



Construction Industry Institute®

Leveraging Technology to Improve Construction Productivity

Volume I: Historical Data Analysis

Carl T. Haas, Ph.D.

Hassan Nassir

Saiedeh Razavi

Duncan Young

University of Waterloo

Paul M. Goodrum, Ph.D.

Jordan Yeizer

Dong Zhai

Daniel Homm

University of Kentucky

Carlos H. Caldas, Ph.D.

David Grau

Jie Gong

The University of Texas at Austin

Construction Industry Institute

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The University of Texas at Austin

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Leveraging Technology to Improve Construction Productivity

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FOREWORD

Successful use of technology to improve construction productivity involves more than the technical characteristics of the technology. Many factors simultaneously influence construction productivity, including work force characteristics, management processes, and technological innovations. To control for these and other external factors, Research Team 240 used a three-pronged approach to develop recommendations, guidelines, and procedures to effectively leverage technology to improve construction projects. To give a full account of each part of this approach, this report is organized into three volumes. Research Report (RR) 240-11 (Volume I) presents the team's data analysis on the ways historical changes in construction equipment, materials, and information technologies have influenced improvements in construction productivity. RR 240-12 (Volume II) details a comprehensive field test of materials tracking and locating technologies that the team conducted to measure how such technologies can improve productivity on typical industrial projects. Finally, RR 240-13 (Volume III) describes a four-stage predictive model that estimates a technology's potential to have a positive impact on construction productivity. In summary, the three volumes of this report illuminate the multifaceted relationship between technology and construction productivity. Through significant statistical analyses, field trials, and tool development, the three parts of this research project have demonstrated how technology can be used to leverage productivity.

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Chapter 1 : TECHNOLOGY IMPACTS ON PRODUCTIVITY

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 1960's (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). Previous research has also identified factors that impact labor productivity at the project level (Maloney 1983; Allen 1985; Thomas et al 1990; and Thomas and Sakaracan 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. 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 micro level were related to changes in equipment technology (Koch and Moavenzadeh 1979, Goodrum and Haas 2002b and Goodrum and Haas 2004).

A comparative quantitative understanding of material technology and construction productivity remains unclear. Material improvements were examined by examining how changes in material technology have influenced labor and partial factor productivity in the U.S. construction industry between 1977 and 2004.

There is reason to believe that IT may eventually have a significant net positive impact on construction projects, yet little evidence exists. One vision predicts that future construction sites will become more “intelligent and integrated” as materials, components, tools, equipment, and people become elements of a fully sensed and monitored environment (Wood and Alvarez, 2005). Furthermore, it is envisioned that the automation of construction processes will augment manual labor for hazardous and labor-intensive tasks such as welding and high-steel work. In such an environment, whether actively or passively, the construction environment will be required to process and share larger volumes of data across multiple systems. What remains uncertain of this and other visions of future jobsites is whether there has been or will be a net project benefit or even an improvement in construction productivity as a result of the increased automation and integration of construction systems. Labor productivity improvement alone may motivate adoption of IT in construction.

Chapter 2 : INTRODUCTION EQUIPMENT TECHNOLOGY

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 section 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 section examines labor productivity changes in the U.S. for 200 different construction activities from 1976 to 1998. Second, the section 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 was collected from three commercially available estimation handbooks.

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

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 ("Effect" 1965) and work by Thomas and Sakaracan (1994), a general model of the factors affecting labor productivity is shown in Figure 2.1.

