Measuring and Improving U.S. Construction Productivity

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Abstract

Although the construction industry is a major component of the U.S. economy, it has experienced a prolonged period of decline in productivity. Due to the critical lack of measurement methods, however, the magnitude of the productivity problem in the U.S. construction industry is largely unknown. To address these deficiencies, efforts are underway that focus on the measurement of construction productivity at three levels: task, project, and industry. We discuss how such measures can be developed, how they are related to the use of information and automation technologies and construction processes over the life of the project, and how to build on several ongoing collaborative efforts aimed at improving the efficiency, competitiveness, and innovation of the U.S. construction industry. We identify and prioritize activities that have the greatest potential for improving the productivity of the U.S. construction industry over the next 20 years. These activities include, but are not limited to, interoperable technology applications via building information modelling (BIM) and effective performance measurement to drive efficiency and support innovation. The paper concludes with a vision for the future built around a suite of standards for measuring task and project-level productivity, a database of task and project-level metrics, guidelines for efficient use of BIM and modularization techniques, and industry-level metrics. Leaders in the U.S. construction industry are aware of the successes and benefits that have accrued from the investments in measuring and monitoring construction safety and can envision the potential for similar improvements in construction productivity.

1. Construction: An Engine for Economic Growth

Construction is an engine of growth for the U.S. economy. Investment in plant and facilities, in the form of construction activity, provides the basis for the production of products and the delivery of services. Investment in infrastructure promotes the smooth flow of goods and services and the movement of individuals. Investment in housing accommodates new households and allows existing households to expand or improve their housing. It is clear that construction activities affect nearly every aspect of the U.S. economy and that the industry is vital to the continued growth of the U.S. economy.

In 2008, the construction industry's contribution to gross domestic product (GDP) was $582 billion, or 4.1 % of GDP (Bureau of Economic Analysis (BEA), 2009). In 2008, the value of construction put in place was $1072 billion (Census Bureau, 2009). Construction also has a major impact on U.S. employment. In 2008, 11.0 million persons were employed in the construction industry (Bureau of Labor Statistics (BLS), 2009). This translates into 7.6 % of the total U.S. workforce. The composition of the construction workforce differs from much of the U.S. workforce due to the large number of self-employed workers (sole proprietorships and partnerships). Within the construction industry, there are 1.8 million self-employed workers. The large number of self-employed workers both reduces the size of the average firm and increases fragmentation within the construction industry, where 79 % of construction establishments with employees have fewer than 10 employees (Census Bureau, 2002a and 2002b). Both factors complicate the adoption of new technologies and practices. Construction employment is affected by both the weather and the business cycle. Thus, year-to-year changes in employment can be substantial, resulting in layoffs and hiring surges. The cyclical nature of construction employment produces shortages in many highly-skilled trades. These shortages adversely impact productivity in the construction industry. Finally, declining construction productivity is exacerbated by the influx of unskilled labor from abroad, many of whom find their first employment opportunity in the construction industry.

2. Productivity and Competitiveness

Given the large impact of construction on the U.S. macroeconomic objectives, effective construction research becomes critical to the economy. Key drivers for change in construction research are sustainability and environmental security; competition due to globalization and offshoring; infrastructure renewal; and information technology. The problem is that the U.S. construction industry invests little in research relative to its significant GDP contribution to the economy. A landmark study co-sponsored by the Civil Engineering Research Foundation (CERF) and the National Science Foundation (NSF) involved a nationwide survey of civil engineering-related research and development (R&D). The study, later published by CERF (1994), is especially noteworthy because it includes R&D associated with each of the key construction industry stakeholders. The CERF study reported that all key construction industry stakeholders combined invested in R&D at a rate that corresponds to only 0.5 % of the value of construction put in place. This translates into approximately $5.4 billion in 2008. A recently published NSF study covering companies performing industrial R&D provides a useful contrast (NSF, 2009). Private sector R&D investments in manufacturing totaled nearly $167 billion in 2007. Underinvesting reduces the potential for research-inspired innovations

that contribute to substantial national benefits—namely constructed facilities that are more user and environmentally friendly, affordable, productive, and that are easier, faster, and more life-cycle cost effective to build, operate, and maintain. Given the impact of construction spending on the U.S. economy's health, construction research becomes a critical variable in generating economic growth.

