Long-Term Impact of Equipment Technology on Labor Productivity in the U.S. Construction Industry at the Activity Level

Paul M. Goodrum[1] and Carl T. Haas[2]

Abstract: In general, U.S. industries have witnessed dramatic changes in core processes over the past 25 years. Well understood technological and managerial advances have allowed the manufacturing sector, for example, to steadily increase its productivity and its profit margins. Similar changes are far less well understood in construction. This research examines 200 construction activities for the effect of technology, specifically equipment technology, on their labor productivity from 1976 to 1998. During that time period, changes in equipment technology are measured using a technology index consisting of five technology change factors. Through analysis of variance and regression analyses, it is found that activities experiencing significant changes in equipment technology have witnessed substantially greater long-term improvements in labor productivity than those that have not experienced a change in equipment technology. This research also reveals that changes in (1) energy, (2) control, and (3) functional range are significantly and positively correlated with improvements in labor productivity.

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Introduction

Although productivity is a key way to characterize economic performance, it is often difficult to measure (Stern 1999). In no other United States' industry is this more true than in the construction industry. Due to the difficulty of measuring real construction output, the Bureau of Labor Statistics (BLS) does not maintain a productivity index for the U.S. construction industry (Rosenblum 2000). With no official productivity index, perceptions of productivity trends vary widely. Aggregate level productivity measures show long-term declines, while activity level productivity measures show long-term improvements (Allmon et al. 2000; Teicholz 2001). At the activity level, extensive research indicates that both labor and partial factor productivity have improved. Factor productivity is the cost of the resources required for one unit of output.

Previous research has identified factors that impact labor productivity at the project level (Maloney 1983; Allen 1985; Thomas et al. 1990; Thomas and Sakarcan 1994). Past research has provided the construction industry with valuable information about how to improve the efficiency and productivity of individual projects. Conversely, little is known about what factors impact labor productivity trends. Equipment technology, a factor that has repeatedly changed over the past 25 years, may be one way to explain some of these construction labor productivity trends.

Koch and Moavenzadeh (1979) considered the change in equipment and labor costs (controlling for inflation) per unit of physical output for various road construction activities from the 1920s to the 1970s. They found that increased usage and advancements in equipment technology were two primary causal agents. 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 1920s to the 1950s when machine power innovations were introduced.

Purpose and Scope

This paper examines how changes in equipment technology have influenced labor productivity in the U.S. construction industry over a 22-year time period in three parts. First, the paper examines labor productivity changes in the U.S. for 200 different construction activities from 1976 to 1998. Second, the paper examines equipment technology changes from 1976 to 1998 using five equipment technology characteristics. Third, the relationship between equipment technology changes and labor productivity changes in construction are examined. Data for the research were collected from three commercially available estimation handbooks.

To analyze construction productivity trends, controls for output and equipment technology innovations must be included (Pieper 1989). Since it is difficult to measure construction productivity at the aggregate level, this research examined changes in construction productivity at the activity level.

[1]Assistant Professor, Dept. of Civil Engineering, 151C Raymond Building, Univ. of Kentucky, Lexington, KY 40506-0281. E-mail: pgoodrum@engr.uky.edu

[2]Professor, Dept. of Civil Engineering, ECJ 5.200, The Univ. of Texas at Austin, Austin, TX 78712-1076.

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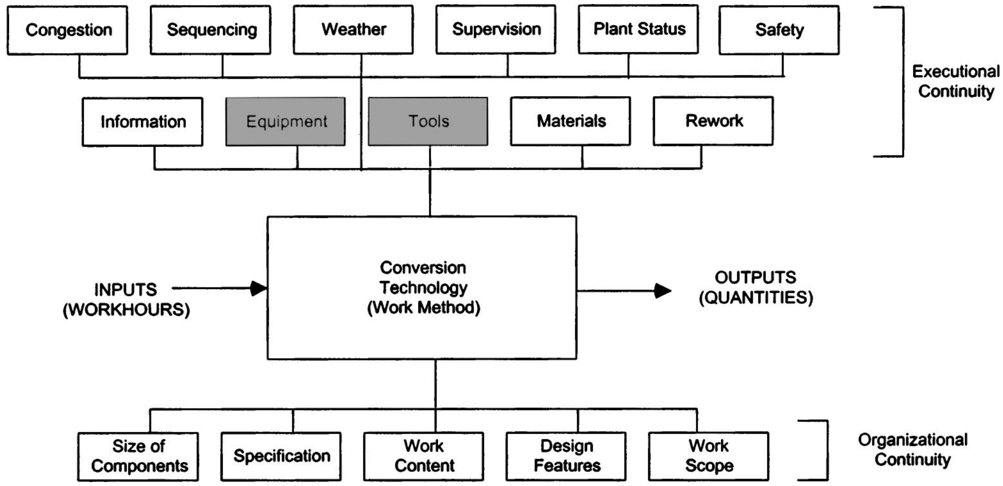

Fig. 1. Factor model of construction labor productivity (Thomas and Sakarcan 1994)

Background

Factors Affecting Construction Productivity

Prior research identified a number of factors as impacting labor productivity in construction. Based on a United Nation's report (United Nations 1965) and work by Thomas and Sakarcan (1994), a general model of the factors affecting labor productivity is shown in Fig. 1.

