QUANTITATIVE EFFECTS OF CONSTRUCTION CHANGES ON LABOR PRODUCTIVITY

By H. Randolph Thomas[1] and Carmen L. Napolitan[2]

ABSTRACT: This paper details, in quantitative terms, the effects of changes and change orders on labor productivity and efficiency. Data for the analyses were daily productivity values from three industrial projects constructed in the 1989–1992 time frame. A total of 522 workdays of data were collected. None of the data involved disputed work or contract claims. Various analysis techniques were applied to the data, including data sorts and averages, analysis of variance tests, and multiple regression. The results confirm that it is possible to perform changes without negatively impacting labor efficiency. There was no negative effect in fewer than half the days when changes were performed. However, the average effect of all changes was a 30% loss of efficiency. Investigations into the cause of efficiency losses showed that there were disruptions when changes work was performed. A regression analysis showed a 25–50% loss of efficiency depending on the type of disruption. A threefold increase in the number of material availability problems was the most obvious disruption associated with change work.

INTRODUCTION

Changes during construction are a particularly irritating and costly problem for owners and contractors. It is recognized that some changes are necessary and inevitable and also time-consuming and expensive compared to the cost of the original scope of work. Yet there is a serious lack of understanding about the impact of changes. To date, there have been no definitive studies reporting in quantitative terms the impact of changes or why these impacts occur.

OBJECTIVES

The objectives of this paper are to quantify the impact of changes on field-labor efficiency and to determine the relationship between changes and various types of disruptions. The objectives are then to question how much the impacts are and why they occur.

The cost of changes largely consists of indirect, engineering, material, equipment, and field-labor costs. Of these, field labor costs are the most difficult to estimate, measure, and control. Because craft work hours are directly related to labor costs, the impact of changes is measured by quantifying work-hour inefficiencies at the crew level.

DEFINITIONS

In this paper, the following definitions are used. "Changes" are any change made to the original scope of work. No distinction is made regarding whether payment is promised or why the change is needed. A "disruption" is an event that is known or has been reported in the literature to adversely affect labor productivity. Examples include lack of materials, lack of tools or equipment, congestion, and accidents. "Efficiency" is the relative loss of productivity compared to some baseline period. A value less than unity means performance poorer than the baseline period. The "performance ratio" (PR) is the ratio of the actual unit rate expressed as the measured work hours per unit divided by the expected or baseline unit rate. It is defined such that values greater than unity mean that performance is worse than the baseline. "Productivity" is the work hours during a specified time frame divided by the quantities installed during the same time frame. The time frame can be daily, weekly, or the entire project (cumulative). This measure is commonly called the unit rate.

BACKGROUND

Many articles have been written describing in general terms the effects of changes on labor productivity. Most deal with legal aspects, documentation, substantiation, and claims management. Many of the articles avoid quantitative issues and do not assist in the understanding of how to minimize the damages resulting from changes. An article by Dellon and Dellon (1988) is typical. Although the basic causes of claims and a laundry list of potential impacts are given, the article is too general to be of much value in understanding or preventing claims.

Several articles describe resolution techniques (Yanoviak 1987) and provide a perspective on negotiated settlements, arbitration, and litigation. The emphasis is on after-the-fact documentation and resolution techniques. Little guidance is provided for understanding or minimizing the impact of changes.

Substantiating cost is the subject of a paper by Dieterle and Maziarz (1991). A distinction is made between incurred cost and claimed cost. The authors argue that much of the difference results from federal and state unemployment taxes, social security payments, and other elements of payroll burden. The authors also compare the Blue Book and Cost Reference Guide (CRG) equipment rental rates, and show that the monthly charges for a D7G dozer and an Insley 600 excavator are considerably less than the CRG Ownership rate. The focus of the paper seems to be on accounting procedures.

Very little information has been published on the quantification of the effects of changes on labor efficiency. The two articles described as follows rely on data from contract claims and disputes.

Zink (1990) described a measured mile method (MMM), which is a method for establishing a baseline for quantification purposes. The focus of the paper is on labor efficiency, and the author suggests that the MMM can be used to quantify work-hour overruns by comparing the work-hour utilization rate during some baseline period to the rate during an impacted period. The methodology relies on a work-hour–trend curve rather than a productivity-trend curve. Using work hours can lead to erroneous results because it represents only half

---

[1] Prof. of Civ. Engrg., Pennsylvania Transp. Inst., Pennsylvania State Univ., 203 Res. Ofc. Build., University Park, PA 16802.

[2] Grad. Student, Dept. of Civ. Engrg., Pennsylvania State Univ., 212 Sackett Build., University Park, PA.

Note. Discussion open until February 1, 1996. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on August 9, 1993. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 121, No. 3, September, 1995. ©ASCE, ISSN 0733-9364/95/0003-0290–0296/$2.00 + $.25 per page. Paper No. 6739.

