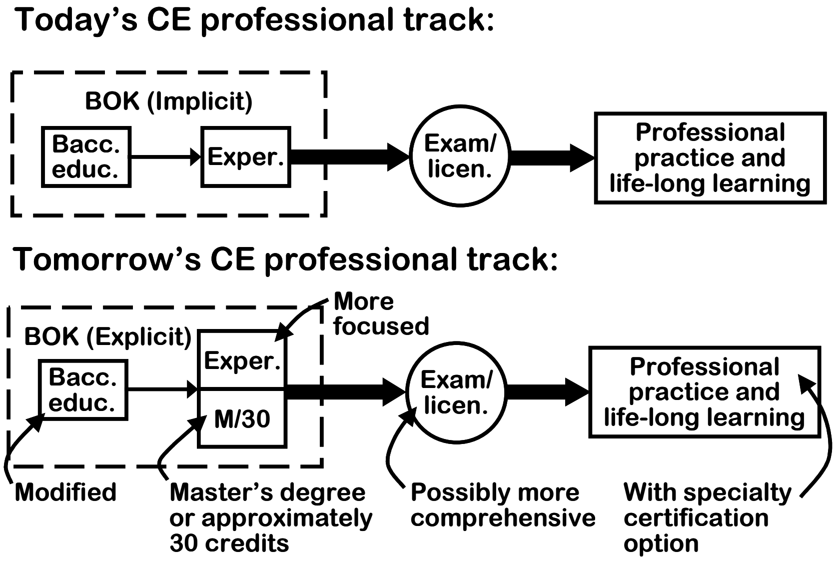


FIGURE E.1 Implementation of American Society of Civil Engineers (ASCE) Policy Statement 465 will improve the lifelong career of tomorrow’s civil engineer (ASCE, 2008).

TABLE E.1 Entry into the Practice of Civil Engineering at the Professional Level Requires Fulfilling 24 Outcomes to the Various Levels of Achievement

Outcome Number and Title	To Enter the Practice of Civil Engineering at the Professional Level, an Individual Must Be Able to Demonstrate This Level of Achievement[a]
Foundational Outcomes	
1. Mathematics	*Solve* problems in mathematics through differential equations and *apply* this knowledge to the solution of engineering problems. (L3)
2. Natural sciences	*Solve* problems in calculus-based physics, chemistry, and one additional area of natural science and *apply* this knowledge to the solution of engineering problems. (L3)
3. Humanities	*Demonstrate* the importance of the humanities in the professional practice of engineering. (L3)
4. Social sciences	*Demonstrate* the incorporation of social sciences knowledge into the professional practice of engineering. (L3)
Technical Outcomes	
5. Materials science	*Use* knowledge of materials science to *solve* problems appropriate to civil engineering. (L3)
6. Mechanics	*Analyze* and solve problems in solid and fluid mechanics. (L4)
7. Experiments	*Specify* an experiment to meet a need, conduct the experiment, and analyze and *explain* the resulting data. (L5)
8. Problem recognition and solving	*Formulate* and solve an ill-defined engineering problem appropriate to civil engineering by *selecting* and applying appropriate techniques and tools. (L4)
9. Design	*Evaluate* the design of a complex system, component, or process and *assess* compliance with customary standards of practice, user's and project's needs, and relevant constraints. (L6)
10. Sustainability	*Analyze* systems of engineered works, whether traditional or emergent, for sustainable performance. (L4)
11. Contemporary issues and historical perspectives	*Analyze* the impact of historical and contemporary issues on the identification, formulation, and solution of engineering problems and *analyze* the impact of engineering solutions on the economy, environment, political landscape, and society. (L4)
12. Risk and uncertainty	*Analyze* the loading and capacity, and the effects of their respective uncertainties, for a well-defined design and *illustrate* the underlying probability of failure (or nonperformance) for a specified failure mode. (L4)
13. Project management	*Formulate* documents to be incorporated into the project plan. (L4)
14. Breadth in civil engineering areas	*Analyze* and solve well-defined engineering problems in at least four technical areas appropriate to civil engineering. (L4)
15. Technical specialization	*Evaluate* the design of a complex system or process, or *evaluate* the validity of newly created knowledge or technologies in a traditional or emerging advanced specialized technical area appropriate to civil engineering. (L6)
Professional Outcomes	
16. Communication	*Plan, compose,* and *integrate* the verbal, written, virtual, and graphical communication of a project to technical and nontechnical audiences. (L5)
17. Public policy	*Apply* public policy process techniques to simple public policy problems related to civil engineering works. (L3)
18. Business and public administration	*Apply* business and public administration concepts and processes. (L3)
19. Globalization	*Analyze* engineering works and services in order to function at a basic level in a global context. (L4)
20. Leadership	*Organize* and *direct* the efforts of a group. (L4)
21. Teamwork	*Function* effectively as a member of a multidisciplinary team. (L4)
22. Attitudes	*Demonstrate* attitudes supportive of the professional practice of civil engineering. (L3)
23. Life-long learning	*Plan* and *execute* the acquisition of required expertise appropriate for professional practice. (L5)
24. Professional and ethical responsibility	*Justify* a solution to an engineering problem based on professional and ethical standards and *assess* personal professional and ethical development. (L6)