This paper focuses on two of the 15 factors identified in Fig. 1, "Equipment" and "Tools." Computers, telecommunications, and networking capabilities are not considered in this research.

Technology's Impact on Production Techniques

Measuring technology change has challenged economists and engineers for years. Previous research has examined relative changes in capital versus labor costs as a measure of technology use (Salter 1966; Koch and Moavenzedah 1979). In the context of economic theory, capital refers to all goods used to produce other goods and services, including factories, machinery, and equipment (Ammer and Ammer 1984). These goods are often referred to as either fixed capital, such as buildings or machinery, or circulating capital, such as raw material stocks. This paper focuses on fixed capital, including equipment costs for tools and machinery, and measures changes in fixed capital to labor costs as one measure of equipment technology change using the following formula:

$$\Delta\text{capital-to-labor ratio} = (K_{98'}/L_{98'}) - (K_{76'}/L_{76'}) \qquad (1)$$

where $K_{98'}$=1998 unit capital costs; $K_{76'}$=1976 unit capital costs; $L_{98'}$=1998 unit labor costs; and $L_{76'}$=1976 unit labor costs.

The capital-to-labor ratio is used with the assumption that technological advances require less labor (Salter 1966; Koch and Moavenzedah 1979). For example, consider a factory that uses two units of machinery and ten workers and produces ten units of output. A new version of the machinery uses three units of machinery but only five workers and produces the same amount of output. This technological improvement represents a relative increase in capital-to-labor requirements.

The decline of real construction wages (adjusted for inflation) presents a problem in estimating labor costs for the capital-to-labor ratio. Although real wages started to outpace inflation in the late 1990's, there was a long-term decline in real construction wages from 1976 to 1998 (Allmon et al. 2000; Oppedahl 2000). Although subject to further research, the decline in real wages may be due to a combination of factors, including the decline of unionization, decline in worker skills, increase in migrant workers, increase in fringe benefits, and improvements in construction safety (Oppedahl 2000; Goodrum 2001).

Methodology

Productivity Defined

Labor productivity is the ratio of output to labor hours (BLS 2000). One of the challenges in measuring productivity is 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 values of productivity rather than absolute values solves this problem, therefore, the percent change in labor productivity from 1976 to 1998 is used to measure productivity for each activity in this study. This is accomplished using the following formula:

$$\%\ \text{change in labor productivity, 1976–1998} = \left(\frac{\text{labor productivity 1998} - \text{labor productivity 1976}}{\text{labor productivity 1976}}\right) \times 100 \qquad (2)$$

Equipment Technology Defined

This research only examines the effect of changes in equipment technology on labor productivity, specifically, the equipment technologies of hand tools and machinery. Hand tools include pneumatic nail guns, electric drills, circular saws, and similar types of tools. Machinery includes cranes, grout pumps, bulldozers, and similar types of machinery.

Data Sources

The primary labor productivity data came from estimation handbooks including: *Means building construction cost data* (Means

1976), *Richardson's process plant construction estimating standards* (Richardson Engineering Services 1976), and *Dodge unit cost* books (Dodge cost guides 1976). These handbooks are designed to provide construction cost data for the purpose of project estimation and budgeting.

These handbooks provide unit labor costs, unit equipment costs, physical output data, and work-hour requirements for construction activities. While the handbooks are a valuable source of information about productivity across time, there are some limitations to the data. The contractors who provide the figures for the manuals are not required to construct a project using their estimations; this leads some contractors to offer inflated estimates of construction costs (Pieper 1989). Despite these limitations, there is precedence for using estimation manuals as a source of information about productivity (Thomas 1987), and unlike other sources, estimation manuals provide data going back to 1976.

Converting the value of construction output measured in financial terms to real output is an unresolved issue in studies on construction productivity. Construction real outputs adjusted using construction specific inflation indices do not reflect changes in quality resulting from innovation and design improvements in construction (Dacy 1965; Gordon 1968; Rosefielde and Mills 1979; Pieper 1990). This conversion tends to overestimate inflation, and this creates an underestimation of construction real output and labor productivity. The use of the estimation handbooks (to examine productivity at the construction activity level) alleviates this problem, because the manuals report direct physical output.

Data were manually collected from the 1976 and 1998 estimation manuals of *Means* (Means 1998), *Richardson* (Richardson Engineering Services 1998), and *Dodge* (Dodge cost guides 1998). There were three criteria used to select activities for inclusion in the study. The first criterion was the same activity was found in both the 1976 and 1998 estimation manuals. A number of activities included in the 1976 manual were not in the 1998 manual due to changes in methodology, materials, or lack of use in construction. Likewise, a number of new activities were included in the 1998 manual due to new methodology or materials. Second, activities from a diverse range of technological changes were selected. Third, activities were selected to represent a wide range of activity types from a range of different divisions as identified by the Construction Specification Institute (CSI) master format.

Two hundred activities were used in the analyses with 100 activities from *Means*, 50 from *Richardson*, and 50 from *Dodge*, with an overlap in similar activities across the three manuals.