A recent article by Teicholz (2004) highlights the magnitude of the U.S. construction industry's perceived decline in productivity. As measured by constant contract dollars of new construction work per field work hour, labor productivity in the construction industry has trended downward over the past 40 years at an average compound rate of -0.6 % per year. That is, construction projects have required significantly more field work hours per constant dollar of contract. This is particularly alarming when compared to the increasing labor productivity in all non-farm industries, which has trended upward at an average compound rate of 1.8 % per year. In other words, the construction industry seriously lags other industries in developing labor saving ideas and in finding ways to substitute equipment for labor. Teicholz reiterates the points noted earlier for their adverse impact on construction labor productivity, namely the lack of R&D spending and fragmentation within the industry. He also notes that despite the fact that there has been a significant adoption of new information technology by the construction industry over the past 35 years, these applications tend to run in a stand-alone mode that does not permit improved collaboration by the project team.

It should be noted that not everyone in the construction industry agrees with Teicholz's assessment. For example, Young and Bernstein (2006), in their McGraw Hill *SmartMarket Report*, contend that the U.S. construction industry is making productivity improvements through innovation with new technologies, processes, and services. Teicholz asserts, however, that a fragmented market with very small players makes application of these innovations less frequent than desired for a healthy increase in industry productivity. Another reason Teicholz finds declining productivity is that it focuses on field work. For example, many of the improvements in construction productivity in the oil and gas industries stem from the use of offsite fabrication facilities, where component production is well-controlled and highly-automated (Construction Users Roundtable, 2007). The debate about whether construction productivity is declining, holding its own, or increasing cannot be easily resolved, because there are no industry-level measures of productivity for either the construction industry as a whole or its components (i.e., commercial, industrial, infrastructure, and residential). Such measures do exist for manufacturing, and they are routinely disseminated by the BLS.

To address these challenges, the National Institute of Standards and Technology (NIST) requested that the National Research Council (NRC) appoint a 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 prepare a report that identified and prioritized 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 over the next 20 years.

To gather data for its report, the NRC committee 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 three commissioned white papers, at the November 2008 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. These activities are highlighted in the NRC report that states, "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." (NRC, 2009) The five activities, entitled "Opportunities for Breakthrough Improvements," are: (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; and (5) Effective performance measurement to drive efficiency and support innovation (NRC, 2009). Although the focus of this paper is on effective performance measurement (activity 5), it also provides limited coverage of activities 1 through 4. Readers wishing in-depth discussions are referred to the NRC report and NIST Special Publication 1101 (Huang *et al.*, 2009).

3. Construction Productivity: Task, Project, Industry

The nature of the construction process points to a need for measures of construction productivity at three levels: (1) task; (2) project; and (3) industry. ***Tasks*** refer to specific construction activities such as concrete placement or structural steel erection. ***Projects*** are the collection of tasks required for the construction of a new facility (e.g., the construction of a new commercial office building) or renovation (i.e., additions, alterations, and major replacements) of an existing constructed facility. ***Industry*** measures are based on the North American Industrial Classification System (NAICS) codes for the construction sector and represent the total portfolio of projects.

Producing measures of construction productivity at each level involves the development of both metrics (i.e., the definition of the appropriate measure that forms the basis for the calculation) and tools (i.e., the means through which construction industry stakeholders can perform the calculation for the selected metrics). Once produced, these metrics and tools will help construction industry stakeholders make more cost-effective investments in productivity enhancing technologies and life-cycle construction processes; they will also provide stakeholders with new measurement and evaluation capabilities (Construction Industry Institute [CII], 2003a).

Leading industry groups, such as the Construction Industry Institute (CII, 2005), Construction Users Roundtable (CURT), and FIATECH (FIATECH, 2004), have identified the critical need for fully integrating and automating life-cycle construction processes. Having metrics and tools will address that need and enable those industry groups and other stakeholders to: (1) evaluate the performance of promising automation and integration technologies and (2) measure the value of real-time monitoring and control of construction processes.

3.1 Task

Task level metrics are widely used within the construction industry. Most task level metrics are single factor measures and focus on labor productivity. For example, RSMeans has published task level

metrics for many years (RSMeans, 2006). Typical task level metrics published by RSMeans estimate how much of a given output is produced by a designated crew in a normal 8-hour day. In this case, the denominator is the number of hours associated with a designated "crew day." Thus, for a designated crew day, higher output is better. In this case, higher output equates to higher task labor productivity. The CII Benchmarking and Metrics Program uses a different metric to measure task labor productivity. CII fixes the output (e.g., volume of concrete put in place) and measures the labor hours required to produce that output (Mulva, 2008). In this case, the denominator is the fixed output and the numerator is the number of labor hours. Thus, for a given amount of output, lower labor hours is better. In this case, lower labor hours equates to higher task labor productivity.

