Partial Factor Productivity and Equipment Technology Change at Activity Level in U.S. Construction Industry

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Abstract: Despite a decrease in industry level measures in construction productivity, there has been a steady increase in construction productivity at the activity level. This research examines equipment technology as one factor that may explain that increase. The relationship between changes in equipment technology and partial factor productivity is examined for 200 activities over a 22 year time period. Specifically, the paper examines the relative impact of different types of equipment technology for five technology factors: energy, control, functional range, information processing, and ergonomics. Through ANOVA and regression analyses, it is found that activities that experienced a significant change in equipment technology also witnessed substantially greater long-term improvements in partial factor productivity than those that did not experience a change.

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Introduction

The United States construction industry (including new and renovation construction, design, equipment, and materials) accounts for more than 10% of the total gross domestic product (Bureau 2000). Despite its significant influence on the overall U.S. economy, the aggregate productivity performance of the construction industry is unmeasured for the most part. At issue in analyzing trends in construction productivity is how to deflate output to accurately represent changes in quality as a result of innovation and design improvements in construction (Pieper 1989). Due to a lack of suitable inflation indices to measure real construction output, the U.S. Bureau of Labor Statistics maintains productivity indices for all major industries except construction (L. Rosenblum, personal communication, October 31, 2000).

In an effort to improve productivity, many industries have spent considerable time and money studying how technology influences productivity. These studies have led to sizeable gains in productivity and profit margins. However, due to a lack of longitudinal productivity data in construction, there has been little effort to quantify the factors that impact productivity trends. This paper examines how changes in equipment technology have influenced partial factor productivity (defined below) changes in the U.S. construction industry. Furthermore, this paper avoids the difficulty of measuring real construction output at industry sector levels by examining changes at the activity level.

Definitions

Before proceeding further, the terms central to the research effort should be defined:

- Equipment technology: This paper analyzes the changes in equipment technology, specifically hand tools (e.g., nail guns, electric drills, and circular saws) and machinery (e.g., cranes, grout pumps, and bulldozers).
- Capital: In the context of economic theory, capital refers to all goods that are used to produce other goods and services, including factories, machinery, and equipment (Ammer et al. 1984). These goods are often referred to as either fixed capital (i.e., durable items such as buildings and machinery) or circulating capital (i.e., raw material stocks). This paper focuses on fixed capital (hereafter capital), including equipment costs for both tools and machinery, as listed in the study's data sources.
- Productivity: Undoubtedly, confusion regarding productivity can be caused by the myriad of different ways to define it. A common measurement of construction productivity is factor productivity (Thomas et al. 1990), which is defined as

$$\text{Factor Productivity} = \frac{\text{PhysicalOutput(Units)}}{\text{Labor(\$)} + \text{CirculatingCapital(\$)} + \text{FixedCapital(\$)}} \tag{1}$$

For this paper, Eq. (1) is modified by removing the circulating capital (or materials) component in order to accommodate this investigation's focus on equipment technology. This produces the following measure of partial factor productivity:

$$\text{Partial Factor Productivity} = \frac{\text{PhysicalOutput(Units)}}{\text{Labor(\$)} + \text{FixedCapital(\$)}} \tag{2}$$

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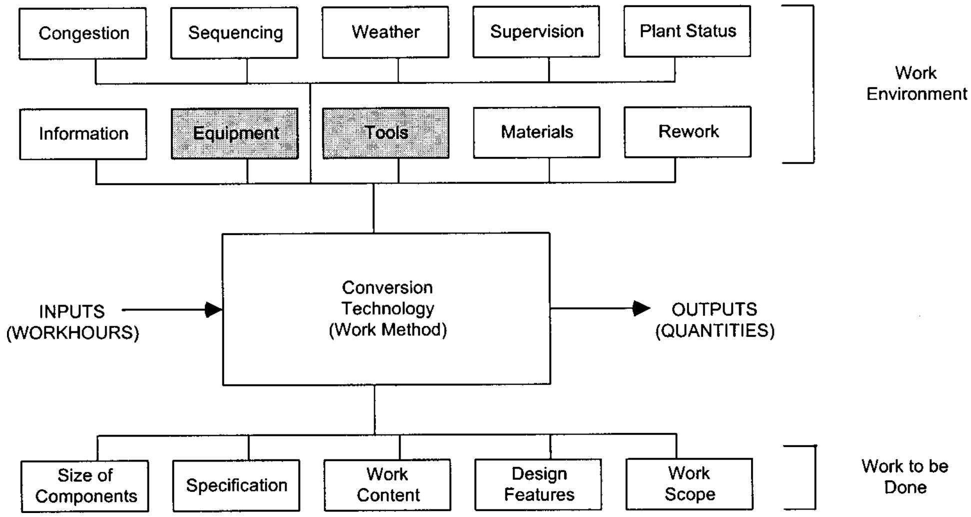

Fig. 1. Factor model of construction labor productivity [after Thomas et al. (1994)]

Background

Prior research has identified a number of different factors that impact labor productivity in construction. (Labor productivity is the ratio of physical output per unit of work hour requirements.) Although this paper focuses on partial factor productivity, similar factors influence both labor and partial factor productivity. Research conducted by the United Nations (1965) grouped these factors into two categories: work environment and work to be done. Thomas and Sakaracan (1994) identified the 15 most common factors that fall under these two categories (Fig. 1). This paper examines the impact of two of these fifteen factors: "Equipment" and "Tools" (hereafter, "equipment technology").

