Relationship between Changes in Material Technology and Construction Productivity

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Abstract: There have been substantial changes in both material technology and construction productivity over the past several decades. By analyzing the changes in both material technology and productivity among 100 construction activities from 1977 to 2004, this research examines the strength and types of relationships that exist within these two occurrences. Through analysis of variance (ANOVA) and regression analyses, the researchers found that activities experiencing significant changes in material technology have also experienced substantially greater long-term improvements in both their labor and partial factor productivity. The research did find that a stronger relationship exists between changes in material technology and partial factor productivity than in labor productivity. The research also found that changes in the unit weight of materials had a significant relationship to labor productivity, while changes in installation and modularity had a significant relationship to partial factor productivity. The research findings will help industry practitioners to better understand how they may leverage technology to improve construction productivity, while also helping researchers understand the theoretical relationships between technology and construction productivity.

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Introduction

Over the past couple of decades, technology improvements have dramatically changed the process of construction, as well as the quality of construction output. Unfortunately, the industry poorly measures both outcomes. As a result, the perception exists that construction is a technologically stagnant industry, at least by comparison to other industries. This perception is not new. 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). This belief in declining productivity, which influences workforce strategies, technology adoption, research programs, and industry perceptions, is based on a number of productivity studies using industrial and macroeconomic data. Studies completed in the 1980s reported that construction real output (value added) per work hour declined by an annual rate of 2.4 to 2.8% between 1968 and 1980 (Stokes 1981; BRT 1983; Allen 1985). More recently, studies using industry data from the United States Department of Commerce and the U.S. Bureau of Labor Statistics (BLS) indicate that construction's labor productivity declined from 1964 to 2000 at an annual compound rate of 0.72% (Teicholtz 2000).

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Other evidence contradicts these measures. Previous research examined labor and partial factor productivity trends using microeconomic data for 200 activities (Goodrum et al. 2002). The results indicated widespread improvement in construction productivity across multiple construction divisions, ranging from 0.2 to 2.8% per year between 1976 and 1998, especially in machinery dominated divisions such as site work. In addition to these measured improvements, there is also much anecdotal evidence shared by industry leaders that productivity has actually improved (Bernstein 2003; Tuchman 2004).

Some economists, researchers, and industry observers believe that little technological change occurs in the construction industry. Construction has not adopted assembly lines and robotics to the extent that other industries have; however, there have been significant technical advances in construction techniques, machinery, and methods. For example, advancements in on-board microprocessors and hydraulic controls allow excavator operators to more precisely control their boom and shovel position, to function with larger operating envelopes, to more accurately monitor engine and other system parameters, and to quickly diagnose critical system failures. Previous research indicated that many of the productivity improvements at the microlevel were related to changes in equipment technology (Koch and Moavenzadeh 1979; Goodrum and Haas 2002; Goodrum and Haas 2004). However, one measure of technology advancement is expenditures on research and development (R&D), and it is clear that construction lags behind other industries in this regard. According to a recent study by Hassell et al. (2001), the construction, building, and housing industry is believed to invest less than 0.5% of the value of its sales in R&D, while the national average is approximately 3%. The study examined R&D expenditures not only in regard to new developments in construction methods but also new developments in construction products.

While it seems evident that changes in equipment technology

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correlate with corresponding improvements in productivity, a comparative quantitative understanding of material technology and construction productivity remains unclear. This paper examines how changes in material technology have influenced labor and partial factor productivity in the United States construction industry between 1977 and 2004. The researchers present this examination in three parts. First, the paper examines labor and partial factor productivity changes in the United States between 1977 and 2004 for 100 different construction activities utilizing commercially available estimation data. Second, the paper examines changes in material technology over the same time period using five material technology characteristics. Third, the relationship between material technology changes and productivity changes in construction are examined. Since it is difficult to measure construction productivity at the aggregate level for a number of reasons (Goodrum et al. 2002), this research examines changes in construction productivity at the activity level.

Methodology

Productivity Defined

While there are numerous measures of productivity, this research addresses two productivity measures: labor and partial factor productivity. Labor productivity is the ratio of output to labor hours (BLS 2006). One challenge in measuring productivity is that the unit of measurement depends on the construction activity. A concrete placement activity may be measured in cubic yards of concrete placed per hour, whereas a structural steel placement activity may be measured in linear feet of steel placed per hour. Using relative instead of absolute values of productivity solves this problem, so the percentage change in labor productivity from 1977 to 2004 is used to measure productivity for each activity in this study by using the following formula, assuming the labor productivity changed in linear fashion from 1977 to 2004:

$$\%\text{ change in labor productivity, '77 – '04} = \frac{\text{labor productivity, '04} - \text{labor productivity, '77}}{\text{labor productivity, '77}} \times 100 \tag{1}$$

Another common measurement of construction productivity is factor productivity (Thomas et al. 1990), which is defined as

$$\text{factor productivity} = \frac{\text{physical output (units)}}{\text{labor (\$)} + \text{material (\$)} + \text{equipment (\$)}} \tag{2}$$

For this paper, the researchers modified Eq. (2) by removing the fixed capital (or equipment) component in order to accommodate this investigation's focus on material technology. This produces the following measure of partial factor productivity:

$$\text{partial factor productivity} = \frac{\text{physical output (units)}}{\text{labor (\$)} + \text{material (\$)}} \tag{3}$$