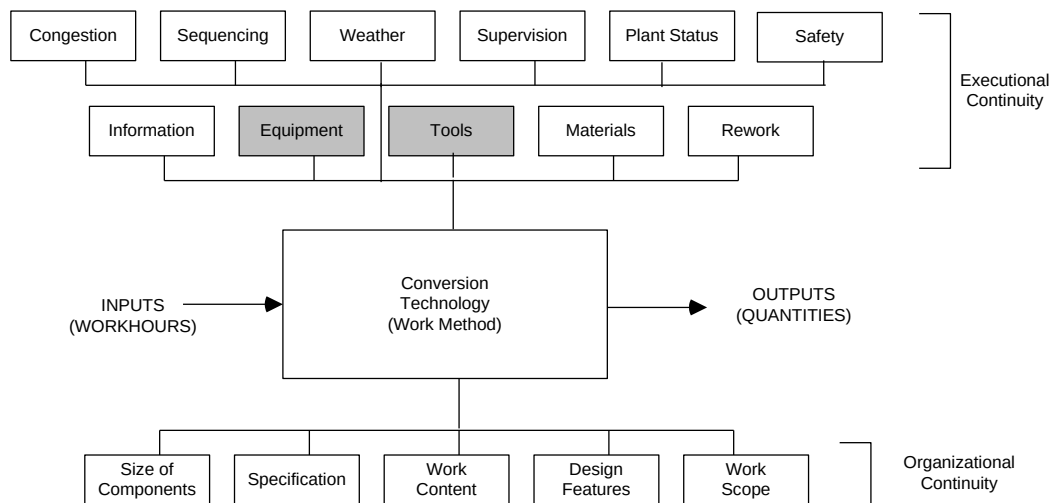


Figure 2.1 Factor Model of Construction Labor Productivity (Thomas and Sakaracan 1994)

This section focuses on two of the fifteen factors identified in Figure 2.1, "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 Moavenezdah 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 as either fixed capital, such as buildings or machinery, or circulating capital, such as raw material stocks. This section 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:

$$\Delta Capital - to - Labor - Ratio = \left(\frac{K_{98'}}{L_{98'}} \right) - \left(\frac{K_{76'}}{L_{76'}} \right) \quad (2.1)$$

Where: $K_{98'}$ = 1998 Unit capital costs

$K_{76'}$ = 1976 Unit capital costs

$L_{98'}$ = 1998 Unit labor costs

$L_{76'}$ = 1976 Unit labor costs

The capital-to-labor-ratio is used with the assumption that technological advances require less labor (Salter 1966; Koch and Moavenezdah 1979). For example, consider a factory that uses 2 units of machinery and 10 workers and produces 10 units of output. A new version of the machinery uses 3 units of machinery but only 5 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 and 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:

$$\% \text{ Change in Labor} = \left(\frac{\text{Labor Productivity, '98} - \text{Labor Productivity, '76}}{\text{Labor Productivity, '76}} \right) * 100 \quad (2.2)$$

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 Company, Inc. 1976, 1998), Richardson's Process Plant Construction Estimating Standards (Richardson Engineering Services 1976, 1998), and Dodge Unit Cost Books (McGraw-Hill Inc. 1976, 1998). 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 was manually collected from the 1976 and 1998 estimation manuals of *Means* (Means Company, Inc.), *Richardson* (Richardson Engineering Services), and *Dodge* (McGraw-Hill Inc.). 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) masterformat.

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.

1. 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.

2. Level of Control – Level of control relates to advances in machinery and hand tools that transfer control from the human to the machine.
3. Functional Range – Changes in equipment’s functional range are those changes that expand a tool’s or machine’s range of capabilities.
4. 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.
5. 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 micro-level 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).

Table 2.1 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
	Preprogrammed 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 Function) (or	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

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 2.1. 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 Inc. 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:

$$Technology\ Index = \frac{\sum_{1}^N (\Delta E + \Delta C + \Delta F + \Delta R + \Delta I)}{N} \quad (2.3)$$

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.

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 the following table.

Table 2.2 Technology Index Example for Installing Plywood Roof Sheathing.

Technology Characteristic	1976 Equipment		1998 Equipment		Technology Index Score
	Hammer	Circular Saw	Nail Gun	Circular Saw	
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

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 2.4).

$$\text{Labor Productivity, Year X} = \frac{\text{Expected Physical Output (Units)}}{\text{Workhour Requirements (Hrs)}} \quad (2.4)$$

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

$$\% \text{ Change in Labor Productivity, '76-'98} = \left(\frac{\text{Labor Productivity, '98} - \text{Labor Productivity, '76}}{\text{Labor Productivity, '76}} \right) * 100 \quad (2.5)$$

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 $\pm 9.17\%$. Activities were grouped by division, per the CSI masterformat, and the average change in labor productivity per division was calculated. The results are shown in Figure 2.2.