There may be factors other than those identified by Thomas and Sakaracan (1994) that affect partial factor productivity. For example, in labor productivity, work hour requirements per unit of output are less likely to be influenced by socioeconomic phenomena and workforce related issues than partial factor productivity's estimate of cost requirements per unit of output. However, labor and capital costs in partial factor productivity are heavily influenced by factors outside technology. One workforce issue that appears to heavily influence partial factor productivity is the decline in construction real wages since 1976.

Although real wages in general in the United States began to outpace inflation in the late 1990s, there has been a long-term decline in construction real wages since the 1970s (Allmon et al. 2000; Oppedahl 2000). Other industries, such as manufacturing, have also experienced declines in real wages; however, the declines have typically been greater in construction. This greater decline may be due to a combination of socioeconomic factors including an increase in migrant laborers in construction, fringe benefits, and construction safety, and a decrease in union membership and worker skills (Oppedahl 2000; Goodrum 2001).

Others have examined the impact of equipment technology on construction productivity in highway construction (Koch and Moavenzadeh 1979). Koch and Moavenzadeh considered the change in equipment and labor costs (controlling for inflation) per unit value of physical output, which mirrors this paper's measure of partial factor productivity, for various road construction activities from the 1920s to the 1970s. Increased usage and attributed advancements in equipment technology were noted as the primary causal agents. Koch and Moavenzedah found that many activities experienced increases in capital costs with relative declines in labor costs, which reflected an increased use of technology. One other significant finding was an apparent decline in the rate of productivity improvements over time. Most of the improvements occurred from the 1920s to the 1950s, when innovations in machine power were introduced.

Economists have examined the relative impact of technology on various measures of productivity in general. Technology tends to have a greater impact on labor productivity than factor productivity (Salter 1966; Rossow 1977). [The studies referred to as Rossow (1977) and Koch and Moavenzadeh (1979) are part of the same research effort. Janet A. Koch was formerly Janet A. K. Rossow.] Economists typically describe this as the labor-saving bias effect in technical change. For example, a worker with the most powerful hammer drill may have greater labor productivity than a worker with a less powerful and less expensive hammer drill. However, partial factor productivity may decline if the increased cost of the more powerful hammer drill outweighs the labor savings and output increases. For technology adoption more generally, factor productivity improvements will depend on output increases, capital costs, and labor savings.

Methodology

Data Sources

The data for this analysis was collected on 200 activities from three sources: *Means Building Construction Cost Data*, *Richardson's Process Plant Construction Estimating Standards*, and *Dodge Unit Cost Books*. These manuals provide unit labor costs, unit equipment costs, and physical output data on various construction activities for the purpose of project estimating and budgeting. While the manuals are a valuable source of time-series data on productivity, there are some weaknesses in the data. The contractors who provide the figures for the manuals know that they are not required to construct a project using their estimations; this leads contractors to offer inflated estimates of construction costs (Pieper 1989). Despite these limitations, there is precedence for using estimation manuals as a source for expected levels of productivity (Thomas and Yiakoumis 1987), and unlike other sources, estimation manuals provide data going back to 1976.

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Data was manually collected from Means, Richardson, and Dodge for 1976 and 1998. (Prior to 1976, estimation manuals did not record output data, which is why this time frame is used in this paper.) Three criteria were used to select activities for inclusion in the study. The main criteria was that the activity appeared in both the 1976 and 1998 estimation manuals. (A number of activities included in the 1976 manuals were phased out of 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 manuals due to new methodology and materials. The various reasons why activities were not included in both time periods provide a random factor affecting which activities listed in the manuals were included in the study.) The second criteria was that the activities represented a wide range of degrees of technical change. Finally, the included activities represent a wide range of types of activities from different divisions of the Construction Specification Institute (CSI) Masterformat. Two hundred activities were used in the analyses, with 100 from Means, 50 from Richardson, and 50 from Dodge, and there is an overlap in activity types across the three manuals.

Measure of Partial Factor Productivity

One of the challenges in analyzing productivity statistically is that productivity has different units of measurement for each construction activity. For example, a concrete placement activity may have a partial factor productivity measurement in cubic yards of concrete placed per unit costs, while structural steel placement may be measured by linear feet of steel placed per unit costs. Using relative instead of absolute values is a way to solve this issue. Therefore, the percentage change of partial factor productivity for each activity between 1976 and 1998 is used.

Costs Adjustment

In order to control for inflation, the Census Construction Cost Index is used to normalize both labor and equipment costs to 1990 levels. A description of the Census Construction Cost Index can be found at the Department of Commerce website (http://www.census.gov/prod/3/98pubs/c30-9805.pdf).