Both the RSMeans and the CII task labor productivity metrics include explicit measures of output and labor hours in the values reported. Such metrics are easy to understand and are widely used within the industry as a basic estimating tool. To differentiate these metrics from alternative formulations, we use the term "raw metrics" to refer to these ratios of input and output. These metrics are raw in the sense that they include the units of measure and are based on unadjusted outputs and labor hours. For example, the relative prices for selected labor inputs and the given output may vary over time. There can be many reasons for such changes (e.g., expanded use of information and automation technologies, use of equipment with increased functionality, and changes in construction processes).

The CII Benchmarking and Metrics Program collects data on a project basis, where productivity is but one data element. The raw task level metrics produced by CII include not only the average productivity for that task—referred to as a baseline measure—but the full set of observed values. The observed raw task productivity values are then rank ordered into a distribution. Once this is done, the raw task productivity values can be assembled into quartiles. CII researchers can then examine the characteristics for a given task associated with projects in the best performing quartile and in the worst performing quartile. This topic is explored further in Section 5.1 of this paper.

A task productivity index is an alternative to the raw metrics discussed previously. An index is a dimensionless number, pegged to a reference data set, where the reference data set establishes the baseline value for one or more components of the index. An index can be a ratio of raw metrics. An index can also incorporate additional information, such as the value of a deflator to help control for changes in relative prices over time. Because the index is a dimensionless number, users can focus on the changes in the index value rather than the functional form of the metric underlying the index.

3.2 Project

Project level metrics are more complicated because a project is a collection of tasks. The inputs and outputs for a given task, say concrete placement, differ from those of another task, say structural steel erection. Thus, it is not possible to aggregate the individual raw task productivity metrics into a project productivity metric unless adjustments are made.

One way to make these adjustments is to use a reference data set to calculate baseline values for each task, in the same way as described in Section 3.1. Information is still needed, however, to calculate a

meaningful project level productivity metric. For instance, information yielding the task weight (share that it represents to the overall project) is required.

A project level productivity index can also be used to track changes in project productivity over time. In this case, the reference data set corresponds to time zero. For each index component, the values for the task weights and the task baseline values appearing in the denominator are equal to values computed in the reference data set. The numerator in each index component then becomes the average value of the corresponding task productivity in the future data set. As noted earlier, an index can also include a deflator to adjust for changes in relative prices over time.

A variant of Teicholz's formulation can be used to produce an alternative project level productivity index. In this case, the index is the quotient of two ratios, in each ratio the numerator is the value of construction put in place and the denominator is the number of field work hours. A reference data set can be used to fix a baseline value for the ratio of value put in place to field work hours. The baseline value for the ratio is then used as the denominator in the index calculation. How an individual project compares to the baseline is determined by inserting its ratio of value put in place to field work hours in the numerator of the index. Alternatively, this project level productivity index can be used to track changes in productivity over time by following the process described in the previous paragraph.

3.3 Industry

At the industry level, productivity—the amount (or value) of output produced per unit of input— provides a measure of industrial efficiency. BLS publishes two common measures of productivity: (single factor) labor productivity and multifactor productivity (BLS, 1997). BLS measures labor productivity as the ratio of the value of output produced for sale to labor hours worked. Because the value of output is influenced by other forces exogenous to labor, such as changes in technology, multifactor productivity measures provide a useful indicator of industrial productivity. BLS measures multifactor productivity using output, labor, capital, and intermediate purchases input. While multifactor productivity may be viewed as a better measure of productivity (compared to a single factor, labor productivity measure), it is obviously more costly in terms of data required.

The BLS does not collect nor report productivity measures for the construction industry. This appears to be due to the lack of suitable data (Allmon *et al.*, 2000). Some have argued that measuring construction industry productivity is challenging due to the large number of small firms operating on a minimal profit margin, and to the industry fragmentation (Bernstein, 2003). However, the BLS maintains productivity measures for other industries with seemingly similar attributes (e.g., full-service restaurants [NAICS code: 7221]; drinking places [NAICS code: 7224]; automotive repair and maintenance [NAICS code: 8111]). The BLS Current Employment Statistics (CES) survey provides statistics on annual labor hours by industrial classification.

One key element in productivity measurement is output deflators. The BLS has recently produced several producer price indices in the nonresidential sector, and this effort has enhanced the estimates of investments in BEA's National Income and Product Account tables. BEA and BLS may collaborate further to develop other nonresidential building construction indexes, such as price

indexes for highways, hospitals, retail, communication, power, and lodging structures (Lally, 2009). Efforts such as these improve the quality of existing statistics and have spillover benefits for productivity measurement.