[a] Levels 1 through 6 refer to the following levels of achievement, as defined in Bloom's taxonomy: L1—Knowledge; L2—Comprehension; L3—Application; L4—Analysis; L5—Synthesis; L6—Evaluation.

PROGRESS WITH REAL CHANGE

ASCE's PS 465 states that fulfillment of the BOK includes a combination of the following:

- A baccalaureate degree in civil engineering;
- A master's degree, or approximately 30 coordinated graduate or upper-level undergraduate semester credits or the equivalent agency/organization/professional society courses providing equal quality and rigor; and
- Appropriate experience based on broad technical and professional practice guidelines that provide sufficient flexibility for a wide range of roles in engineering practice. In symbolic form, this portion of PS 465 is referred to as

$$B + M/30 \ \& \ E$$

Because the BOK focuses on well-defined results—the outcomes—and does not prescribe the means to achieve them, and because the BOK calls for "raising the bar," the BOK has already proven to be a productive forum for educators and practitioners and has produced concrete results within and outside the civil engineering discipline. For example:

- The BOK has been used to modify the ABET Inc. Program Criteria for Civil and Similarly Named Engineering Programs (civil engineering program criteria) and the ABET General Criteria for Master's Level Programs (master's level criteria) and will continue to be used to improve at least the former.
- The BOK is being used to design and/or revise engineering curricula at highly varied institutions. Some example universities, to name just a few, are the University of Alabama, The Citadel, the University of Illinois, the Lawrence Institute of Technology, the Rose-Holman Institute of Technology, the University of Texas at Tyler, the University of Utah, and the University of Wisconsin.
- The BOK has influenced the modification of the National Council of Examiners for Engineering and Surveying (NCEES) Model Law and Rules to require formal education beyond the bachelor's degree in the future.
- The BOK has prompted elevated discussion of and work on the responsibility of practitioners to coach and mentor young engineers. This is one result of the BOK indicating that experience is needed to complete fulfillment of about two-thirds of the civil engineering outcomes. Figure E.2 clarifies the connections among outcomes, achievement, formal education, and experience.

While independent of the ASCE BOK effort, other U.S.-based engineering disciplines have initiated BOK or similar reforms. For example:

- The American Society of Mechanical Engineers (ASME) convened a summit in the spring of 2008 to explore engineering solutions for a healthier, safer, cleaner, and more sustainable world. The summit focused on what mechanical engineering will become between now and 2028, and attendees worked to understand how the mechanical engineering profession could respond to present and future challenges and what critical knowledge and competencies mechanical engineers will need over the coming 20 years. In defining the "competitive edge of knowledge," ASME noted that "mechanical engineering education will be restructured to resolve the demands for many individuals with greater technical knowledge and more professionals who also have depth in management, creativity and problem-solving" (ASME, 2008).

	Level of Achievement					
	1	2	3	4	5	6
Outcome Number and Title	Knowledge	Comprehension	Application	Analysis	Synthesis	Evaluation
Foundational						
1. Mathematics	B	B	B			
2. Natural sciences	B	B	B			
3. Humanities	B	B	B			
4. Social sciences	B	B	B			
Technical						
5. Materials science	B	B	B			
6. Mechanics	B	B	B	B		
7. Experiments	B	B	B	B	M/30	
8. Problem recognition and solving	B	B	B	M/30		
9. Design	B	B	B	B	B	E
10. Sustainability	B	B	B	E		
11. Contemporary issues and historical perspectives	B	B	B	E		
12. Risk and uncertainty	B	B	B	E		
13. Project management	B	B	B	E		
14. Breadth in civil engineering areas	B	B	B	B		
15. Technical specialization	B	M/30	M/30	M/30	M/30	E
Professional						
16. Communication	B	B	B	B	E	
17. Public policy	B	B	E			
18. Business and public administration	B	B	E			
19. Globalization	B	B	B	E		
20. Leadership	B	B	B	E		
21. Teamwork	B	B	B	E		
22. Attitudes	B	B	E			
23. Lifelong learning	B	B	B	E	E	
24. Professional and ethical responsibility	B	B	B	B	E	E