As with labor productivity, the research utilized a relative measure of partial factor productivity by measuring the percentage change in partial factor productivity between 1977 and 2004 using the following formula, assuming the partial factor productivity changed in linear fashion from 1977 to 2004:

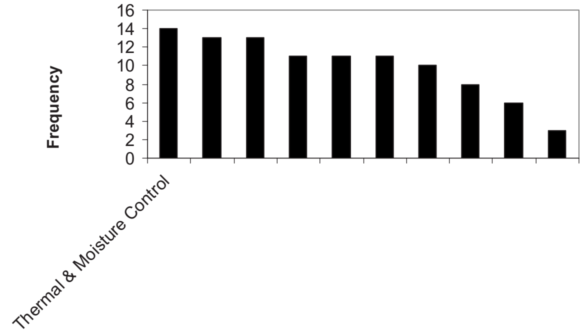

Fig. 1. Distribution of construction activities by division

$$\%\text{ change in partial factor productivity, '77 – '04} = \frac{\text{partial factor productivity, '04} - \text{partial factor productivity, '77}}{\text{partial factor productivity, '77}} \times 100 \tag{4}$$

Data Source

The researchers collected output and input data for 100 activities from the 1977 and 2004 manuals of the Means Building Construction Cost Data. The manual annually collects daily output, crew size, and cost data on more than 12,000 construction activities from 16 divisions of the Construction Specifications Institute MasterFormat. Although the manuals are designed to develop project cost estimates and project budgets, the writers and other researchers have used the estimation manuals as a source of expected levels of productivity in previous research (Thomas and Yiakoumis 1987 and Goodrum and Haas 2002). For our research, data were manually collected from Means 1977 and 2004 manuals. Three criteria were used to select activities for inclusion in the study. The first criterion, and perhaps the most obvious, is that an activity had to appear in both the 1977 and 2004 estimation manuals. Although this is a necessary criterion considering the continuity of the data, the researchers acknowledge that it does limit the degree of technical change measured by the study. There are new activities that have arisen as a result of radical changes in material technology, with cast-in-place sanitary sewer lines being one example. A second criterion is that the overall activities represent a wide range of degrees of material technical change. Finally, the included activities represent a wide range of types of activities from different divisions of the Construction Specification Institute (CSI) Masterformat (Fig. 1). The researchers randomly selected the activities from the pool of qualified activities to form a random sample.

The researchers identified the state of construction material technology for the study' sampled activities from 1977 and 2004 by using a variety of historical documents. Although the 1977 and 2004 *Means Building Cost Manuals* were a major contributor, other data sources were also used. *Archived Sweets* manuals, which includes advertisements for materials and supplies directed to the construction industry, were used to gather data on the materials and their specifications. In addition, archived *American Society for Testing and Material* (ASTM) *Manuals*, *Engineering News Record* (ENR), and numerous other archived construction trade publications were utilized to gather the data on how materials had changed over the timeframe of the study.

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Cost Adjustment

In order to compare partial factor productivity measures over time, adjustments were made to the cost inputs to account for inflation by utilizing the consumer price index (CPI). The CPI is an inflation index comprised by the U.S. BLS. By measuring the price change for a market basket of consumer goods and services, the CPI is the most widely used measure of inflation by the United States Federal Government, and it is often used as an indicator of the effectiveness of its economic policy. Even though the CPI is not specific to the construction industry, its broadly encompassing and widespread use as a measure of inflation in the United States justified its use in the research.

Technology Factors

O'Connor and Yang (2004) investigated the reason for the construction industry's reluctance to implement new technologies. They indicated that a lack of information and understanding regarding technological benefits had contributed to the industry's apparent technical stagnation. To achieve a critical understanding of technology's impact on construction performance, the authors herein developed a metric based on a literature review and industry interviews that were used to quantify the changes in material technology between 1977 and 2004. The metric is composed of five factors separated into two groups based on their quantitative or qualitative nature, which are described below and include: weight reduction, strength, curability, installation, and modularity.

Quantitative Factors

Weight Reduction. Weight reduction measures the reduction in the unit weight of a material between 1977 and 2004. Such material improvements have the potential of promoting easier handling by craft workers. This factor is calculated by measuring the percentage difference between the unit weight of the material in 1977 and in 2004, as shown by the following formula:

$$\text{Weight reduction(WT)} = \frac{\text{material weight 1977} - \text{material weight 2004}}{\text{material weight 1977}} \times 10 \tag{5}$$

The purpose of multiplying by 10 in Eq. (5) is to normalize the outcome and compare it to the values of curability, installation, and modularity, which are multiples of one.

Strength. Technological advancements, especially with new admixtures and design of concrete mixtures, have increased the materials' unit strength. These improvements have been incorporated into the analyses by the strength variable, which measures the percentage change in a material's unit strength between 1977 and 2004 [Eq. (6)]

$$\text{strength(ST)} = \frac{\text{material strength 2004} - \text{material strength 1977}}{\text{material strength 1977}} \times 10 \tag{6}$$

The purpose of multiplying by 10 in Eq. (6) is the same as Eq. (5).