4. Factors Affecting Construction Productivity

Much has been published about the factors that affect construction productivity. Although a comprehensive treatment is beyond the scope of this paper, several key factors are usually cited in the literature. These factors are concerned with: (1) life-cycle construction processes; (2) technology utilization; (3) skilled labor availability; and (4) offsite fabrication and modularization.

4.1 Life-Cycle Construction Processes

Management practices affect productivity over the life cycle of a construction project in a number of ways, including planning, resource supply and control, and supply of information and feedback. Management practices that are inflexible or applied inappropriately can introduce inefficiencies that reduce productivity. To address these problems, organizations such as CII have developed a suite of best practices aimed at improving the project execution process. These practices are directed at all phases of the project life cycle, from design, through procurement, fabrication, construction, commissioning, and operations and maintenance (CII, 1999). In-depth analyses of the value of best practices on cost and schedule control, as well a field rework have been performed (CII, 2003).

4.2 Technology Utilization

Technology utilization impacts construction productivity in a number of ways. Historical changes in construction equipment have resulted in sustained improvements in task level productivity. Goodrum and Haas (2002) have shown that these improvements stem from better control, amplification of human energy, increased functionality, better ergonomics, and better information processing and feedback. Goodrum *et al.* (2009) came to a similar conclusion regarding material characteristics that lead to reductions in unit weight and installation flexibility. Analyses of CII Benchmarking data covering information and automation technologies revealed significant task level productivity improvements (CII, 2008).

4.3 Skilled Labor Availability

One of the greatest challenges facing the U.S. construction industry is the ability to attract and retain qualified workers. This is underscored by the fact that shortages of skilled workers continue to plague the construction industry (CII, 2003b). Employers have attempted to identify the root causes and to develop strategies to overcome these shortages. CII and others have funded research on the problem and generated potential solutions (CII, 2003b). Despite this research and efforts to stem the problem, the construction industry's skilled worker pool continues to shrink. The decreasing number of young people entering the work force and the failure to recruit from non-traditional labor pools exacerbate this trend. Over the past 30 years, real wages of construction workers have declined relative to those of other workers. Poor industry image, tough working conditions, and the industry's perceived poor

safety record also have contributed to the decline in the number of people willing to enter and remain in the industry.

4.4 Offsite Fabrication and Modularization

Prefabrication, preassembly, modularization, and offsite fabrication (PPMOF) offer potential benefits in the increasingly competitive global marketplace. Owners want better facilities faster, at the lowest possible cost, and with increased safety. Both owners and contractors view PPMOF as a means to meet challenges of demanding schedules, adverse site conditions, and limited availability of skilled labor. However, CII research shows that using these methods requires careful consideration of their implications for engineering, transportation, coordination, and project organization (CII, 2002). Recent advances in design and information technologies, combined with increasing emphasis within the industry to address cost, schedule, and labor issues, have proven the use of PPMOF to be more viable than ever. In a recent CURT publication, CII Director Wayne Crew noted that "the use of PPMOF has increased in the last 10 years, especially with new technologies such as building information modeling and internet design capabilities (CURT, 2007)." Future workforce shortages will likely encourage the use of PPMOF. PPMOF benefits such as reduced construction time, decreased costs, and increased safety have all contributed to its popularity, and while many companies in the oil and gas industries have used it for decades, others are realizing its full set of benefits.

5. Efforts Aimed at Improving Construction Productivity

Concerns over the perceived decline in construction productivity have stimulated interest in ways to use technology and management practices to address this challenge. Current industry efforts aimed at the seamless flow of information in an interoperable design and construction environment seek to promote labor productivity both by enabling the project team to respond quickly and effectively to new requirements, changes in scope, site conditions, and delivery delays and by promoting the use of value adding processes and technologies. The CII Strategic Plan (CII, 2005), the FIATECH Capital Projects Technology Roadmap (FIATECH, 2004), and CURT's efforts to address owner issues associated with productivity improvement and cost reduction are several noteworthy examples.