FIGURE E.2 The Body of Knowledge (BOK) rubric integrates outcomes, levels of achievement, formal education, and prelicensure experience (ASCE, 2008b). NOTE: B—portion of the BOK fulfilled through the bachelor's degree; M/30—portion of the BOK fulfilled through the master's degree or equivalent (approximately 30 semester credits of acceptable graduate-level or upper-level undergraduate courses in a specialized technical area and/or professional practice area related to civil engineering); E—portion of the BOK fulfilled through the prelicensure experience.

- In 2005, the American Academy of Environmental Engineers (AAEE) Board of Trustees created the Body of Knowledge Development Working Group and charged it with “defining the BOK needed to enter the practice of environmental engineering at the professional level (licensure) in the 21st Century” (p. 7). While AAEE is in the stages of defining knowledge required for a degree in environmental engineering, the BOK will also serve as a guideline for college curricula. As of this writing, a working group has completed a draft BOK, noting that completion of the environmental engineering BOK is achieved through a combination of baccalaureate-level work, master’s-level work, and professional experience. While the BOK includes the expected focus on engineering technical fundamentals in mathematics, physics, and chemistry, the BOK also takes in conceptual analysis, creative design, sustainability, contemporary and global issues, multidisciplinary teamwork, leadership, and effective communication (AAEE, 2008).
- The chemical engineering profession, driven in part by the recognition that, over the past 40 years, the undergraduate curriculum in chemical engineering has remained nearly unchanged, conducted three workshops in 2003 that produced a vision and model for reform of undergraduate chemical engineering education (Armstrong, 2006).

The future holds promise and potential. As noted earlier, U.S. engineering reform has begun. Disciplines that pioneer the reform effort may experience a decline in the number of students that they attract—a loss of those young people who seek an easier route. More importantly, the pioneering disciplines will attract a larger number of bright, ambitious, diligent, and appreciative students who want a career whose educational and other programs prepare them for challenging and satisfying careers in the 21st century.

RECRUITING TOMORROW’S WORKFORCE

More than education begins in the early grades. Career recruitment begins then, too. There is no question that workforce recruitment is one of the greatest challenges facing the construction industry today. Today’s newborns and students currently in kindergarten through grade 12 (K-12) classrooms make up the workforce of the future. They will replace the current workforce in 20 to 30 years and by 2050 will be at the peak of their careers. Many of them become interested in the subject matter that will form their future career choices at 10 to 12 years of age. While they will not begin to make substantive contributions in their field of choice for several years, the time to begin preparing them for a meaningful future starts now.

Significant efforts to effectively brand and market careers in engineering have already begun. The National Academy of Engineering (NAE) noted that engineering has an image problem: many K-12 teachers and students have a poor understanding of what engineers do (Cunningham et al., 2005). Other data indicate that the public thinks that engineers are not engaged or involved in contemporary societal or community issues (Harris Interactive, 2004). And, when respondents were asked to rate the prestige of relative professions, engineering was well below the ranking for medicine, nursing, science, and teaching (Harris Interactive, 2006). NAE thus initiated a message development project, one goal of which is to attract young people to careers in engineering. According to NAE, “A better understanding of engineering should encourage students to take higher level math and science courses in middle school, thus enabling them to pursue engineering education in the future. This is especially important for girls and underrepresented minorities, who have not historically been attracted to technical careers in large numbers” (NAE, 2008, p. 2).

The NAE project applied mass-marketing techniques, generating a new positioning statement for engineering, messages, and taglines—all aimed at improving the public’s general understanding of engineering. The powerful and positive positioning statement for engineering is below:

> No profession unleashes the spirit of innovation like engineering. From research to real-world applications, engineers constantly discover how to improve our lives by creating bold new solutions that connect science to life in unexpected, forward-thinking ways. Few professions turn so many ideas into so many realities. Few have such a direct and positive effect on people's everyday lives. We are counting on engineers and their imaginations to help us meet the needs of the 21st century. (NAE, 2008, p. 5)

In *Changing the Conversation,* NAE (2008) recommended four courses of action, condensed for this discussion:

- The engineering community should adopt and actively promote the positioning statement, and use it as an anchor for all public outreach.
- Four messages that evolved from the project—engineers make a world of difference; engineers are creative problem solvers; engineers help shape the future; and engineering is essential to our health, happiness, and safety—should be adopted by the engineering community in ongoing and new public outreach activities.
- Additional research should commence to test a number of taglines for nationwide use in an engineering public awareness campaign.
- An online public relations tool kit should be developed for the engineering community that includes examples of how messages can be used effectively in advertising, news releases, and brochures.