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). One issue encountered when developing a measure for this factor is that materials have a significantly different curing time that can range from hours to days. To better represent a unitless factor, the curability factor was developed through a multinomial measure based on the percentage change in the curability time. Because the exact values about the improvement of curability time were often not available when the writers collected the data, the following categorical values are used to assess curability:

1. Curability=0 if there was no change in the curability time of a material between 1977 and 2004;
2. Curability=1 if there was a change of 5–15% between the curability time in 1977 and 2004; and
3. Curability=2 if there was a change greater than 15% between the curability time in 1977 and 2004.

Qualitative Factors

The research identified two qualitative material technological factors that intuitively have an impact on construction productivity but that are difficult to quantitatively measure. As a result, these factors are best represented through a multinomial scale, which is based on descriptors of changes that have occurred during the 27 year period of this investigation.

Installation. Some technological advancements have allowed material to be installed in adverse environmental conditions, such as extreme temperature and moisture conditions. To reflect the improved durability of materials during their installation, the installation factor was rated for the construction materials used in each activity for both 1977 and 2004 according to the following:

- IN1, material can only be installed under normal conditions =0;
- IN2, material can be installed in either extreme temperature or moisture conditions=1; and
- IN3, material can be installed under any temperature and moisture conditions (requires previous coding as IN2)=2.

Finally, the total change in installation was determined by the difference in the ratings between 1977 and 2004.

Modularity. Changes in materials' modularity involve reduction in the amount of material customization performed on site prior to its installation. Prefabrication of individual components restricted to a discrete construction activity was also included in this category, although off-site prefabrication of complete systems (e.g., off-site prefabrication of complete reactor vessels) that have essentially replaced multiple activities at the construction workface was not. The writers acknowledge that off-site prefabrication of complete systems has had a significant impact on construction productivity, but since such prefabrication has essentially involved introduction of new construction activities than which occurred in 1977, such level of prefabrication was not included in the analyses. As a result, the study's estimation of modularity likely underestimates this type of material technology's impact on construction productivity. Like the installation factor, the modularity factor (MO) was rated for materials in each activity for both 1977 and 2004 according to the following:

- M1, material is not modular (100%customization required on site=0;
- M2, material has minimal modularity but still requires on-site customization=1;
- M3, material has substantial modularity but still requires minimal on-site customization (requires previous coding as M2) =2; and
- M4, material requires no on-site customization=3.

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Table 1. Technology Index Example for below Grade Waterproofing

Technology characteristic	1977 material: One-component membrane system	2004 material: Two-component membrane system	Technology index score
(a) Quantitative factors			
Weight	No change		0
Strength	No change		0
Curability	Time to cure reduced by greater than 15%		2
(b) Qualitative factors			
Installation	IN1	IN2	1
Modularity	M1	M1	
Total sum			3
Final index score (total sum divided by 5)			6

The change in modularity was then based on the difference in the ratings between 1977 and 2004.

Technology Index. The five technology indexes described were combined to calculate an overall material technology index. For each activity in the study, the level of material technology change for all of the materials in an activity was identified based on each technology factor in both 1977 and 2004. The materials technology index was calculated as an evenly weighted average of the five technology factors [Eq. (7)]

$$\text{materials technology index(MTI)} = \frac{(\text{WT} + \text{ST} + \text{CU} + \text{IN} + \text{MO})}{5} \tag{7}$$

The technology index score was used in different analyses to determine the relationship between the changes in material technology and productivity. The writers acknowledge that each material factor may have a varying level of influence on construction productivity and assuming an evenly weighted average is one weakness of this study. Unfortunately, two data populations would have been needed to develop a materials index with varying weight. In theory, one population would have been needed to first identify the varying weights, through either quantitative analysis or expert opinion, and the second population would have been necessary to perform the ANOVA and regression analyses as presented herein. Unfortunately, utilizing a second data population was outside the scope of this research, so the writers utilized an evenly weighted index as done in previous research efforts (Goodrum and Haas 2002, 2004).

To illustrate the calculation of the MTI, consider the activity of waterproofing below grade using liquid applied bituminous coating systems. In 1977, the liquid applied waterproofing systems were primarily single component systems which were often sensitive to both temperature and humidity during application and required up to 72 h to properly cure. Today, two component systems have become common and can be applied at temperatures as low as 25°F and set at 180 min at the before mentioned temperature (Henshell and Griffin 2000). With this in mind, the writers found no documented change in either the weight reduction, strength, or modularity factors. Rather, the changes influenced the curability and installation as shown in Table 1.

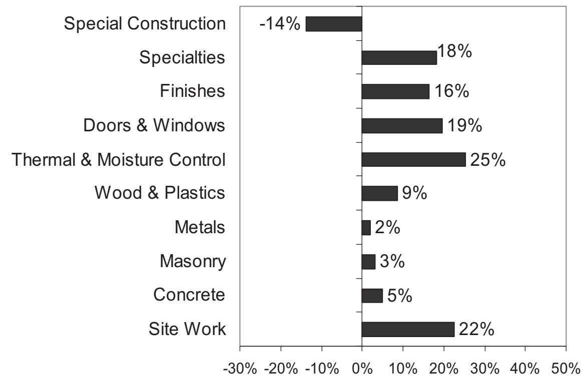

Fig. 2. Means percent change in labor productivity 1977–2004 in construction tasks by division

Analyses

Change in Productivity at Activity Level

One hundred activities selected from the *Means Building Cost Estimation Manual* were analyzed in this research effort. Cost, physical output, and work hour data were collected from the *Means Building Cost Estimation Manual* from the years 1977 and 2004.