Technology Factors

To examine how different mechanisms of equipment technology change have influenced construction labor productivity, five factors were identified (defined below and examples discussed later) to characterize changes in technology.

Amplification of Human Energy

Amplification of human energy is defined as technology designed to make an activity physically easier to perform. In its simplest terms, it can be regarded as the shift in energy requirements from human to machine and causing an increase in output.

Level of Control

Level of control relates to advances in machinery and hand tools that transfer control from the human to the machine.

Functional Range

Changes in equipment's functional range are those changes that expand a tool's or machine's range of capabilities.

Ergonomics

Ergonomics has been generally defined as technology that alleviates physical stresses imposed on a worker and helps the worker cope with the work environment.

Information Processing

Over time, construction equipment has been designed to provide greater and more accurate information regarding internal and external processes.

Technology Index

Unlike previous research on technology and productivity, this research developed and used a technology index to measure the progress of equipment technology over time. Rather than solely relying on theoretical economic measures to determine technological growth, which ignore the mechanics of cause and effect, this research attempts to measure actual technology characteristics. These characteristics provide specific quantitative measures of equipment technology changes, and these measures are provided for each construction activity. The authors identified and examined 43 types of hand tools and 31 types of machinery in 200 construction activities. Equipment technology changes were identified using equipment catalogs, handbooks, and specifications. Although the technology index quantifies changes in equipment technology, it does not capture all of the technological changes that have occurred in construction equipment across the 22-year time period under consideration. Although this research's microlevel analyses help to resolve some productivity measurement difficulties, it is not able to account for systematic improvements resulting from completely new methods (e.g., trenchless technology, computers, and data networks).

The technology index measures the aggregate change in equipment technology. Table 1 illustrates the scoring of the technology factors in the technology index (Goodrum 2001).

For all of the tools and machines used in each activity, the defined level of equipment technology was identified using the technology factors present in 1976 and 1998. The authors determined the change in equipment technology from 1976 to 1998 using the criteria delineated in Table 1. For example, Caterpillar's 225 LC hydraulic excavator was equipped to provide the driving energy to move a pile of dirt in 1976. By 1998, the equivalent model, Caterpillar's 325 LN, had the same capability but the flywheel horsepower had increased by 33 horse power (Caterpillar 1999). This piece of equipment would have been coded E4 in 1976 and E5 in 1998 because its driving energy had increased. The amount of amplification of human energy change for that machine would be 1 (E5−E4=4−3=1). For activities that involved a number of different tools and machines, changes for all of the tools and machines were summed to provide a total technology change score for that activity. Next, the total combined technology score was divided by the number of tools as shown in the following formula:

$$\text{Technology index} = \frac{\Sigma_1^N(\Delta E+\Delta C+\Delta F+\Delta R+\Delta I)}{N} \qquad (3)$$

where ΔE=change in energy; ΔC=change in control;

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Table 1. Technology Index Scoring System

Technology factor	Defined Level of Equipment Technology	Code	Score
Level of control (or Control)	Hand tools	C1	0
	Manually controlled devices	C2	1
	Assisted controlled devices	C3	2
	Telecontrolled devices	C4	3
	Preprogramed devices	C5	4
Amplification of human energy (or Energy)	Equipment supplies no driving energy	E1	0
	Equipment supplies some driving energy	E2	1
	Equipment supplies measurably more energy but not all (requires previous coding as E2)	E3	2
	Equipment supplies all the driving energy	E4	3
	Equipment supplies all the driving energy plus more than before (requires previous coding as E4)	E5	4
Information processing	Equipment provides no level of information feedback	I1	0
	Equipment provides basic level of information feedback regarding internal operating factors	I2	1
	Equipment provides internal information and is able to respond to own information	I3	2
	Equipment provides information regarding external and internal factors	I4	3
	Equipment provides information regarding internal and external factors and responds to both	I5	4
Functional range (or Function)	Equipment provides no enhancement to operator's capabilities	F1	0
	Equipment expands operator's capabilities	F2	1
	Equipment expands operator's capabilities more than before (requires previous coding as F2)	F3	2
Ergonomics	Equipment provides no relief to operator from physical stresses	R1	0
	Equipment provides relief from physical stresses	R2	1
	Equipment provides additional relief from physical stresses (requires previous coding as R2)	R3	2

ΔF=change in functional range; ΔR=change in ergonomics; ΔI=change in information processing; and N=number of tools and machinery in the activity.

To further illustrate how the technology index works, consider the following activity as an example: the installation of plywood roof sheathing. In 1976, the conventional tools used in this activity were the hand held hammer and the circular saw. By 1998, the hammer had been replaced by the use of the pneumatic nail gun. Also by 1998, the circular saw was still used, but circular saws had become more powerful by offering an increase in loaded revolutions per minute (representing a change in energy) and had also become lighter and operated with less vibration (both representing a change in ergonomics). The changes in equipment technology for this roof sheathing activity can, therefore, be quantified by the technology index as shown in Table 2.