Public understanding, message development, and clarifying what engineers do for educators, parents, and school-age children is a positive development, and NAE should be recognized for its foresight and accomplishments in taking such a market-driven approach. There is no question, however, that mathematics is a key ingredient for a successful career in engineering and construction. In the United States there is reason for concern. A recent report, for example, noted that the United States is failing to develop the mathematical skills of girls and boys, and especially among those who could excel at the highest levels. The study by Janet E. Mertz, an oncology professor at the University of Wisconsin, and published in *Notices of the American Mathematical Society*, notes that while many girls and boys have "exceptional talent in math—the talent to become top math researchers, scientists and engineers—they are rarely identified in the US." The reason, notes the author, is that American culture does not value talent in mathematics and thus discourages students from excelling in the field (Mertz et al., 2008). Collectively society must recognize mathematics as an essential skill that all students should develop to their highest potential. The goal should be to instill an appreciation for high academic performance and not just to reserve it for athletic achievement.

Further evidence of the need for a continued and stronger focus on mathematics and science is documented through various studies conducted by the U.S. Department of Education. In a recent study of the mathematical abilities of U.S. 12th graders, less than one-quarter performed at or above a proficient level in mathematics, and just 2 percent performed at an advanced level (U.S. DOE, 2007). The same report noted that average mathematics scores for 17-year-olds were not measurably different from scores recorded in 1973 or 1999.

In addition, research indicates that U.S. students are more likely to complete degrees in arts and humanities and in business, social sciences, law, and other fields, and less likely to complete degrees in engineering and health. Internationally comparable data on degrees conferred at the postsecondary level have been collected through the Organization for Economic Cooperation and Development (OECD). While the total number of engineering degrees conferred in the United States was relatively high compared with that of other OECD countries, the proportion of graduates earning degrees in engineering in the United States was relatively low. The proportion of U.S. graduates earning degrees in engineering (6.4 percent) in 2004 was lower than the other five Group of Eight (G-8) countries reporting data, including Canada, France, Italy, Germany, and Japan (NCES, 2007).

To obtain further clarification on the scope of the challenge faced in this country in exposing young people to careers in construction and engineering, the National Center for Educational Statistics (NCES) offers some startling results. In 2005, NCES investigated the percentage of high school graduates who concentrated in selected occupational areas by the occupational credits that they earned (NCES, 2005). Table E.2 illustrates three important points: the paucity of high school graduates exposed to potential construction and engineering career paths; the small number of students receptive to and appropriately prepared for careers in engineering; and proof that to attract students to careers in construction and engineering, the construction industry must compete with other fields.

TABLE E.2 Percentage of High School Graduates Who Concentrated in Engineering or Construction Occupational Areas, by Number of Occupational Credits Earned, 2005

Occupational Concentration	2-Credit Concentration	3-Credit Concentration
Engineering technologies	2.4	1.0
Construction and architecture	2.1	1.2

SOURCE: NCES (2005).

In addition to a cultural shift in favor of academic performance, there are numerous programs and efforts under way that help introduce students to careers in construction and engineering. It is a career choice that provides excellent wages and benefits, and one that offers tremendous potential for entrepreneurship. The U.S. Department of Labor's Bureau of Labor Statistics predicts that job opportunities in construction will be excellent in the future, growing at a faster pace than the rest of the U.S. workforce over the next 10 years (U.S. DL, BLS, 2008).

To help meet the growing demand for the construction and engineering workforce, an outstanding infrastructure already exists. This infrastructure is in the form of career academies, special events, and associated activities that promote careers in engineering and construction. Examples follow.