Using the output and work hour data for the period under study (1977–2004), the change of labor productivity between 1977 and 2004 was calculated for each of the 100 sampled activities based on Eq. (1). The average percentage of change in the labor productivity of the 100 activities sampled between 1977 and 2004 was 13.5%, with an annual improvement compound rate of 0.47%. The researchers grouped the activities by division, per the CSI masterformat, and the average change in labor productivity per division was calculated (Fig. 2). As Fig. 2 demonstrates, the divisions composed of the research's sampled activities experienced different degrees of productivity. The division with the greatest improvement was thermal and moisture control with an increase of 25.24% (0.84% compound rate of improvement), followed by the site work division at 22.48% (0.75% compound rate of improvement). The special construction division actually experienced an average decline in labor productivity, at least among the study's activities sampled.

The change in partial factor productivity for the same 100 sampled activities was also examined through Eqs. (3) and (4). The input cost (labor and material cost) for partial factor productivity was corrected for inflation using the CPI, as discussed earlier. The rate of change in the partial factor productivity between 1977 and 2004 was on average 15.5%, with an annual improvement compound rate of 0.54%. As with labor productivity, the division that witnessed the largest partial factor productivity increase was the thermal and moisture control division, with an increase of 41.15% and with an annual improvement compound rate of 1.28% between the years 1977 and 2004. Fig. 3 demonstrates that all of the categories of sampled activities experienced different degrees of productivity improvement except specialties, which decreased by −24.0% with an annual compound rate of decline of −1.01%, doors and windows at −2.4% with an annual compound rate of decline of −0.09%, and special construction with a decrease of −15.6% with an annual compound rate of decline of −0.62%. The category that saw the greatest increase in partial factor productivity was the thermal and moisture control category, which also experienced the greatest improvement in

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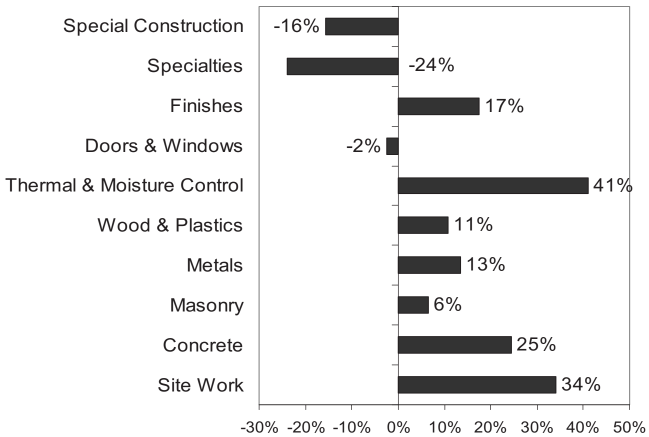

Fig. 3. Means percent change in partial factor productivity 1977–2004 in construction tasks by division (CPI inflation adjusted)

labor productivity among the sampled activities, with an increase of 41.1% in partial factor productivity (1.28% compound rate).

Certainly, there are a multitude of difference issues that can be examined to help explain the observed changes; however the research focused only on one particular factor, changes in material technology.

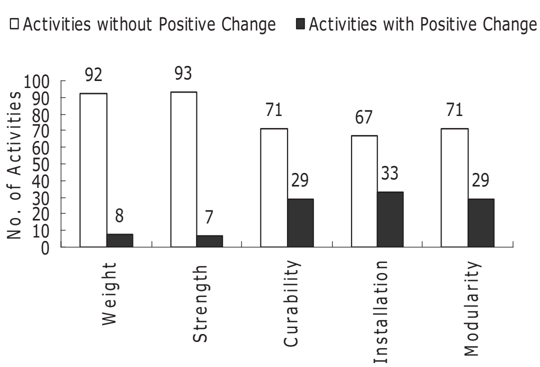

Fig. 4. Number of activities that have experienced positive change in material technology for each technology factor

Change in Material Technology

Fig. 4 depicts the number of activities that have experienced a positive change in material technology in construction material for each technology factor in at least one of the activities. The degree of positive change is illustrated in Table 2, which shows the average technology index broken down by the index score for each technology factor for activities grouped by CSI division. The material technology index (MTI) was calculated based on the procedures described in previous sections and the example shown in Table 1. The mean score of the MTI was 0.20 with a maximum score of 0.83. As discussed below, this is a reflection of the little change that was observed among the activities sampled in the weight and strength factors.

As shown in Fig. 4, the most common type of change in material technology among the sampled activities was a change in the installation variable, followed by changes in modularity and curability. Less than 10% of the activities sampled experienced either a change in unit weight or in unit strength. According to the average values of technology factors in Table 2, the researchers observed that the greatest change occurred in installation and modularity, followed by curability. In addition, Table 2 indicates that the thermal and moisture control division experienced the greatest overall change in material technology, with the installation factor experiencing the greatest degree of change followed by curability and modularity. The changes in the liquid applied waterproofing systems already described are one example of an improvement in the installation factor in the thermal and moisture control division. Cold weather admixtures, in the concrete division, also allow placement of concrete in colder temperatures than was previously possible.