Analysis of Results

Change in Construction Labor Productivity at the Activity Level

Using physical output and crew formation data from the estimation handbooks, the overall percent change in labor productivity (physical output per work hour) was calculated for each activity from 1976 to 1998. Expected physical output and crew formation data from the estimation manuals were used to calculate each activity's labor productivity [formula (4)].

$$\text{Labor productivity, year } X = \frac{\text{Expected physical output (units)}}{\text{Workhour requirements (hours)}} \tag{4}$$

Next, the percent change in labor productivity from 1976 to 1998 was calculated for each activity using the following formula:

Table 2. Technology Index Example for Installing Plywood Roof Sheathing

Technology characteristic	1976 Equipment: Hammer	1976 Equipment: Circular saw	1998 Equipment: Nail gun	1998 Equipment: Circular saw	Technology index score
Control	CI	C2	C2	C2	1
Energy	E1	E2	E2	E3	2
Information processing	I1	I1	I1	I1	0
Functional range	F1	F1	F1	F1	0
Ergonomics	R1	R1	R2	R2	2
				Total sum	5
Final index score (total sum divided by number of tools, 2)					2.5

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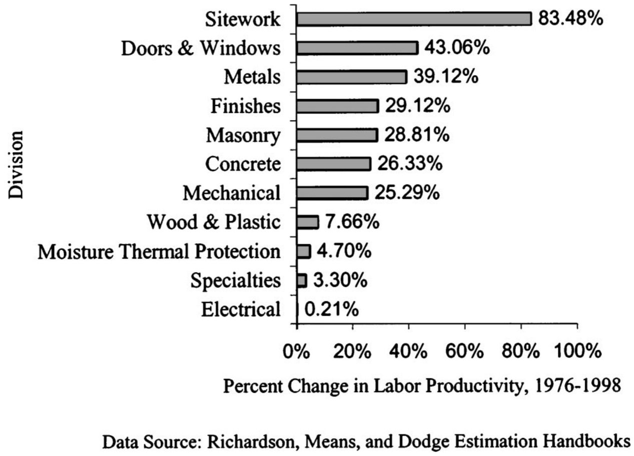

Fig. 2. Mean percent change in activity level labor productivity by division, 1976–1998

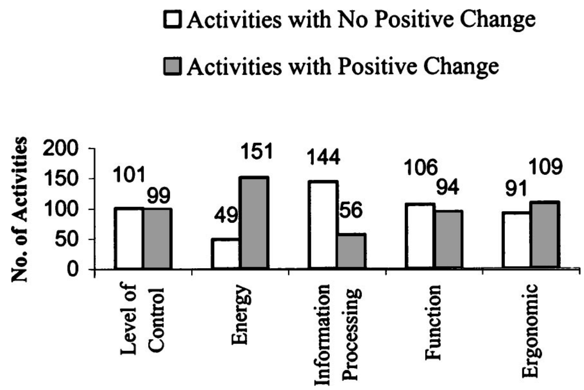

Fig. 3. Positive changes in equipment technology by technology factor, 1976–1998

$$\% \text{ change in labor productivity, } 1976-1998 = \left(\frac{\text{labor productivity } 1998 - \text{labor productivity } 1976}{\text{labor productivity } 1976}\right) \times 100 \quad (5)$$

The average improvement in labor productivity for the sampled activities over the 22-year period was 30.93% with an annual improvement compound rate of 1.23%. A one-sample T-test indicates that the 95% confidence interval for the average change in labor productivity was ±9.17%. Activities were grouped by division, per the CSI master format, and the average change in labor productivity per division was calculated. The results are shown in Fig. 2.

Although these results show that labor productivity on average improved from 1976 to 1998 for the study's 200 activities, there were some exceptions. Thirty activities experienced a decline in labor productivity. Sixty-three activities saw no change in labor productivity, while 107 activities improved in labor productivity.

It is clear from this sample that different sectors of the construction industry experienced different changes in labor productivity. On average, sitework activities experienced the greatest improvement in labor productivity, while electrical and moisture-thermal protection activities experienced only a small increase in labor productivity. Further research is required to determine the reasons behind these various sector changes.

Change in Equipment Technology

Fig. 3 depicts the number of activities that have experienced a positive change in equipment technology in at least one tool or piece of machinery for each technology factor. The degree of positive change is illustrated in Table 3, which shows the average technology index broken down by the index score for each technology factor for activities grouped by division.

Fig. 3 reveals that more than 75% of the activities under consideration experienced an increase in energy output. Table 3 indicates that the metals, wood and plastic, and sitework divisions experienced the greatest increase in tool and machinery energy output. As an example, welding machines increased wattage output for activities in the metals division. Powder-actuated systems, also in the metals divisions, offered greater depth penetration for installing studs in metal decking. In addition, by 1998 cranes offered more lifting capacity than in 1976. In the wood and plastic division, circular saws operated at higher revolutions per minute, and the pneumatic nail gun required less human energy than hand held hammers. Further, most site work machinery offered increased horsepower output (e.g., front-end loaders, dump trucks, backhoes, bulldozers, graders, asphalt pavers, and scrapers).