- Construction career academies provide students with experiences and information to help build a future career. Such academies are developed around the theme of construction. The goal is to expose students to an array of career choices within the industry. Upon completion of their work at an academy, high school students can transition into the workforce or move on to postsecondary education. Construction firms are vital in this program, partnering with schools to provide opportunities for job shadowing, field trips, mentoring, and internships. The first construction career academy, sponsored by the Associated General Contractors (AGC) of America, was the East Ridge High School Construction Career Academy in Chattanooga, Tennessee. This academy opened in the fall of 2002. Success with this academy has led to the opening of many others across the nation. The AGC of Wisconsin currently has three academies, and several more are in various stages of development. Furthermore, AGC of Wisconsin is planning a workforce development/construction industry promotional campaign. One aspect of this campaign is an informational, interactive Web site aimed at middle and high school students.
- The National Center for Construction Education and Research (NCCER) sponsors an annual "Careers in Construction Week" each October, to boost public awareness of the hard work and contributions of the nation's craft professionals. In addition, the week promotes recognition among parents, teachers, guidance counselors, and students of the rewarding career opportunities available in construction (NCCER, 2008).

NCCER provides innovative suggestions for introducing students to careers in construction. Among them are these:

—*Walk and Learn.* Coordinate a walk to school to get children thinking about the built environment. Help students understand how construction affects every aspect of their lives. Explain the different types of jobs that are involved in building what they see around them.

—*Bargain Shopping.* Host a booth or event at an area shopping center. Colleges and contractors have successfully recruited young people into the industry through shopping malls.

—*Open Up Your Site.* Ask a local construction site to host a field trip. Arrange for students to tour the site and gather firsthand information on what it takes to have a successful career in construction.

—*Hunt for Knowledge.* Organize a "Construction Treasure Hunt" in the community. Have students walk a prearranged course around the school or community and search for answers to questions about the built environment. Ask local industry professionals to donate prizes.

As part of Careers in Construction Week, NCCER provides contractors, schools, and trade associations with free promotional materials, such as DVD career-related videos, and career resources, including posters, sample news releases, print ads, and a planning guide.

NCCER is a not-for-profit educational foundation affiliated with the University of Florida's School of Architecture. NCCER provides craft training, management education, and safety and other resources for the construction, maintenance, and pipeline industries.

- The National Association for Women in Construction (NAWIC) promotes early learning through its Block Kids Building Program. Block Kids is an annual competitive, national building program sponsored at the community level by NAWIC chapters and other organizations. Now in its 20th year, the program is open to elementary students in grades 1-6. It introduces them to the construction industry and promotes future careers in the industry. The competition involves the construction of various structures with interlocking blocks and three of the following items: a small rock, string, foil, and posterboard (NAWIC, 2008).

NAWIC also sponsors a national "Women in Construction Week" each year in the spring. More than 100 NAWIC chapters across the United States celebrated the event on March 1-7, 2009. The week provides a time for more than 5,500 NAWIC members to raise awareness of the opportunities that the construction industry holds for potential employers and to highlight women as a visible, growing force in the industry.

As part of the weekly celebration, NAWIC offers a number of informational ideas to help promote construction and the contributions of women. Here are a few examples:

—Get involved in community projects with organizations such as Habitat for Humanity.

—Sponsor educational seminars and workshops and partner with retailers such as Home Depot or Lowe's, or construction-related organizations in your community.

—Request city, state, or other government leaders to issue a proclamation declaring March 1-7 as "Women in Construction Week."

—Organize a mobile career fair at local schools, or host a construction industry social for a breakfast, lunch, or dinner (NAWIC, 2008).

- Associated Builders and Contractors, Inc. (ABC), sponsors a number of initiatives that either showcase careers in construction or provide training for those with aspirations to work in the industry. For example, thousands of apprentices and craft students train in more than 20 construction industry crafts through a national ABC network of 78 chapter offices throughout the country. ABC is also involved on college campuses through its ABC Student Chapters Program, a network of more than 50 colleges and universities that offer construction-related degree programs nationwide. At the community level, student chapters facilitate the interaction of ABC member firms, construction faculty, and college students through a variety of industry association and school events including meetings, speakers, internships, community projects, fundraisers, career fairs, job-site tours, and other activities (ABC, 2008).
- ZOOM into Engineering is a program sponsored by the American Society of Civil Engineers (ASCE) that introduces the excitement and accomplishment of engineering and engineers to students in

grades K-5. ASCE encourages its members to make use of the program's available materials and to go into classrooms and connect with girls' and boys' clubs to share information on careers in engineering. Through the program, students explore the basic math and science concepts that are essential for an engineering education and for a career as an engineer. ZOOM into Engineering includes eight fun, hands-on mathematics, science, and engineering activities for use in classrooms. The program represents a tremendous opportunity for engineers to show children the fundamentals of the engineering profession and the types of activities that they might be engaged in on the job. ASCE notes that the program does more than prompt students to become civil engineers: "These educational outreach programs also build a basic civil engineering knowledge necessary for citizens to make informed decisions on infrastructure issues in their community and world" (ASCE, 2008a).