In addition to being influenced by inflation, labor costs, as previously described, have been notably influenced by declining construction real wages. Whether the declines are a reflection of a change in the skill level of the construction workforce is currently unknown. Therefore, the question arises whether labor costs should be adjusted for the declines in real wages. The argument for adjustment rests on the assumption that real wage declines in general are a result of economic phenomena. This argument supports the use of an adjustment for construction labor costs, because the declines reflect changes in labor market conditions instead of changes in the value of the workforce. In this sense, real wage adjustments serve to help normalize the wage data in order to represent real labor quantities expended in the construction activities. The argument against adjusting construction real wages assumes a widespread gross decrease in the skill level of construction workers as the main cause of real wage declines. In this sense, technology may be simplifying the work process (and increasing productivity) by accommodating the decline in worker skill levels. In reality, real wage declines are probably due to a combination of these and perhaps other factors. To consider effects of real wage declines with and without adjustment, a real wage index was developed using historical wage data from the Bureau of Labor Statistics; the index adjusts wages while controlling for inflation (Goodrum 2001).

Technology Measures

As indicated in the background discussion, previous research in construction and economics has found the relative changes in capital to labor costs to be an indication of the increased use of technology (Salter 1966; Koch and Moavenzedah 1979). In addition to five other factors of technological change, this paper reports the change in capital to labor costs as one measure of equipment technology change using the following formula:

$$\Delta\text{Capital-to-Labor-Ratio} = (K_{98'}/L_{98'}) - (K_{76'}/L_{76'}) \qquad (3)$$

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.

To examine how the different mechanisms of equipment technology change have influenced partial factor productivity in construction, the following five factors were identified to characterize changes in technology;

1. Level of control: Level of control concerns advancements in machinery and hand tools that transfer control from the human to the machine.
2. Amplification of human energy: Amplification of human energy is defined as technology designed to make an activity physically easier to perform. In its simplest form, it is the shift in the energy to do work from human to the machine.
3. Information processing: Over time, construction equipment has been designed to provide greater and more accurate information regarding internal and external processes.
4. Functional range: Changes in the equipments' functional range are those changes that expand a machine or tool's capabilities.
5. Ergonomics: Ergonomics is generally defined as technology that alleviates physical stresses imposed by the work environment on the human operator.

Technology Index

One of the key differences between this research and previous research on technology and productivity is the development of a technology index to measure the progress of equipment technology over time. Rather than solely relying on the use of theoretical economic measures to determine technology growth which ignore the measures' underlying mechanics of cause and effect, this paper attempts to measure actual technology characteristics. These characteristics provide specific quantitative measures of equipment technology changes for each construction activity. The writers identified and examined 43 types of hand tools and 31 types of machinery for 200 construction activities. Obviously, many hand tools and machinery were used in several 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. Although the paper's microlevel analysis helps resolve the issues of accurately measuring construction productivity, the paper's microlevel analysis ignores systematic improvements due to completely new methods such as trenchless technologies and new tools like computers and data networks.

The technology index measures equipment technology changes in the aggregate. The scoring of the technology factors shown in Table 1 make up the technology index (Goodrum 2001). This information was used in the statistical analyses.

For each activity in the study, the level of equipment technology change from 1976 to 1998 for all of the tools and machinery

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Table 1. Technology Index Scoring System

Factor	Defined level	Level ID	Score
Level of control	Manual hand tools	C1	0
	Manually controlled devices	C2	1
	Assisted controlled devices	C3	2
	Telecontrolled devices	C4	3
	Preprogrammed devices	C5	4
Amplification of human 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 driving energy	E4	3
	Equipment supplies all 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	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

used in that activity were identified. The change in equipment technology from 1976 to 1998 provides the basis for the score. For example, if an item of machinery was coded I2 for Level of Information Processing in 1976 and I3 for Level of Information Processing in 1998, the equipment technology change score due to Information Processing was 1 (I3−I2=2−1=1). For activities that involved a number of different tools and machines, changes for every tool and machine were totaled to obtain an equipment technology change summary score. The total equipment technology change score was then divided by the number of tools used to yield the technology index in the following formula:

$$\text{TechnologyIndex}=\frac{\Sigma_1^N(\Delta E+\Delta C+\Delta F+\Delta R+\Delta I)}{N} \qquad (4)$$

where: ΔE=change in energy; ΔC=change in control; ΔF=change in functional range; ΔR=change in ergonomics; ΔI=change in information processing; and N=number of tools and machinery in the activity.

Measured Change in Construction Partial Factor Productivity at Activity Level

Using physical output and cost data from the estimation manuals, the overall percent change in partial factor productivity from 1976 to 1998 for each activity was calculated. For the sampled activities, the average increase in partial factor productivity without adjustment for real wage declines was 54.42%, with a 95% confidence interval of ±12.19% and an annual compound rate of improvement of 1.99%. The average increase in partial factor productivity with adjustments for real wage declines was 22.69%, with a 95% confidence interval of ±9.55% and an annual compound rate of improvement of 0.93%.

Although these results indicate that partial factor productivity improved overall for the study's 200 activities from 1976 to 1998, there were some exceptions. Activities were grouped by division of the CSI Masterformat. The mean percent change in partial factor productivity from 1976 to 1998 was calculated for each division. Fig. 2 illustrates the changes in partial factor productivity (including the real wage adjustment) for each division of the CSI Masterformat.

On average, sitework activities experienced the greatest partial factor productivity improvement, while wood and plastic and specialty activities experienced little change or a decline. Further research is needed to determine the reasons behind the various sector changes.