As depicted in Fig. 3, 49.5% of these construction activities experienced an improvement in equipment level of control. 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 hand held hammer in the wood and plastic division as well as in formwork installation in the concrete division. Also in the concrete division, pump trucks are now equipped with remote controlled booms, and concrete vibrators automatically adjust the vibration frequency to match the concrete's slump.

Changes in functional range occurred in almost half of the activities (see Fig. 3). Through advances in hydraulic controls and microprocessors, machinery for sitework now offers more control precision and a greater reach with booms and buckets. Excavators and backhoes are capable of digging deeper.

Fig. 3 indicates that more than half of the construction activities experienced some improvement in ergonomics. For example, by 1998 many hand tools (circular saws, hand drills, pneumatic nail guns, and caulking guns) were lighter, less noisy, and vibrated less than their predecessors.

Almost all of the advances in information processing occurred in the area of heavy machinery, which explains why most construction activities did not experience a change in information processing. Table 3 indicates that most of the changes in information processing occurred in machinery dominated divisions (e.g., sitework and concrete). For example, some heavy machinery now offer self-monitoring and self-diagnostic systems.

In using the technology index, it is important to consider whether the technology factors are independent of each other. If the factors are highly correlated, collinearity will exist, and collinearity will increase the standard error in the regression. Table 4 examines the correlation across the technology factors for each of the study's 200 activities using each factor's component score in the technology index.

The highest degree of correlation is between the technology factors energy and control followed by energy and ergonomics with pairwise correlation values of 0.49 and 0.48, respectively. As a rule of thumb, collinearity exists when one pairwise correlation among a set of variables exceeds 0.90 or when several of the

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Table 3. Mean Technology Index (TI) Score (Broken Down by Each Technologies' Factor Score) by Division, 1976–1998

Division	TI_{energy}	$TI_{control}$	$TI_{function}$	$TI_{ergonomics}$	$TI_{info.processing}$	TI_{total}
Masonry	0.36	0.09	0.15	0.24	0.02	0.86
Specialties	0.25	0.25	0.25	0.00	0.25	1.00
Electrical	0.50	0.11	0.32	0.39	0.07	1.39
Finishes	0.64	0.15	0.34	0.42	0.08	1.63
Moisture and thermal protection	0.75	0.25	0.34	0.59	0.03	1.97
Doors and windows	0.68	0.23	0.45	0.58	0.08	2.01
Mechanical	0.68	0.39	0.36	0.32	0.29	2.04
Concrete	0.77	0.53	0.34	0.38	0.30	2.32
Wood and plastic	0.94	0.61	0.04	0.84	0.10	2.53
Metals	0.99	0.72	0.84	0.34	0.05	2.93
Site work	0.79	0.49	0.43	0.53	0.70	2.94

Note: $TI_{control}$, TI_{energy}, $TI_{info.processing}$, $TI_{function}$, and $TI_{ergonomics}$ denote each technology factor's component score in the technology index (TI_{total}); $TI_{total} = TI_{control} + TI_{energy} + TI_{info.processing} + TI_{function} + TI_{ergonomics}$.

correlations exceed 0.70. Collinearity did not exist among the technology factors in the data (see Table 4).

Change in Equipment Technology on Construction Productivity

Analysis of variance (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 technology factors, the ANOVA analyses compared changes in labor productivity from 1976 to 1998 for (1) activities that experienced an improvement and (2) activities that did not experience an improvement (Fig. 4).

With the exception of ergonomics, the activities that experienced improvement in equipment technology experienced more improvements in labor productivity that those activities that did not, and this finding was statistically significant. Activities experiencing an improvement in energy, control, functional range, and information processing had at least twice as great of an improvement in labor productivity than activities experiencing no improvement in the technology factors. The greatest relative labor productivity improvements were due to advances in energy followed by advances in control, functional range, and information processing. A review of the F values indicates all technology factors, except ergonomics, were statistically significant. Ergonomics may not be significant because it is mainly intended to improve the health and safety of the construction worker, and these improvements affect productivity only indirectly.

Regression Analysis

A series of simple and multiple regressions were used to further examine the relationship between equipment technology and labor productivity.

Regression Analysis—The Base Analyses

The first regression modeled the relationship between changes in the capital-to-labor ratio [see Eq. (2)] and labor productivity [see Eq. (5)]. The results are presented in Fig. 5.

The regression line in Fig. 5 indicates that changes in labor productivity increased as changes in the capital-to-labor ratio also increased. The results are not surprising; one would expect an increased use of capital coupled with the declining use of labor to facilitate an increase in labor productivity.

It is interesting to note, however, that there were some activities that experienced a decrease in the capital-to-labor ratio and an increase in labor productivity (see Fig. 5). One explanation for this effect exists in the manufacturing technology improvements that allowed tools and machinery to be produced more efficiently and the increased use of overseas (and less expensive) labor to manufacture tools and machinery. Both factors can reduce production costs. The cost of corded electrical drills is one example. In 1976, the typical 1/3 HP corded reversible drill cost approximately $100 (in 1998 dollars). In 1998, a similar drill cost only $38 (Sears and Roebuck 1976, 1998).