ZOOM into Engineering is one of three ASCE programs aimed at primary-school students. Other ASCE programs include Building Big, for students in grades 6-8, and West Point Bridge Designer, for students in high school. More details on these programs can be found on the ASCE Web site. Visit http://www.asce.org and click on "Kids and Careers."

- Project Lead the Way (PLTW) is a not-for-profit organization that promotes courses for middle and high school students in engineering and the biomedical sciences. PLTW accomplishes this by forming partnerships with schools, higher-education institutions, and private businesses to increase the quantity and quality of engineers and engineering technologists being graduated from the country's educational programs. PLTW began in the 1997-1998 school year. Today, PLTW programs are offered in more than 3,000 schools throughout the United States. Additional information is available at http://www.pltw.org.

Building a viable workforce for the future is a concern shared by other organizations as well. The transportation industry, for example, is facing a workforce crisis and is creating a national strategy to recruit more people to fill anticipated needs in management, planning, engineering, construction, and operations positions. The Transportation Research Board (TRB) has identified several activities for its action plan for 2009 (TRB, 2008), including the following:

- Develop and host a Web site (www.trb-education.org) that serves as a repository for information on transportation workforce issues.
- Set up an exhibit booth at the TRB annual meeting in January 2009 to help address workforce issues and to promote the Web site mentioned above.
- Carry out several activities at the TRB annual meeting, including these:

  —Sponsor a poster session on "How to Get People Interested in Transportation."
  —Host a session that focuses on what employees want from their employers and a session that includes case studies illustrating how some organizations have learned to be flexible and how they have helped employees transition into new jobs.

In addition, TRB plans to rely on distance learning, Webinars, and online courses to reach working professionals seeking to advance their careers.

A GREATER ROLE FOR PARAPROFESSIONALS

Future success and achievement for the construction industry will also rely on greater use of paraprofessionals and technicians. In civil engineering, as an example, the use of paraprofessionals is undergoing thorough study by the Paraprofessional Exploratory Task Force (PETF), an ASCE committee formed in the spring of 2008 to define, recognize, and incorporate paraprofessionals as an important part of civil engineering. As a measure of definition, the committee provided the following terms to describe positions and corresponding levels of responsibility in civil engineering practice:

- *Engineering professional:* An engineering professional (EP) is a position that encompasses responsible charge of engineering work and therefore must be held by an individual licensed to practice engineering. An EP can comprehend and apply advanced knowledge of widely applied engineering principles in the solution of complex problems.
- *Engineering paraprofessional:* An engineering paraprofessional (EPP) is a position supporting an EP. An EPP works under the responsible charge of an EP but may exert a high level of judgment in the performance of his or her work. EPPs can comprehend and apply knowledge of engineering principles in the solution of broadly defined problems. EPPs are generally engineering technologists, but engineers, engineer interns, and professional engineers can also provide engineering paraprofessional services.
- *Engineering technician:* An engineering technician (ET) is a position in which the individual supports an EP and/or EPP. An ET works under the responsible charge of an EP and often under the direction of an EPP. ETs are typically task oriented, with levels of judgment typically commensurate with those specific tasks. ETs can comprehend and apply knowledge of engineering principles in the solution of well-defined problems. ETs are generally technicians, but engineering technologists, engineers, and professional engineers can also serve in this position.