Fig. 4 also indicates that 29% of these construction activities experienced improved modularity, with the greatest improvement occurring in the concrete division. For example, autoclaved aerated concrete (AAC) is now being used in a variety of building construction systems. AAC consists of small masonry like units and a variety of specially manufactured shapes and preassembled wall sections. Using one material to build the entire structural and insulation system allows for rapid construction, and their dimensional accuracy requires less on-site adjustment. Modular windows and doors have also significantly reduced the amount of on-site customization required for their installation.

Changes in curability occurred in 29% of the activities (Fig.

Table 2. Average Material Technology Index for Each Technology Factor for Activities Grouped by Construction Specification Institute (CSI) Division

Division	Weight					Material technology index
	Reduction	Strength	Curability	Installation	Modularity	
Site work	0.14	0.12	0.64	0.45	0.27	0.32
Concrete	0.15	0.26	0.46	0.46	0.54	0.37
Masonry	0.10	0.00	0.55	0.09	0.09	0.17
Metals	0.00	0.00	0.13	0.38	0.38	0.18
Wood and plastics	0.13	0.00	0.30	0.20	0.50	0.23
Thermal and moisture control	0.09	0.00	0.79	0.93	0.50	0.46
Doors and windows	0.00	0.00	0.00	0.23	0.31	0.11
Finishes	0.01	0.00	0.27	0.18	0.09	0.11
Specialties	0.00	0.00	0.00	0.00	0.33	0.07
Special construction	0.00	0.00	0.00	0.33	0.33	0.13
Average	0.06	0.04	0.31	0.33	0.33	0.21

Note: Weight reduction (WT); strength (ST); curability (CU); installation (IN); and modularity (MO) denote each technology factor's component score in the material technology index (MTI), which was calculated through Eq. (7).

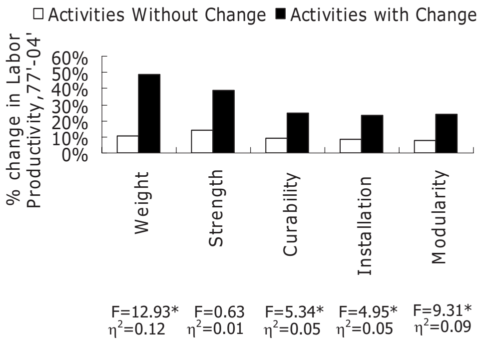

Fig. 5. Percent change in labor productivity for activities with change in material technology and activities with no change in material technology, 1977–2004, $^{*}p<0.05$

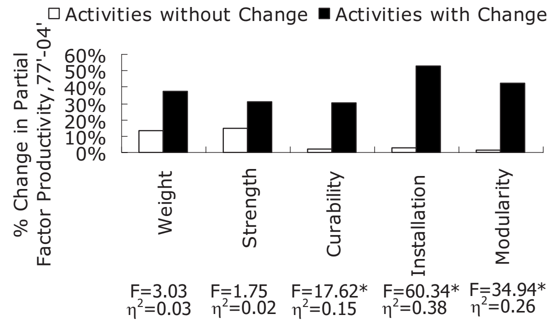

Fig. 6. Percent change in partial factor productivity for activities with change in material technology and activities with no change in material technology, 1977–2004, $^{*}p<0.05$

4). Most of these changes occurred in the thermal and moisture control, site work, masonry, and concrete divisions. Developments in waterproofing coating systems and new admixtures for concrete admixtures allow these materials to cure at accelerated rates. Concrete admixtures improved not only activities in the concrete division, but also activities in site work, which utilized concrete mixtures (e.g., cast-in-place concrete piles, concrete sidewalk, and concrete slurry trenches).

Very few of the activities sampled were found to have experienced a change in unit strength and unit weight. Concrete and site work divisions experienced the greatest change in these material characteristics. A low measure of these changes is most likely an indication of the previously mentioned weakness of this study, rather than an indication that these changes are rare. Changes in material strength and weight have allowed the building of structures that could not possibly have been built decades ago. These structures incorporate construction activities not previously executed on a project and would therefore have not been included in this research, since one criterion for activity inclusion in the study was that it occurred in both 1977 and 2004.

Relationship between Changes in Material Technology and Construction Productivity

ANOVA is used to test whether two or more groups have statistically significant different means. The ANOVA test estimates the statistical significance of the difference between the means (F value), and it measures the amount of variation in the dependent variable that is explained by the independent variables (η^2). Using the material technology factors, the ANOVA analyses compared changes in labor and partial factor productivity from 1977 to 2004 between two groups of activities: (1) activities that experienced an improvement per each of the study's material technology factor; and (2) activities that did not experience an improvement (Fig. 5).

With the exception of the strength factor, the activities that experienced improvement in material technology experienced more improvements in labor productivity than those activities that did not, and this finding was statistically significant. Activities experiencing an improvement in weight, curability, installation, and modularity had at least twice as great of an improvement in labor productivity as activities experiencing no improvement in these four factors. The greatest relative labor productivity improvements were due to advances in weight, followed by modularity, curability, and installation. A review of the F values indicates that all technology factors, except strength (F value $=0.63$, sig. $=0.43$), were statistically significant at the 0.05 level. Although activities that experienced a change in strength also experienced larger increases in labor productivity, the differences were not statistically significant. 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 expediting the process of construction.

The ANOVA analyses of changes in material technology versus changes in partial factor productivity are shown in Fig. 6.