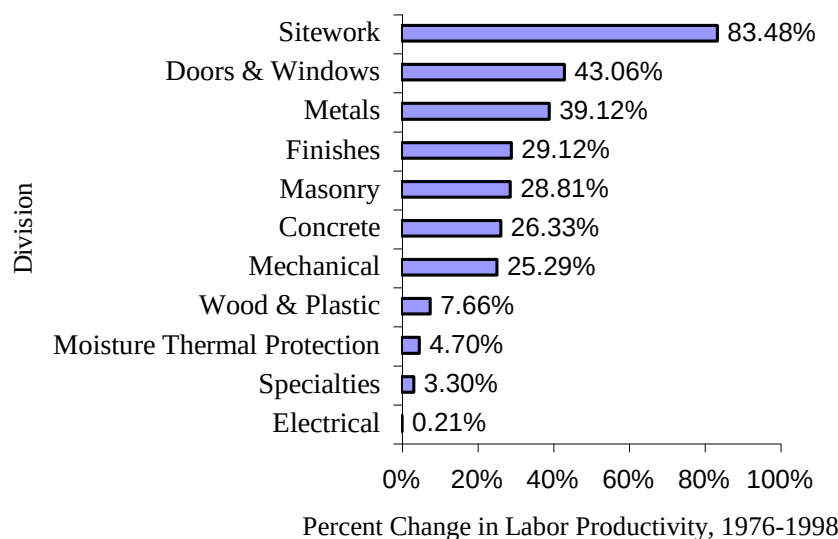


Figure 2.2 Mean Percent Change in Activity Level Productivity by Division, 1976 to 1998

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

Figure 2.3 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 2.3, which shows the average technology index broken down by the index score for each technology factor for activities grouped by division.

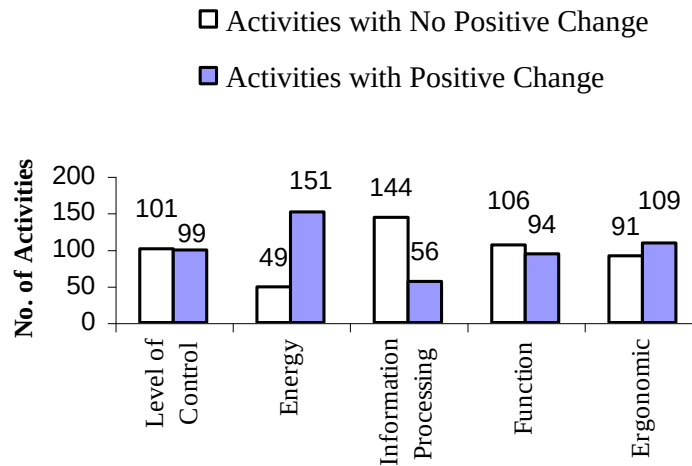


Figure 2.3 Positive Changes in Equipment Technology by Technology Factor, 1976-1998

Table 2.3 Mean Technology Index Score (Broken Down by Technology Factor Scores) 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 & 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}

Figure 2.3 reveals that more than 75% of the activities under consideration experienced an increase in energy output. Table 2.3 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 Figure 2.3, 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 semi-automatic 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 Figure 2.3). Through advances in hydraulic controls and microprocessors, machinery for sitework now offer more control precision and a greater reach with booms and buckets. Excavators and backhoes are capable of digging deeper.

Figure 2.3 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 2.3 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 offers 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 2.4 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.

Table 2.4 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.

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 correlations exceed 0.70. Collinearity did not exist among the technology factors in the data (see Table 2.4).

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 (Figure 2.4).

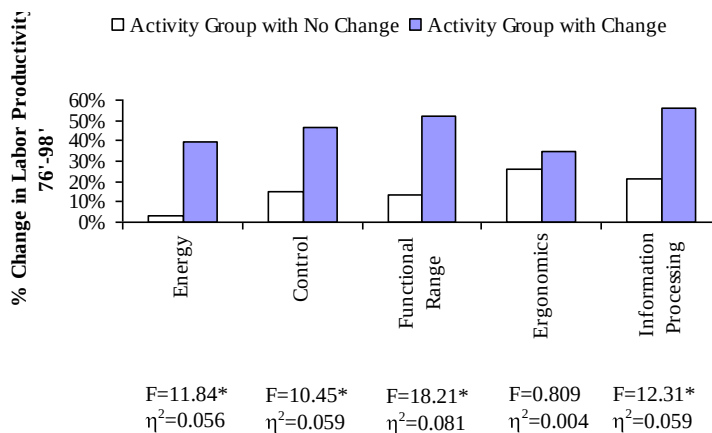


Figure 2.4 Percent Change in Labor Productivity for Activities with a Change in Equipment Technology and Activities with no Change in Equipment Technology, 1976-1998, * $p < 0.05$

With the exception of ergonomics, the activities that experienced improvement in equipment technology experienced more improvements in labor productivity than those activities that did not, and this finding was statistically significant. Activities experiencing an improvement in energy, control, functional range, and information