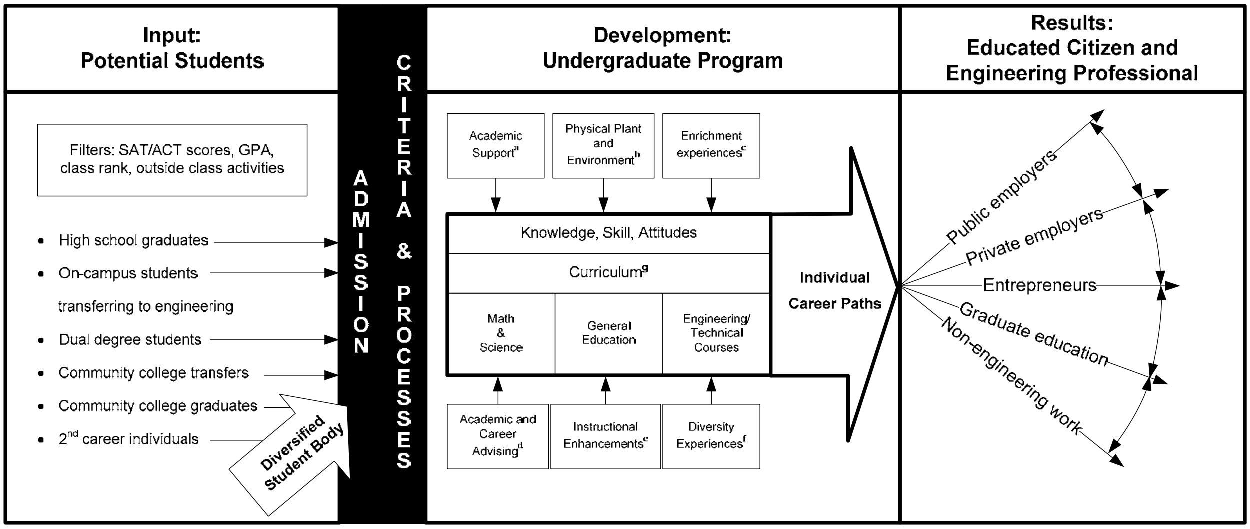
In PETF's final report to the ASCE board of directors, the committee described the roles, responsibilities, and respective ranges of engineering activities and authority for engineering paraprofessionals and engineering technologists. PETF noted there were just 537 graduates of bachelor's degree civil engineering technology programs in 2006 and further stated: "given the relatively sparse numbers of institutions with CET programs and the sheer lack of numbers of CET graduates, the demand could well outstrip supply" (PETF, 2008, p. 44).

To better integrate paraprofessionals into the engineering profession, PETF recommends the following:

- The roles and titles for EPs, EPPs, and ETs in the civil engineering community need to be better defined in order to accurately reflect their contributions to civil engineering practice and to provide guidance on the appropriate levels of education, licensure, and certification.
- In order to provide a more consistent workforce and to help ensure its competence, there may be a need for standardizing formal credentials and requirements that demonstrate entry-level and continuing competency of EPPs.
- The skills and knowledge of EPPs may not be well utilized across the civil engineering community, so EPPs' contributions and utilization should be recognized and communicated to employers, potential EPPs, students, parents, code/regulatory officials, and others.
- To better integrate EPPs into the civil engineering community, there need to be more opportunities for EPPs to participate in relevant professional societies.
- Increased recognition of the contributions of EPPs may increase demand and opportunities for EPPs in the civil engineering community and may result in a need for additional educational infrastructure to provide an adequate number of civil engineering technology graduates.

CONCLUSION AND NEXT STEPS

With so many pressures facing humankind, the engineering and construction industry's responsibility takes on a new sense of urgency. Required is a systems view of engineering education to clarify the goals of Policy Statement 465, described earlier, and to provide meaning and direction to civil engineering educational reforms. Such a view helps us understand where we are now and where we need to be to meet future challenges.



a Academic support includes supplemental instruction and drop-in tutoring in subjects like math, chemistry, physics, in addition to entry level engineering classes such as EMA303.

b Make lab facilities more available for use as well as create a more inviting department environment.

c Includes co-ops, summer internships, travel abroad experiences, and participating in one of the over 50 student organizations.

d Focus on transition from COE into departments and from the department to professional practice.

e Improved student learning and technology enhanced experiences.

f Create a robust environment and experiences that diversifies and broadens each students.

g Future engineers will require formal education beyond the bachelor's degree.

FIGURE E.3 Systems view of preparing the engineering professional. NOTE: COE, College of Engineering. SOURCE: Adapted from Deming (1994).

According to Deming (1994), taking a systems view of any process involves addressing such components as raw materials, available resources, supply chains, production modes, distribution, customers, needs, and products. Figure E.3 represents a systems view of current civil engineering education, adapted from Deming's model. Beginning with the "supply" or "input" of raw intellectual talent (i.e., students) provided from a variety of sources (e.g., high schools, community colleges, and other institutions), the educational system produces graduates who are educated citizens and engineering professionals.

In the future, civil engineering education must serve the ongoing, emerging, and even unexpected needs of stakeholders and clients. It must also serve to build a strong, steadfast profession for those who join its ranks. A systems view of the educational process enables stakeholders and practitioners the opportunity to examine the individual elements that come together in an exciting blend of human talent and potential, education and educational reform, and a never-changing BOK. Such an approach will help ensure that those who pursue their careers in engineering and construction will enjoy their work, will take satisfaction from meeting the needs of society, and will be ready for the changes and challenges the future is sure to bring.