5.1 Correlating Task and Project Productivity with Best Practice Use

Proponents of construction productivity metrics tend to focus on the measurement of task labor productivity. Although the value of producing task-level metrics is widely accepted, the current methodology for producing these metrics has not focused on identifying improvement opportunities. To address this issue, NIST launched a "data mining" effort in collaboration with CII to analyze how best practices and automation and integration technologies affect construction productivity at the task and project levels. The study published as NIST GCR 09-925 develops statistical relationships that correlate increased use of best practices and integration and automation technologies with construction productivity. Additional analyses were conducted to correlate the combined use of best practices and integration and automation technologies on reductions in cycle time, reductions in construction cost, and reductions in field rework, which also affect construction productivity. Major findings were that technologies can facilitate the implementation of specific best practices, such as

Front End Planning, Alignment, and Project Risk Assessment. Technologies and specific best practices, when used synergistically, can improve productivity of capital projects and may also decrease the amount of rework. These findings help key industry stakeholders understand how increased use of best practices and integration and automation technologies impacts the bottom line.

5.2 Leveraging Technology to Improve Construction Productivity

CII in collaboration with FIATECH established a research team on leveraging technology to improve construction productivity (CII, 2008). Since many factors impact construction productivity, the research team adopted a three-pronged approach to better control for any external factors. First, it examined how historical changes in construction equipment, materials, and information technologies influenced improvements in construction productivity. Second, a field test of materials tracking and locating technologies was conducted to measure how using such technologies can improve productivity on prototypical CII construction projects. Previous CII research identified materials tracking and locating technologies as significant factors impacting construction productivity. The use of radio-frequency identification (RFID) tags and a Global Positioning Satellite (GPS) system were coupled to track materials in lay down areas in two CII member projects (CII, 2008). Improved materials tracking was shown to increase productivity at the workface because material retrieval became more efficient. Third, a predictive model that estimates the potential for a technology to have a positive impact on construction productivity was developed and tested. The predictive model addresses a technology's costs, its feasibility, its usage history, and its impact characteristics. One of the major results of the predictive model is that as a particular technology matures, it will yield higher performance scores. Technologies with high performance scores may no longer be cutting edge, but they provide a low-risk and potentially high-reward alternative to an unproven technology. However, not all companies will limit their technology search to mature, proven technologies. The predictive model is especially valuable in identifying key characteristics of emerging technologies that provide attractive risk-reward tradeoffs. Therefore, using the predictive model to choose among alternative technology investments is the first step in leveraging technology to improve construction productivity.

BIM is one technology that can enhance productivity of an entire project, from the planning phase to the decommissioning phase. Eastman *et al.* (2008) describe BIM as "a new approach to design, construction, and facility management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in digital format." A previous NIST study on interoperability estimated the cost of inadequate interoperability in the U.S. capital facilities industry to be $15.6 billion per year (Gallaher *et al*., 2004), and therefore enhanced interoperability has a great potential in efficiency gains.

5.3 Vision for the Future

A vision for the future is to develop the enabling measurement science for achieving breakthrough improvements in construction productivity that takes into account the complexity and variability of construction and leads to well-controlled, repeatable processes. This vision includes the creation of: (1) Standard practices for measuring task-level and project-level productivity; (2) Database of task-level and project-level productivity measures for capital facilities; (3) Guidelines for efficient use of

BIM and PPMOF techniques; and (4) Industry-level productivity metrics. Achieving the vision is more likely now because the enabling technologies are sufficiently mature to be applied to construction processes, the cost of computing is no longer a barrier, and the industry is demanding new capabilities for assessing and improving construction productivity. Leaders in the U.S. construction industry are aware of the successes and benefits that have accrued from the investments in measuring and monitoring construction safety (CII, 2007) and can envision the potential for similar improvements in construction productivity. These leaders recognize that meeting the challenges of managing increasingly complex, collaborative projects with changing mixes of stakeholders and increased global competition requires the application of new measurement techniques to achieve breakthrough productivity improvements.

6. Summary

This paper identifies and prioritizes technologies, processes, measurement science, and deployment activities that have the greatest potential to significantly advance the productivity and competitiveness of the U.S. construction industry over the next 20 years. Much is currently being done to address the underlying causes of the perceived decline in construction productivity. However, key stakeholders often have a myopic view of how to best address the underlying causes and remove barriers to change within the industry. The November 2008 NRC workshop provided an opportunity to bring together construction industry stakeholders to identify common problems, generate consensus on ways to address some of these problems, and set priorities for attacking challenges to the industry that will require a long-term effort to address. By providing a common forum for discussion and planning, the NRC workshop was a first step in enabling the U.S. construction industry to achieve higher levels of efficiency and competitive advantage in the global marketplace. This paper provides a vision for the future for developing the enabling measurement science for achieving breakthrough improvements in construction productivity, including the development of construction productivity metrics at the task, project, and industry levels.

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