Technology Change

Fig. 3 shows the number of activities that experienced a change in equipment technology in at least one tool or item of machinery

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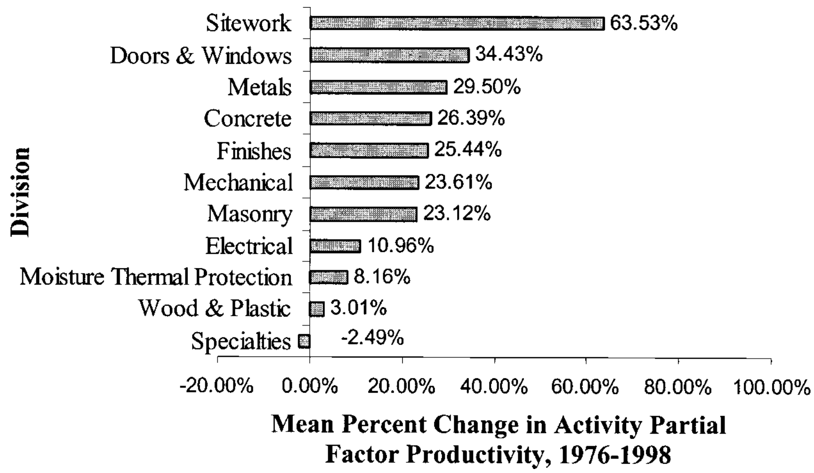

Fig. 2. Mean percent change for activity partial factor productivity by division, 1976–1998

for each of the technology factors. The degree of change is revealed in Fig. 4, where the mean technology index score is broken down by the technology factor score for each division of activities.

As shown in Fig. 3, more than 75% of the activities experienced an increase in energy output. Fig. 4 indicates that the metals, wood and plastic, and sitework divisions experienced the greatest amount of change in tool and machinery energy output. One example of change in energy output in the metals division involves welding machines, which offer increased wattage output. The powder actuated systems in the metals divisions used in metal decking offer greater depth penetration for installed studs. In addition, by 1998, cranes offered more lifting capacity than available in 1976. In the wood and plastic division, circular saws operated at higher RPMs, and the pneumatic nail gun required less human energy than a hand-held hammer. Most site work machinery increased in horsepower output including front-end loaders, dump trucks, backhoes, bulldozers, graders, asphalt pavers, and scrapers.

As seen in Fig. 3, almost half of construction activities experienced a change in the amount of human control needed. Welding machines in the metals division, for instance, are now equipped with remote controlled amperage adjusters and powder actuated systems with semiautomatic loading capability. The pneumatic nail gun has replaced the hand-held hammer in the woods and plastic division and 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 (Fig. 3). Through advancements in hydraulic controls and microprocessors, sitework machinery now have greater precision and a longer reach for booms and buckets. Excavators and backhoes are capable of digging deeper.

Fig. 3 shows that more than half of the construction activities experienced some change in ergonomics. For example, by 1998 many hand tools in 1998, such as circular saws, hand drills, pneumatic nail guns, and caulking guns, were lighter and operated with less noise and vibration than their predecessors.

Almost all of the advances in information processing occurred in heavy machinery. This finding explains why most construction activities did not experience such an improvement in equipment technology. This trend is further evidenced in Fig. 4, which shows