The ANOVA analysis of partial factor productivity and technology factors revealed that there was a substantial and statistically significant relationship among the analyzed activities, although the findings were not as statistically significant as the labor productivity analysis. Only the factors curability (F value $=17.62$, sig. $=0.00$), installation (F value $=60.34$, sig. $=0.00$), and modularity (F value $=34.94$, sig. $=0.00$) were found to have a statistically significant relationship with changes in partial factor productivity. Of these three factors, changes in installation had the greatest statistical and substantial relationship with improvement in partial factor productivity, followed by changes in modularity and curability.

Regression Analysis

A series of simple and multiple regressions were used to further examine the relationship between changes in material technology and the associated changes in labor and partial factor productivity.

Regression Analysis—Base Analyses

The first regressions modeled the relationship between changes in the material technology index on both labor and partial factor productivity (Fig. 7). Both simple regressions show a positive relationship between increases in the MTI and improvements in construction productivity. The material technology index explained 12% of the total variability in the changes in labor productivity and 41% of the total variability in partial factor productivity. The estimated parameters of the linear models are significantly different than 0 according to the measured F values [see Table 3, Eq. (A) and Table 4, Eq. (A)].

Further Regression Models

Next, regression models were built by introducing a series of dichotomous (binary) variables for the five material technology factors, which included strength, weight, curability, installation, and modularity. Each dichotomous variable was coded 1 if any material in the activity experienced a change in material technol-

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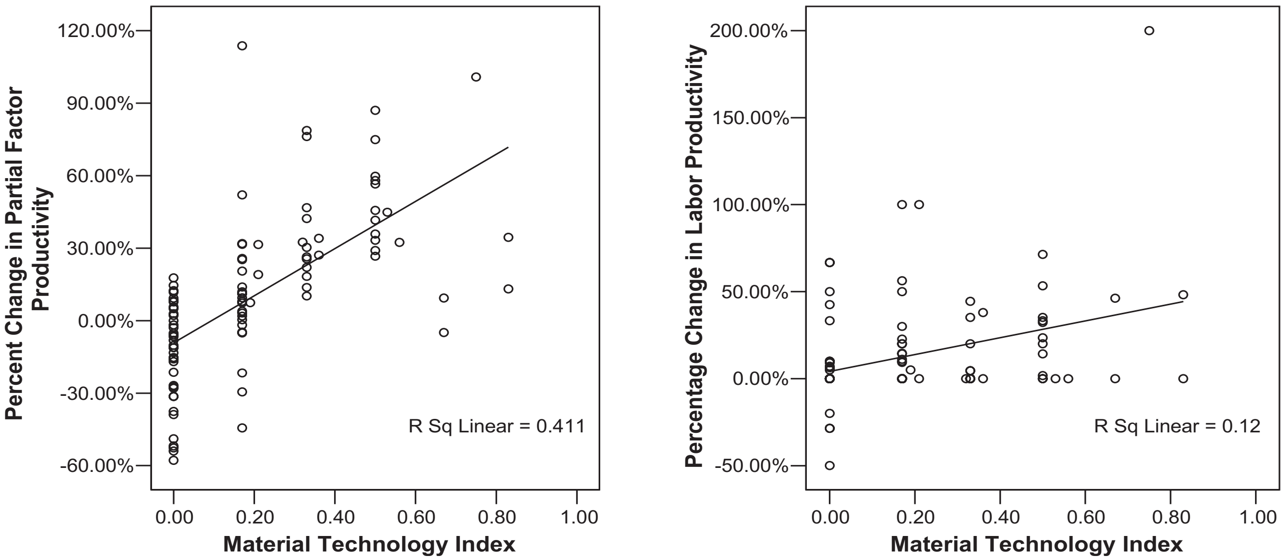

Fig. 7. Scatterplots with regression lines for percent change in labor productivity and partial factor productivity on material technology index, 1977–2004

ogy, as described by the variable from 1977 to 2004, or 0 if otherwise. Each variable was added individually to the regression analysis to examine their individual statistical significance to the overall regression model [Eq. (8)]

$$P = \alpha + \beta_1 \text{MTI} + \beta_{2,i} T_i \tag{8}$$

where P denotes the percentage change of labor productivity or partial factor productivity; MTI denotes the material technology index; T_i denotes the dichotomous variable; and α, β_1, and $\beta_{2,i}$ denote the regression coefficients ($i=1-5$ denotes strength, weight, curability, installation, and modularity, respectively).

If more than one dichotomous variable was statistically significant in the separate models as measured by their individual t value, then a combined model was developed that included all significant variables [e.g., Table 3, Eq. (G)]. The regression coefficients for the dichotomous variables indicate the amount of change in the y intercept of the regression line for the activities coded 1 compared to the regression line for the activities coded 0. All models passed the collinearity tests, so it was valid to include MTI and the other dichotomous variables in the regression models.

The regression models for labor productivity are shown in Table 3. The material technology factor weight produced statistically significant effects on labor productivity above the 95% confidence level. This factor, along with the material technology index, explained 17% of the total variation in labor productivity according to the adjusted coefficient of determination [Table 3, Eq. (C)]. Activities with a decrease in the unit weight of construction materials experienced a 31.0% increase in labor productivity compared to other activities that did not experience a change in unit weight [Table 3 Eq. (C)]. Two variables, strength and installation, actually had negative coefficients, indicating that activities with these changes in material technology actually experienced less improvement in labor productivity than did other activities that did not experience either change. However, the statistics were not significant for either of the variables. In regard to coefficient for the strength variables, there are a number of motivations behind improving the unit strength of material, which include improvements in safety and quality both during construction and over the life cycle of a facility. As these analyses indicate, a positive correlation between the increase in the unit strength of materials and improvements in labor productivity was not observed.