Next, the relationship between changes in labor productivity and the technology index (TI) was examined. The regression line illustrated in Fig. 6 indicates that increases in the technology index and labor productivity were best fit with a quadratic formula for the technology index.

Next, regression models were constructed to estimate the effects of the technology index and capital-to-labor ratio on the percent change in labor productivity (see Table 5). The models in Table 5 report a significant correlation between the increase in equipment technology and increase in labor productivity. The relationship between capital-to-labor ratio and labor productivity was best fit with a linear regression (Eq. A) that explained 16% of the total variance in labor productivity. Although there was a slight increase in the R^2 when a quadratic term for capital-to-labor ratio was added (Eq. B), the t-value for the quadratic term

Table 4. Correlation Matrix for Technology Index Factors Using Components of the Technology Index (TI)

	TI_{energy}	$TI_{control}$	$TI_{function}$	$TI_{ergonomics}$	$TI_{info.processing}$
TI_{energy}	1.00	0.49**	0.42**	0.48**	0.18**
$TI_{control}$	0.49**	1.00	0.24**	−0.08	0.31**
$TI_{funct.\ range}$	0.42**	0.24**	1.00	0.01	0.26**
$TI_{ergonomics}$	0.48**	−0.08	0.01	1.00	0.00
$TI_{info.processing}$	0.18**	0.31**	0.26**	0.00	1.00

Note: ** Correlation is significant at the 0.01 level (2-tailed); correlations calculated using Pearson's r.

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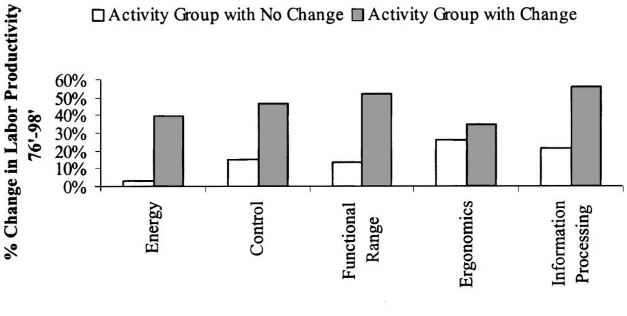

Fig. 4. Percent change in labor productivity for activities with a change in equipment technology and activities with no change in equipment technology, 1976–1998, $*p<0.05$

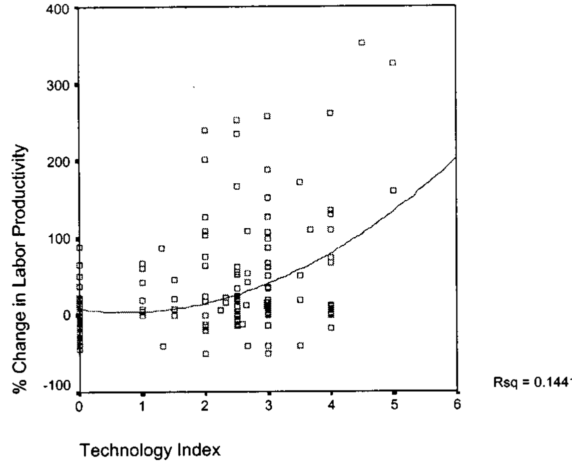

Fig. 6. Scatter plot with quadratic regression line for the percent change in labor productivity on the technology index, 1976–1998

(0.63) is not statistically significant. A quadratic term for the technology index was used in the final model (Eq. D), and this model explained 24% of the total variance in labor productivity.

Data Validation by Regression

The reliability and validity of the data used here can be examined by comparing results across the three estimation handbooks. Table 6 reports regression models estimating the effects of the capital-to-labor ratio and technology index on changes in labor productivity, and there is one model per data source.

All three data sources provide similar results (Table 6). Each model reveals that as both the capital-to-labor ratio and technology index increase, labor productivity also increases. However, there is a lack of statistical significance in the technology index in the Means (Eq. A) and Dodge (Eq. B) regressions. This is most likely a result of the small sample sizes in Eqs. A and B rather than a lack of relationship, because the technology index was statistically significant in the overall regression model (Table 5, Eq. D, $N=200$).

The size of the coefficients differs across the three data sources, which is partially explained by the distribution of different construction activities across divisions. The three data sources produce similar levels of statistical strength in the F and R^2 values. The F value of the Means regression (Eq. A) is larger than either of the F value for the Dodge (Eq. B) and Richardson (Eq. C) regression, because the F value is proportionate to the sample size. The adjusted R^2 values varied by only 5% points; the models explained the similar amount of the total variation in labor productivity.

Further Regression Models

Next, regression models were constructed to include a series of dummy (binary) variables for the five technology factors (e.g., energy, control, function, ergonomic, and information). Each variable was coded 1 if a tool or machinery in the activity experienced a technological change from 1976 to 1998 or 0 if otherwise. The variables were added to the regression analysis one variable at a time (Table 7, see Eqs. D–I). The most significant variables were retained for the final model (Eq. J).