We all have a powerful role to play in how the built environment responds to and contributes to our quality of life. As engineers, we understand the link between natural systems and the built environment. As builders, we are challenged to create and innovate while meeting the expectations of our clients. Together, we work collaboratively to improve our communities and now we turn our attention, our energies, and our insights to meeting the challenges of a changing and competitive world. Table E.3 introduces "numbers that matter."

TABLE E.3 Numbers That Matter

Preparation for Success	Demographics	Workforce Dynamics
23 percent— Of U.S. 12th graders, 23 percent score at or above proficient in mathematics.	6.4 percent— Proportion of U.S. graduates earning degrees in engineering; lower than many other countries.	0.2 percent— Proportion of engineers in the total U.S. workforce of 146 million workers.
2 percent— Of U.S. 12th graders, 2 percent score at an advanced level in mathematics.	5 percent— Engineering accounted for 1 in 20 of all bachelor's degrees awarded in 2006. For master's degrees, 6 percent.	46.4 percent— Proportion of women in the U.S. workforce.
41.9 percent— Estimated undergraduate retention rate in engineering, class of 2007.	30 percent— Of the U.S. undergraduate population, 30 percent are African-Americans, American Indians, and Latinos. This proportion will grow to 32 percent by 2010, and to 38 percent by 2025.	10.8 percent— Proportion of women in the U.S. engineering workforce. As engineers, 8.0 percent of women are in engineering management.
12 percent— Fewer than 12 percent of baccalaureate engineering graduates in the United States are underrepresented minorities.		

SOURCE: Selected 2005-2007 data from the Engineering Workforce Commission, Commission on Professionals in Science and Technology, and *New Demands in Engineering, Science and Technology* by Slaughter and McPhail, 2007. (AAEE, 2007; Slaughter and McPhail, 2007).

The percentages in Table E.3 provide a blueprint for an action plan to meet the challenges of tomorrow. Specifically, and amplifying on a few selected percentages from this table, that action plan should include:

- *Preparation for Success*

  —Of U.S. 12th graders, 23 percent scored at or above proficiency in mathematics, while just 2 percent scored at an advanced level. Is this preparation for success or preparation for mediocrity? Enabling the United States to reclaim a prominent position in today's global economy requires a renewed focus on mathematics, science, and technology at all levels of education.

  —Of undergraduates in engineering, 41.9 percent stay in engineering. Put another way, nearly 60 percent of students who enter engineering as undergraduates leave to pursue careers in other fields. Engineering curriculum reform, already under way, needs to proceed unabated in reshaping the profession.

  —Less than 12 percent of baccalaureate engineering graduates in the United States are underrepresented minorities. The engineering profession will not truly be preparing for success until it successfully recruits more underrepresented minorities into engineering and related fields.

- *Demographics*

—Of U.S. graduates, 6.4 percent earn degrees in engineering, a figure lower than in many other countries. Furthermore, engineering accounted for 1 in 20 of all bachelor's degrees awarded in 2005, and 6 percent of all master's degrees. Engineering is clearly underrepresented when one analyzes the program and degree choices that college-age students are making.

—Of the nation's undergraduate population, 30 percent are minorities, a proportion that will grow to 32 percent by 2010 and 38 percent by 2025. Concerted efforts must be made to encourage African-Americans, American Indians, Latinos, and other ethnic groups to consider the rewards and satisfactions from careers in engineering.

- *Workforce Dynamics*

—Women make up 46.4 percent of the U.S. workforce. Yet, in engineering, women comprise just 10.8 percent of the workforce, and 8.0 percent of those in engineering management positions. Engineers must work consistently to encourage young girls in science and mathematics at the K-12 level, and further encourage them to consider careers in engineering.

The engineering and construction professions are noted for their collective accomplishments and achievements. The calling now is to build a robust future for our collaborative professions. The needs are clear:

- We have no mutually shared vision for the future;
- For the engineering profession, we lack a coordinated, systematic marketing and recruiting plan to attract young people to the profession;
- We have limited discussions on curriculum reform at the baccalaureate level; and,
- We are not substantively discussing workforce issues and inclusion of paraprofessionals and engineering technologists.

Global competition for resources, talent, and customers is heating up, making business less predictable and more competitive than ever before. Those with foresight use these times to their advantage, finding opportunity where others find formidable challenge. It is time for leaders to lead, and to collaborate, cooperate, and communicate to transform our approach to the future.

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