The regression models for partial factor productivity are shown in Table 4. The material technology variables installation and modularity produced statistically significant effects, above the 95% confidence level, on partial factor productivity in Eqs. (E) and (F) and were retained for the comprehensive regression Eq. (G) (Table 4). These variables, along with the MTI, explained 48% of the total variation in partial factor productivity, according to the adjusted coefficient of determination [Table 4, Eq. (G)]. Activities with a change in the installation factor experienced a 23.6% increase in partial factor productivity compared to other activities that did not [controlling for changes in modularity-see Table 4, Eq. (G)]. Considering the same regression equation (G), activities experiencing a change in modularity experienced a corresponding added increase in partial factor productivity of 15.8%. However, the statistical significance of the modularity variable was less in comparison to the installation variable; the t value for the modularity variable was 2.44, and the t value for the installation variable was 3.30.

The writers acknowledge that the R square values for the labor productivity model are low. However, there are many other factors such as equipment technology and management effectiveness that can impact construction productivity but were not incorporated into the regression equations. Considering that the regression models were not intended to identify all the factors that impact productivity rather than examine only the influence of material technology, the observed R square values appear to be reasonable in the writers' opinion. It is also noted that the material technology index had a stronger substantial and statistical relationship with partial factor productivity than the labor productivity, which is surprising considering that technology, overall, typically has a labor saving bias on production. This unexpected result is discussed in the next section.

Discussion of Results

Overall, the analyses show that changes in material technology are correlated with improvements in both labor and partial factor

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Table 3. Regression of Material Technology Index and Binary Variables on Percent Change in Labor Productivity

Equation	Constant	MTI	Strength	Weight	Curability	Installation	Modularity	F	Sig.	R^2	Adj. R^2
A	4.17 (1.08, 0.28)	48.34 (3.66[a], 0.00)	—	—	—	—	—	13.36[a]	0.00	0.12	0.11
B	3.98 (1.04, 0.30)	53.85 (4.00[a], 0.00)	−30.01 (−1.76, 0.82)	—	—	—	—	8.37[a]	0.00	0.15	0.13
C	3.39 (0.91, 0.37)	39.72 (3.04[a], 0.00)	—	30.96 (2.97[a], 0.00)	—	—	—	11.64[a]	0.00	0.19	0.17
D	4.10 (1.05, 0.30)	46.04 (2.75[a], 0.01)	—	—	1.81 (0.23, 0.82)	—	—	6.64[a]	0.00	0.12	0.10
E	4.25 (1.09, 0.28)	53.11 (2.84[a], 0.01)	—	—	—	−3.12 (−0.36, 0.72)	—	6.68[a]	0.00	0.12	0.10
F	3.72 (0.96, 0.34)	36.93 (2.27[a], 0.03)	—	—	—	—	9.29 (1.20, 0.23)	7.42[a]	0.00	0.13	0.12

Note: The numbers in parentheses are associated t values and significant values of the regression unstandardized coefficients.
[a]t and F value with a statistical significance greater than 95%.

Table 4. Regression of Material Technology Index and Binary Variables on Percent Change in Partial Factor Productivity

Equation	Constant	MTI	Strength	Weight	Curability	Installation	Modularity	F	Sig.	R^2	Adj. R^2
A	−9.21 (−2.67, 0.01)	97.60 (8.27[a], 0.00)	—	—	—	—	—	68.37[a]	0.00	0.41	0.40
B	−9.24 (−2.67, 0.01)	98.23 (8.06[a], 0.00)	−3.46 (−0.22, 0.82)	—	—	—	—	33.88[a]	0.00	0.41	0.40
C	−9.31 (−2.68, 0.01)	96.50 (7.94[a], 0.00)	—	3.93 (0.41, 0.68)	—	—	—	33.98[a]	0.00	0.41	0.40
D	−9.22 (−2.65, 0.01)	97.40 (6.53[a], 0.00)	—	—	0.15 (0.02, 0.98)	—	—	33.84[a]	0.00	0.41	0.40
E	−9.87 (−2.98, 0.00)	62.33 (3.92[a], 0.00)	—	—	—	23.05 (3.15[a], 0.00)	—	42.26[a]	0.00	0.47	0.46
F	−9.94 (−2.93, 0.00)	78.98 (5.53[a], 0.00)	—	—	—	—	15.16 (2.23[a], 0.03)	35.79[a]	0.00	0.44	0.43
G	−10.65 (−3.28, 0.00)	42.15 (2.40[a], 0.02)	—	—	—	23.57 (3.30, 0.00)	15.79 (2.44[a], 0.02)	31.58[a]	0.00	0.50	0.48

Note: The numbers in parentheses are associated t values and significant values of the regression unstandardized coefficients.
[a]t and F value with a statistical significance greater than 95%.