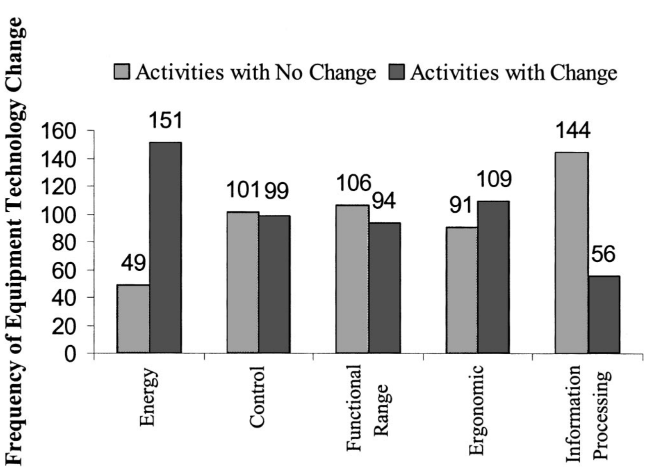

Fig. 3. Changes in equipment technology by technology factor, 1976–1998

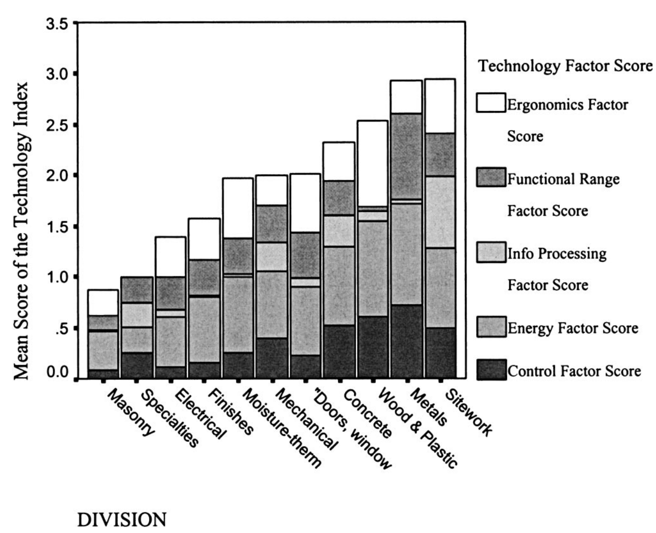

Fig. 4. Technology index score and technology factor score by activity division

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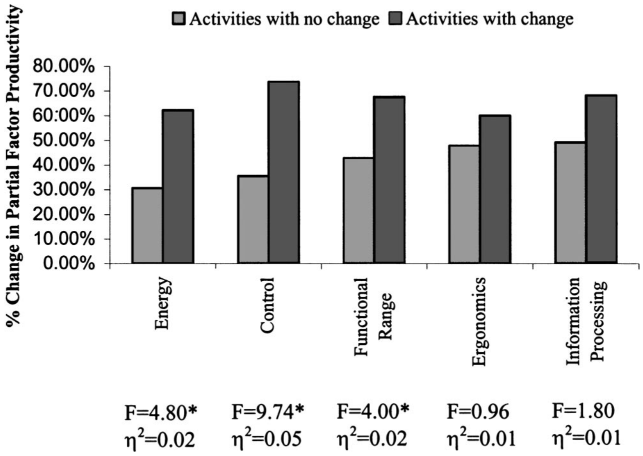


Fig. 5. Comparison of percent change in partial factor productivity improvement for activities that experienced change in equipment technology and activities with no change, $*p<0.05$

most of the changes in information processing are focused in machinery dominated divisions, such as sitework and concrete. For example, machinery now also offers self-monitoring and self-diagnostic systems.

Relation between Equipment Technology and Partial Factor Productivity Change

ANOVA Analysis

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 variable (η^2). The ANOVA analyses compared the partial factor productivity changes from 1976 to 1998 for: (1) activities that experienced a change according to the technology factor; and (2) activities that had not. Fig. 5 shows the ANOVA results controlling for inflation without an adjustment for real wage declines.

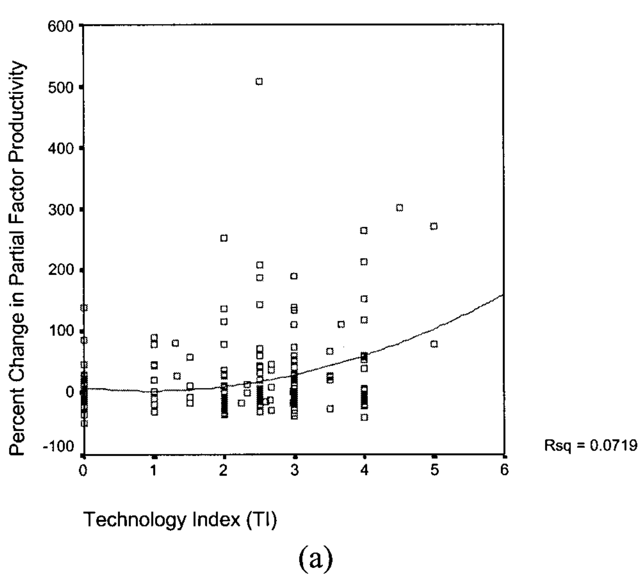
With the exception of ergonomics and information processing, the activities that experienced a change in equipment technology experienced more statistically significant improvements in partial factor productivity than those activities that did not. Activities experiencing an equipment change in energy, control, and functional range increased partial factor productivity by at least 50% more as compared to activities without change. The greatest relative partial factor productivity improvements were due to reductions in human control followed by advances in energy and functional range.

A second ANOVA test included controls for inflation as well as adjustments for real wage declines. The results were similar. The only exception was that information processing, control, energy, and functional range offered statistically greater improvements than revealed in the tests without controls for real wage declines. In addition, the real wage adjusted models had greater statistical strength overall as measured by the F-values and η^2 (Goodrum 2001).

Regression Analyses

A series of simple and multiple regressions were used to further examine the relationship between equipment technology and partial factor productivity. The first series of regressions modeled the relationship between both changes in the capital-to-labor ratio [see Eq. (3)], the technology index [see Eq. (4)], and partial factor productivity. These regressions include the real wage decline adjustment, and they are shown in Fig. 6.

Fig. 6 shows the marginal relationships between: (1) technology index and the percentage change in partial factor productivity; and (2) the change in the capital to labor ratio and the percent change in partial factor productivity. Fig. 6(a) indicates that only 7% of the variation in partial factor productivity is explained by equipment technology changes as measured by the technology index. Fig. 6(b) shows that 10% of the variation in partial factor