The equipment technology factors energy, control, and function produced statistically significant effects above the 80% confidence level on labor productivity. These factors along with the changes in capital-to-labor ratio and technology index explained 24% of the total variation in labor productivity (Table 7, Eq. J). Activities with a positive change in level of control experienced a 15% increase in labor productivity compared to other activities that did not experience a change in control (controlling for energy and function—see Table 7, Eq. J). Meanwhile, positive changes in

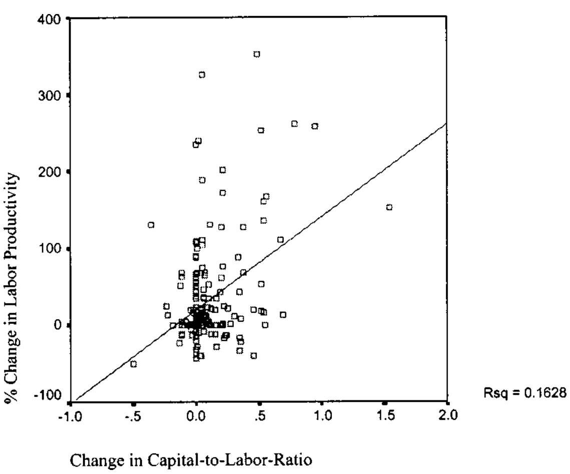

Fig. 5. Scatter plot with regression line for the percent change in labor productivity in the capital-to-labor ratio (K/L), 1976–1998

Table 5. Regression of the Capital-to-Labor Ratio (K/L) and Technology Index (TI) on the Percent Change in Labor Productivity from 1976 to 1998

Eq.	Constant	K/L	$(K/L)^2$	TI	TI^2	F	R^2
A	19.61	120.73				38.31	0.16
	(4.28)	(6.19)					
B	19.72	106.50	20.79			19.30	0.17
	(4.29)	(3.58)	(0.63)				
C	−4.74	103.48		12.10		27.52	0.22
	(−0.61)	(5.33)		(3.77)			
D	4.64	97.13		−8.53	5.59	20.72	0.24
	(0.53)	(5.01)		(−0.93)	(2.40)		

Note: Dependent variable: percent change in labor productivity; t values shown in parentheses; and $N=200$ activities; K/L=change in capital-to-labor ratio; and TI=technology index.

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Table 6. Regression Analyses for Labor Productivity Data Source

	Independent variable					
Means Data Source Regression $N=100$						
Equation	Constant	K/L	TI	TI^2	F	Adj. R^2
A	−4.89	147.27	−1.05	3.35	14.80	0.30
	(−0.45)	(4.94)	(−0.09)	(1.02)		
Dodge Data Source Regression $N=50$						
Equation	Constant	K/L	TI	TI^2	F	R^2
B	9.75	168.12	−11.32	7.48	7.92	0.30
	(0.45)	(3.49)	(−0.48)	(1.31)		
Richardson Data Source Regression $N=50$						
Equation	Constant	K/L	TI	TI^2	F	R^2
C	11.03	70.78	−8.79	3.81	6.22	0.25
	(0.89)	(3.08)	(−0.70)	(1.25)		

Note: Dependent variable: percent change in labor productivity; t values shown in parentheses; N as indicated by data source; K/L=change in capital-to-labor ratio; TI=technology index; adjusted R squared takes into account the number independent variables (k) and number of observations (n) included in a regression. Adjusted $R^2=R^2-(k-1)/(n*k)*(1-R^2)$. It is used here for consideration of the smaller sample sizes versus the number of independent variables in the three separate regressions.

energy increased labor productivity by 24% and changes in function increase it by 13%; the statistical significance was less for both factors [t-value of 1.33 for energy and 1.29 for function—see Table 7, Eq. J].

Additional regressions were performed with adjustments for real wage declines. Using historical wage data from the Bureau of Labor Statistics, a wage index was developed to adjust for real wage declines in the capital-to-labor ratio (Goodrum 2001) as shown in the following formula:

$$\Delta\text{adjusted-capital-to-labor ratio}$$

$$=(K_{98'}/\text{Ladj}_{98'})-(K_{76'}/\text{Ladj}_{76'}) \tag{6}$$

where $K_{98'}$=1998 unit capital costs; $K_{76'}$=1976 unit capital

Table 7. Regression of the Technology Index (TI), Capital-to-Labor Ratio (K/L), and Binary Variables on Percent Change in Labor Productivity