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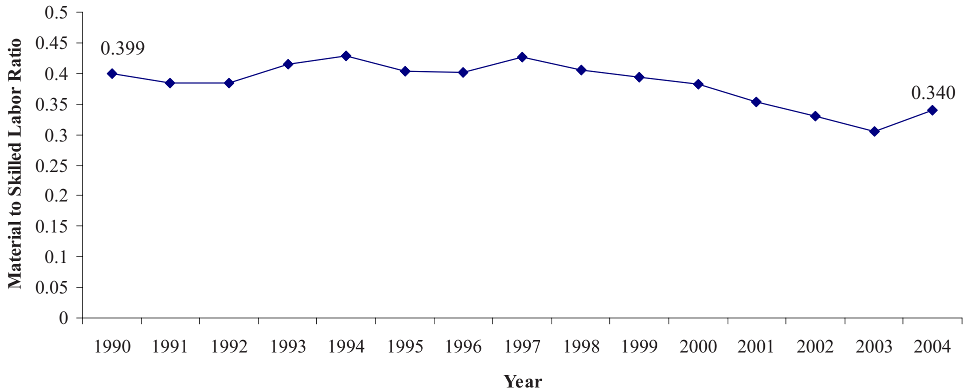

Fig. 8. Material to skilled labor ratio from 1990 to 2004

productivity. The 100 sampled activities witnessed an average increase in labor productivity of 11%, and an average increase in partial factor productivity of 10.7% from 1977 to 2004. The ANOVA analyses indicated that a simple relationship did exist between changes in material technology and changes in labor and partial factor productivity. While four out of the five factors were significantly related to changes in labor productivity, only three (curability, installation, and modularity) out of the five factors were significantly related to changes in partial factor productivity. However, as measured by the eta squared measures, the three material technology measures explained significantly more variation in partial factor productivity than the material technology factors did in the ANOVA labor productivity analyses.

The regression models provided a better understanding of the relationship between material technology and construction productivity. The regression models explained significantly more variation in partial factor productivity than in labor productivity. This finding confirms the relationship between technology and productivity in part and contradicts it in other areas. While the findings confirm a positive relationship between technology and productivity improvement, the findings also show that the relationship was stronger between material technology and partial factor productivity than between material technology and labor productivity. Many studies have found that technology tends to have a greater impact on labor productivity than on factor productivity; technological advance is characterized by the substitution of capital for labor in the manufacture of capital goods, resulting in production's increase in the capital to labor ratio (Salter 1966; Rossow 1977).

If material technology has a greater impact on factor than on labor productivity, it would be expected that material technology has a relative labor using effect in comparison to the added investment in new material technology on production, which would result in a declining material to labor ratio. In order to examine if this is indeed the case, the research examined the overall change in the material to labor cost ratio in construction utilizing the *Engineering News Record*'s MPI and the skilled labor index. The MPI tracks the change in the price of structural cement, structural steel, and lumber from suppliers in 20 cities across the United States. The skilled labor index tracks union wages of carpenters, bricklayers, and iron workers, including fringe benefits. Both indices are components of the *Engineering News Record*'s (ENR) building cost index. As shown in Fig. 8, the material to labor ratio, utilizing both indices, decreased at an annual compounded rate of 1.14% between 1990 and 2004, which is the extent of the data available for both the material and skill labor index from ENR.

Although recently there has been strong growth in material prices (Grogan 2006), the material to skilled labor ratio indicates that the price for skilled labor has been increasing at a faster rate than that of material, at least of the material and labor components measured between 1990 and 2004. This analysis assumes that the effects of inflation are uniform on both construction materials and labor. Based on the decline in the ratio, it is plausible that material technology does have a relative labor using effect on production, but more research is needed in this area to confirm this effect.

Conclusions

These analyses and discussion contribute to the body of knowledge with regard to construction productivity and technology along five areas:

1. Based on the 100 activities sampled, the researchers found further evidence of productivity improvement at the activity level, which confirms the findings of previous efforts (Goodrum et al. 2002);
2. Among the activities sampled, a quantifiable positive relationship exists between improvement in material technology and improvements in construction productivity;
3. The relationship of changes in material technology and construction productivity was notably weaker on labor productivity than on partial factor productivity;
4. The strongest relationship between changes in material technology and labor productivity were found among changes in the unit weight of materials; and
5. The strongest relationship between changes in material technology and partial factor productivity were found among changes in installation and modularity.

Recommendations

The following recommendations with regard to examining the relationship between technology and productivity are made:

1. Future research and development of new materials characterized by changes in installation and modularity are warranted, since these factors were consistently related to improvements

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in construction productivity. In addition, researchers need to analyze the reason why labor productivity and partial factor productivity experienced their greatest effects from different technology factors;

2. While this and previous efforts have examined the relationship between changes in equipment and material technology, the relationship between information technology and productivity is still largely unknown and worthy of future research; and
3. This and other research continues to identify construction productivity improvements at the activity level, which continues to contradict previous studies that show industry measures of productivity have been declining. Research has suggested that one reason for the decline in industry productivity measures are that current measures of industry output do not account for changes in the quality of construction output (Dacy 1965; Gordon 1968; Rosefielde and Mills 1979; Pieper 1990; Gullickson and Harper 2002; Tuchman 2003), but this occurrence has not been quantified. Despite significant studies within the engineering and construction academic community examining construction productivity, there is a dearth of research that has addressed the issue of quality changes in the industry's output, and it is needed to potentially improve current industry output measures.

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