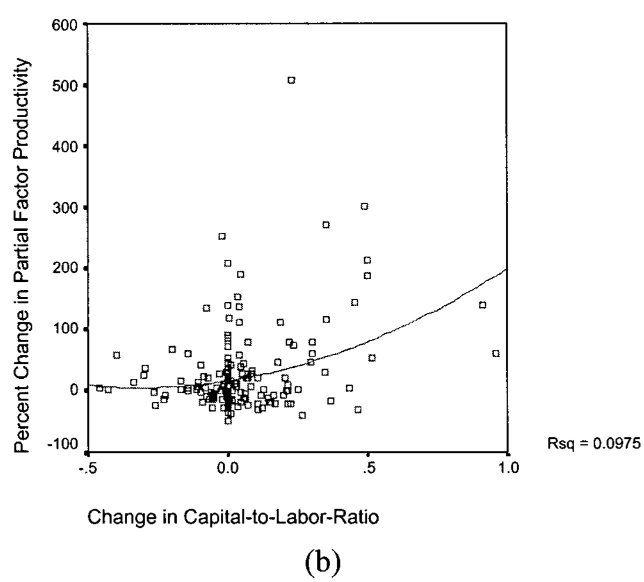


Fig. 6. Scatterplot with quadratic regression line for (a) technology index and (b) change in capital-to-labor ratio versus percent change in partial factor productivity, 1976–1998

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Table 2. Regression of Technology Index, Capital-to-Labor Ratio, and Dummy Variables on Percent Change in Partial Factor Productivity with Real Wage Decline Adjustment

Independent Variable													
Equation	Constant	K/L	$(K/L)^2$	TI	TI^2	Energy	Control	Function	Ergonomic	Information	F	R^2	Adjusted R^2
A	15.97	70.62	112.18								10.59	0.10	0.09
	(3.25)	(2.86)	(2.60)										
B	8.58			−11.65	6.13						7.59	0.07	0.06
	(0.86)			(−1.10)	(2.30)								
C	6.80	65.01	89.91	−10.51	5.18						8.05	0.14	0.13
	(0.70)	(2.68)	(2.10)	(−1.03)	(2.00)								
D	4.87	63.43	89.90	−26.24	7.61	26.90					6.84	0.15	0.13
	(0.50)	(2.62)	(2.10)	(−1.71)	(2.43)	(1.37)							
E	6.36	66.76	86.63	−19.23	6.18		26.08				7.83	0.17	0.15
	(0.67)	(2.79)	(2.04)	(−1.80)	(2.39)		(2.47)						
F	6.89	64.46	90.06	−11.48	5.16			4.55			6.44	0.14	0.12
	(0.71)	(2.65)	(2.09)	(−1.09)	(1.99)			(0.40)					
G	6.59	65.29	90.99	−12.31	5.45				4.24		6.44	0.14	0.12
	(0.68)	(2.69)	(2.11)	(−1.10)	(2.03)				(0.39)				
H	6.85	65.02	91.74	−10.62	5.32					−2.84	6.42	0.14	0.12
	(0.71)	(2.68)	(2.10)	(−1.04)	(2.00)					(−0.24)			
I	5.04	65.53	86.85	−29.62	7.81	18.83	24.23				6.68	0.17	0.15
	(0.52)	(2.73)	(2.05)	(−1.94)	(2.52)	(0.95)	(2.26)						

Note: Dependent variable: percent change in partial factor productivity; t-values shown in parenthesis; $N=200$ activities; K/L = change in capital-to-labor ratio; TI = technology index; adjusted R^2 takes into account number of independent variables (k) and number of observations (n) included in regression. Adjusted $R^2=R^2-(k-1)/(n*k)*(1-R^2)$.

productivity is explained by the increased use of equipment technology as measured by the change in the capital-to-labor ratio.

Alternatively, when real wage declines were left unadjusted, the effect of the technology index and the capital-to-labor ratio declined. Without the real wage decline adjustment, the technology index explained 6% of the total variation in partial factor productivity, and the capital-to-labor ratio explained virtually none of the variation.

It is interesting to note, however, that there were activities in Fig. 6(b) that experienced a decrease in the capital-to-labor-ratio and an increase in labor productivity. One possible 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 labor to manufacture tools and machinery. Both factors can drop production costs. A simple example is the cost of corded electrical drills. In 1976, the typical 1/3 HP corded reversible drill cost approximately $100 (in 1998 dollars). In 1998, a similar drill cost only $38 (according to Sears and Roebuck Catalog Listings from 1976 and 1998).

Next, regression models were constructed to combine the technology index and the capital-to-labor ratio along with a series of dummy (binary) variables to estimate the influence of five technology factors (energy, control, functional range, information processing, and ergonomics). Table 2 shows a series of regression results with inflationary adjustments and real wage decline adjustments. Each dummy variable was coded 1, if any tool or machinery in the activity experienced a technological change from 1976 to 1998 according to the referenced factor, or 0, if otherwise. The dummy variables were added to the regression analysis one variable at a time (see equations *D–H*). The most significant variables were retained for the final model (equation I).

The only technology factors to produce statistically significant effects above the 80% confidence level on partial factor productivity were energy and control (Table 2). Controlling for changes in the level of control, activities with a change in energy experienced an 18.83% additional increase in partial factor productivity in comparison to activities with no change in energy (Table 2, equation I). Changes in the level of control, however, had greater statistical ($t=2.24$) and substantive significance than activities with change in energy. Activities with a change in the level of control experienced a 24.23% additional increase in partial factor productivity (Table 2, equation I).