	Independent variable											
Eq.	Constant	K/L	TI	TI^2	Energy	Control	Function	Ergonomic	Information	F	R^2	Adj. R^2
A	19.61	120.73								38.31	0.16	0.16
	(4.28)	(6.19)										
B	7.79		−10.58	7.19						16.50	0.14	0.14
	(0.85)		(−1.10)	(2.94)								
C	4.64	97.13	−8.53	5.59						20.72	0.24	0.23
	(0.53)	(5.01)	(−0.93)	(2.40)								
D	2.64	96.24	−24.88	8.12	28.00					16.30	0.25	0.24
	(0.30)	(4.98)	(1.82)	(2.89)	(1.60)							
E	4.39	96.18	−13.99	6.23		16.21				16.42	0.25	0.24
	(0.51)	(4.98)	(−1.45)	(2.66)		(1.71)						
F	4.83	95.12	−10.97	5.57			11.45			15.87	0.25	0.23
	(0.56)	(4.89)	(−1.17)	(2.40)			(1.12)					
G	5.00	96.23	−5.43	5.13				−7.33		15.65	0.24	0.23
	(0.58)	(4.95)	(−0.54)	(2.13)				(−0.76)				
H	4.70	99.41	−8.67	5.83					−5.30	15.54	0.24	0.23
	(0.54)	(4.98)	(−0.95)	(2.45)					(−0.49)			
I	2.75	95.57	−26.90	8.26	23.41	13.94				13.53	0.26	0.24
	(0.32)	(4.96)	(−1.96)	(2.95)	(1.32)	(1.46)						
J	2.94	93.20	−30.13	8.29	23.56	14.96	13.11			11.59	0.27	0.24
	(0.34)	(4.82)	(−2.16)	(2.96)	(1.33)	(1.55)	(1.29)					

Note: Dependent variable: percent change in labor productivity; t values shown in parentheses; N=200 activities; K/L=change in capital-to-labor ratio; and TI=technology index.

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Table 8. Regression of the Technology Index (TI), Capital-to-Labor Ratio (K/L) (with Real Wage Adjustments) and Binary Variables on Percent Change in Labor Productivity

	Independent variable										
Eq.	Constant	K/Ladj	(K/Ladj)^2	TI	TI^2	Energy	Control	Function	F	R^2	Adj. R^2
J	3.51	120.90	112.65	−28.63	7.99	19.47	17.27	14.21	16.85	0.38	0.36
	(0.44)	(6.09)	(3.21)	(−2.23)	(3.12)	(1.19)	(1.94)	(1.52)			

Note: Dependent variable: percent change in labor productivity; t values shown in parentheses; $N=200$ activities; K/Ladj=change in capital-to-labor ratio with adjustment for real wage declines; TI=technology index; and wage decline adjustment per BLS historical construction wage data.

costs; $\text{Ladj}_{98'}$ =1998 unit labor costs adjusted for real wage declines; and $\text{Ladj}_{76'}$ =1976 unit labor costs adjusted for real wage declines. No changes were made to the capital costs. The model with the unadjusted capital-to-labor ratio (Table 7, Eq. J) explained 24% of the total variation in labor productivity. The adjusted capital-to-labor ratio (Table 8, Eq. J), on other hand, explained 36% of the total variation. Furthermore, the F and t values in the Table 8 Eq. J were higher than the Table 7 Eq. J. Improvements in energy, control, and function had the strongest effect on the percent change in labor productivity (Table 8); although the coefficient for energy decreased slightly from the Table 7 to 8 (Eq. J).

Particular technology factors proved statistically significant in ANOVA analyses but not in regression analyses, and this may be the result of the added controls for capital-to-labor ratio and technology index in the regression equations. Although significant in the ANOVA analyses, information processing was not statistically significant in the regressions, perhaps because less than 25% of the study's activities experienced an improvement in information processing. This finding may also indicate that improvements in information processing do little to improve labor productivity.

The labor productivity increase and construction real wage decline is worthy of further discussion. Labor productivity improvements have been boosted by equipment technology improvements. It is important to note, however, that technology's effect on productivity may be larger than these data indicate. The effect may be underestimated because of the declining skill level of the construction work force; technology may have facilitated the decline. As one example, changes in level of control (i.e., automation of the construction process) consistently demonstrated the strongest relationship with labor productivity.

While skills and technology appear to positively affect labor productivity, the declining skill level of the construction work force may become an obstacle to, but motivation for, the widespread implementation of future technological advances in the U.S. construction industry. Future technological advances in construction will need to consider the availability of skilled workers to use such equipment. At the same time, the declining skill level of construction workers may create the demand for more technological advances. Therefore, the construction industry should address the development and implementation of advanced technologies, and also consider the skill level of the construction work force.

Summary

It is clear from the preceding discussion that:

1. Most of the study's 200 activities experienced improvements in labor productivity from 1976 to 1998, confirming other research using activity level data and contradicting research using aggregated level data.
2. Technological advances explain some of the labor productivity increase from 1976 to 1998.
3. Substituting equipment technology for labor provides additional explanation of the increase.

Recommendations

Five principal recommendations are offered:

1. Additional research is needed on the use of new technology in construction in order to leverage future improvements in productivity. Specifically, equipment technology (e.g., energy, control, and functional range) has historically benefited labor productivity.
2. Additional research is needed to understand how other technologies (e.g., material technology, paradigm shifts, process changes, and information technologies) impact productivity.
3. The impact of construction technology on other construction performance parameters, such as safety, quality, and the environment, needs to be examined.
4. The development of a reliable productivity index for the U.S. construction industry would permit industry leaders and government officials to design policies and strategies to improve industry performance.
5. Despite the positive effect of technological improvements on activity level productivity from 1976 to 1998, aggregate level productivity measures from the U.S. Department of Commerce and U.S. Bureau of Labor Statistics have remained stagnant or have declined in the last few decades (Teicholtz 2001). The reasons for this apparent discrepancy need to be further investigated.

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