The equipment technology measures reported in Table 2 explain approximately 15% of the total variation in partial factor productivity (equation I). These regressions were not designed to model every possible predictor of partial factor productivity. Instead, these regressions estimate the influence of equipment technology on partial factor productivity. Given the other factors that influence partial factor productivity, referred to earlier, the amount of variation explained by these models indicates that equipment technology significantly influences partial factor productivity changes.

Regression analyses without real wage decline adjustment were statistically weaker. Without the adjustment, the capital-to-labor ratio explained 50% less of the total variance in partial factor productivity (Table 3). While the technology index remained statistically significant, the capital-to-labor ratio did not.

Functional range and information processing were not statistically significant in the regression analyses as they were in the ANOVA analysis. This may be due to the inclusion of controls for the technology index and the capital-to-labor ratio in the regression models. It may also indicate that these two variables do little to increase partial factor productivity.

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

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Table 3. Regression of Technology Index (TI), Change in Capital-to-Labor Ratio (K/L) and Dummy Variables on Percent Change in Partial Factor Productivity without Real Wage Decline Adjustment

Independent Variable										
Equation	Constant	K/L	$(K/L)^2$	TI	TI^2	Energy	Control	F	R^2	Adjusted R^2
I	33.94	27.53	8.83	−36.53	9.62	26.89	28.53	3.25	0.10	0.06
	(2.63)	(0.65)	(0.19)	(−1.80)	(2.32)	(1.02)	(2.00)			

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

ance costs by activity. Reduced insurance costs may be the mechanism through which ergonomics affects partial factor productivity. Future research should consider these and other reasons.

Data Validation

The reliability and validity of the data used here can be examined by comparing the results across the three estimation manuals. Table 4 reports three regression models of capital-to-labor ratio and technology index on partial factor productivity changes, one for each data source. These models were adjusted for real wage declines.

This evidence indicates that all three data sources provided consistent results (Table 4, equations A, B, and C). Each regression model reveals that, as the capital-to-labor ratio and technology index increase, partial factor productivity also increases. However, there is a lack of statistical significance in the technology index in the Means (equation A) and Dodge (equation B) manuals. This is most likely attributed to the small sample sizes in equations A and B rather than a lack of relationship, because the technology index was statistically significant in the overall regression model (Table 2, $N=200$).

The magnitude of the regression coefficients do differ across the three data sources, which can be partly explained by the different distribution of construction activities across different divisions. The three data sources produce similar levels of statistical strength, as seen in the F and R^2 values. (The F-value for the Means' regression is almost exactly twice as large as the regression models for Richardson and Dodge. This is expected, since the F-value is linearly dependent on the sample size, and there were exactly twice as many activities in the Means' data than in each of the Richardson and Dodge manuals' data.) There is particular similarity in the R^2 values across the three regression models, indicating that the models explain a similar amount of the total variation in partial factor productivity. In summary, the relationship between equipment technology improvements and partial factor productivity at the activity level is seen across all three multiple data sources.

As previously discussed, Koch and Moavenzadeh (1979) concluded that equipment technology advancements explained the decrease in equipment and labor unit costs from the 1920s to the 1970s. One activity examined in that research effort was excavation/hauling at various distances. To elaborate on that research effort here, Koch and Moavenzadeh's excavation/hauling unit cost data from the 1930s, 1950s, and 1970s was extended to include 1998. This extension allows us to see if these trends continue to occur (Rossow 1977; Goodrum 2001).

As seen in Fig. 7, unit costs for excavation and hauling continued to decline into 1998. However, the amount of decline from the 1970s to 1998 was not as marked as was seen from the 1920s to 1950s, when significant innovations in equipment technology, such as diesel powered machinery replacing steam and animal powered equipment, were introduced (Rossow 1977). From the 1970s to the 1990s, the type of equipment used did not change. This activity still primarily used bulldozers and scrapers. As was seen in the 1950s to 1970s transition, this equipment simply became more powerful and larger in capacity. Unlike the 1950s to 1970s transition, however, bulldozers and scrapers from the 1970s to the 1990s became more intelligent and ergonomic, and machine control advanced. These types of equipment technology improvements are representative of much of the improvements in other heavy machinery (Goodrum 2001). Although the improved unit costs were only incremental from the 1970s to the 1990s (Fig. 7), the advent of resolved motion control based on positioning systems and laser leveling may result in significant future step changes.

There is a labor-saving bias of technology change in construction. Other research (Goodrum 2001) found stronger relationships between equipment technology and labor productivity than found between equipment technology and partial factor productivity, as

Table 4. Regression Analyses for Percent Change in Partial Factor Productivity Presented by Data Source

Independent Variable								
Equation	Constant	K/L	$(K/L)^2$	TI	TI^2	F	R^2	Adjusted R^2
(a) Means data source regression: $N=100$								
A	−11.04	101.30	134.09	11.33	−2.20	4.89	0.17	0.14
	(−1.28)	(3.73)	(2.57)	(1.19)	(−0.86)			
(b) Dodge data source regression: $N=50$								
B	36.98	−36.43	193.85	−0.06	3.81	2.86	0.20	0.13
	(1.57)	(−0.59)	(1.92)	(−0.02)	(0.60)			
(c) Richardson data source regresssion: $N=50$								
C	10.79	11.67	56.75	−13.74	3.75	2.91	0.20	0.14
	(1.44)	(0.65)	(1.89)	(−1.82)	(2.06)			

Note: Dependent variable: percent change in partial factor productivity; t-values shown in parenthesis; N as indicated by data source; K/L=change in capital-to-labor ratio; TI=technology index.

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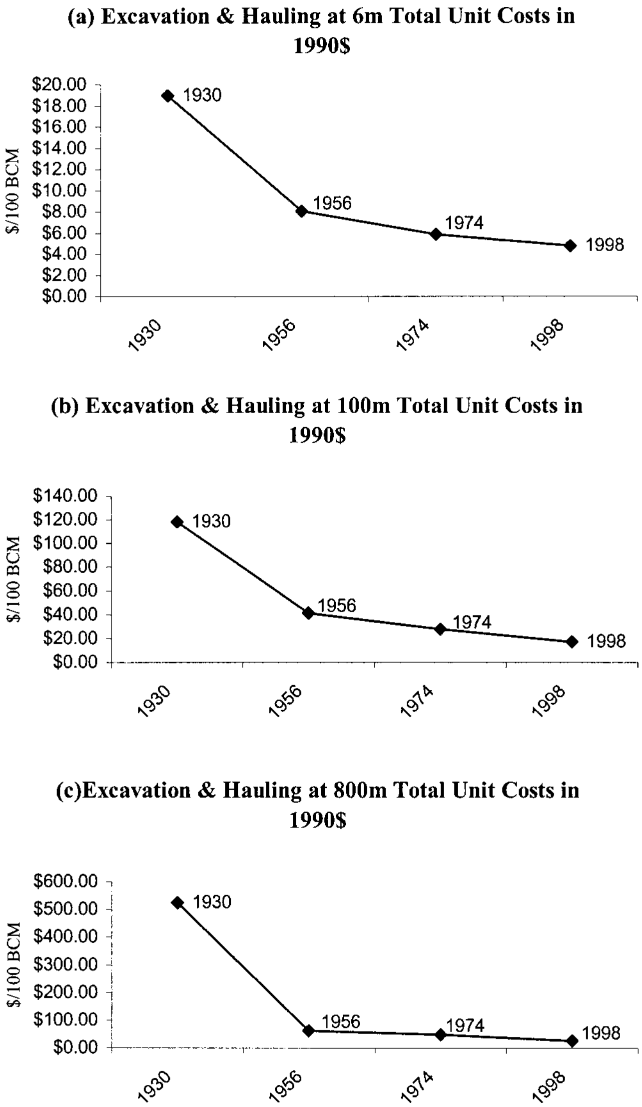

Fig. 7. Total unit costs in 1990 dollars of excavation and hauling at various distances from 1930 to 1998: (a) 6 m; (b) 100 m; (c) 800 m

presented here. Furthermore, equipment technology changes explained twice as much of the variation in labor productivity than it explained in partial factor productivity.

Although the models in this paper performed statistically better when labor costs were adjusted for real wage declines, there are other economic factors that may impact the value measure of construction inputs. This should be investigated in future research. One example is the combination of factors in the manufacture of construction equipment that have decreased the real cost of some tools and machines.

As previously discussed, the real wage declines may partially reflect a shift from a skilled to a less skilled construction workforce. Equipment technology improvements may be contributing to the decline in workforce skills, because there is a consistently strong relationship between improvements in partial factor productivity and changes in equipment level of control, which involve changes in automation resulting in simplification of the construction process. There was a number of equipment technologies not included in the study because of a lack of their diffusion throughout the construction industry. The construction industry should consider the skill level of the existing workforce in the development of new technologies and how it can affect the implementation and diffusion of innovative products and processes.

Conclusions

The findings reported here indicate that

1. Most of the 200 activities considered here experienced improvements in partial factor productivity from 1976 to 1998.
2. Technological advances in construction equipment technology, as measured by the technology index, explain some of the increase in partial factor productivity.
3. Substituting equipment for labor, as measured by the capital-to-labor ratio, provides additional explanation of the increase in partial factor productivity.
4. Equipment technology changes lead to greater improvements in labor productivity than in partial factor productivity.

Recommendations

Six principle recommendations are offered:

1. Additional research and development is needed on the development of new construction equipment technologies in order to leverage future improvements in productivity. Specifically, developments in equipment technology including improvements in energy and control have historically boosted partial factor productivity.
2. Additional research is needed to understand how other technologies impact productivity. Future research should focus on the impact that material technology, paradigm shifts, process changes, and information technology have on construction productivity.
3. The development of truly reliable productivity indices through development of inflation indices sensitive to changes in quality of the final product for sectors of the U.S. construction industry would be a means of improving the industry.
4. Changes in construction equipment manufacturing and how these changes my impact equipment costs and factor productivity measures need to be better understood.
5. The impact of changes in the indirect cost of construction, such as insurance costs and benefits, on partial factor productivity need to be better understood.
6. Despite equipment technological improvements resulting in greater individual activity productivity, current aggregate productivity measures have either remained stagnant or have declined since the 1970s (Teicholtz 2000). Reasons for this apparent contradiction need to be further explored.

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