(input) of the productivity or efficiency equation. The MMM does not consider quantities produced (output).

Leonard (1987) described his quantification investigation of the effects of changes on labor productivity. The study was based on the detailed review of 90 claim cases, each from a separate contract. The cases were divided into two groups—civil/architectural and mechanical/electrical—and the percentage loss of productivity was shown as a function of the percentage of the total work hours spent on changes. The slope of the curves is much shallower than might be expected. For example, a four- or fivefold increase in the percentage of work hours spent on changes lead to a 10–20% loss of productivity.

The Construction Industry Institute's Changes-Impact Task Force investigated 106 projects to determine the factors impacting cost and schedule growth (Zietoun and Oberlender 1993). The data were sorted according to fixed-price and cost-reimbursable contracts, and a number of factors were examined in each grouping. The analysis showed trends towards cost and schedule growth as more money was left on the table and the number of bidders increased. In this study, the number of changes was not a variable in the analysis.

HOW CHANGES AFFECT LABOR PRODUCTIVITY

In this paper, the analysis of how change affect labor productivity is based on the Factor Model (Thomas and Sakarcan 1993). A detailed representation is shown in Fig. 1. The presence of changes is indicated as an indirect factor because of the view that changes themselves do not lead to productivity or efficiency losses. If they did, the losses would be automatic, which most construction professionals agree is not the case. Instead, a construction change causes other disruptive influences to be activated. Consider the following situation in which an owner realizes that an important pressure sensor has been inadvertently left off of the plans. One hundred fifty feet of new conduit and cable are also required. This problem is recognized after much of the work is finished. Thus, the small sensor has led to a larger-scope operation, which is the installation of new conduit and cable, cable terminations, and testing.

Focusing attention on the conduit alone, the installation will likely be more difficult because of several important factors. The work area is more congested than it would have been had the conduit been part of the original scope of work. Additionally, parts of the facility may be operational, necessitating outage permits and other clearances.

Another factor that can seriously affect the work is that the work is done out of sequence. The crew doing the work needs to stop their present assignment and plan and reorganize for the new work. The resulting phenomenon is sometimes called loss of momentum or loss of rhythm. The crew may have to arrange for scaffolding, revise the conduit and cable-routing schedule, coordinate with other crews, and plan many other elements of the work in a level of detail that would not have been required had the sensor been included in the original design.

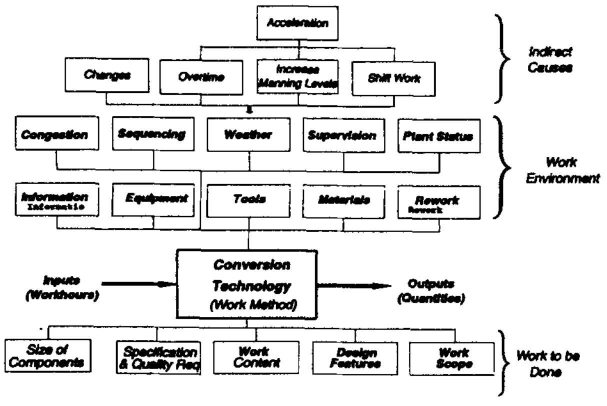

FIG. 1. Factor Model

Another often overlooked factor is the scope of work involved. The crew may have been routinely installing 457.5 m (1,500 ft) of conduit per day on production-type work. Now, they are being asked to plan and install 45.8 m (150 ft) as a change. The total work hours may be several times greater than normally required because the extended initial planning and setup period is distributed over a much smaller scope of work. The result is likely to be reflected in more work hours per meter. It is little surprise that work bid at one rate may take 2–4 times more work hours when done as changed work.

This scenario leads to an important assumption: loss of productivity on changed work is the results of changes in the scope and complexity of the work as well as to the environment in which the work is done. The number of work hours required is very sensitive to changes in the work environment.

OVERALL ASPECTS OF STUDY

This study has several aspects that are different from previous studies. The smallest manpower unit that produces completed output is the crew. Therefore, the measurement focus is on the output of an average crew. Most previous studies have relied on cumulative productivity data, but in this study, unit data (daily) are the primary data format (Thomas and Napolitan 1993).

DATA-COLLECTION PHASE

The objective of the data-collection process is to assure that consistent data from many projects can be collected and then combined into a single database for processing and analysis. This objective is accomplished by defining the study parameters, carefully selecting projects, and applying uniform data-collection procedures.

Definition of Study Parameters

Only the electrical and piping crafts were studied. The work performed by these crafts was further narrowed to crews performing production-related work, such as installing conduit and pulling cable. Crews performing other kinds of work were not considered.

Project Selection

Projects were selected based on the following criteria. The labor environment was required to be tranquil, and projects in which an inordinate number of changes were anticipated were avoided. Experimental, unique, and poorly designed or managed projects were also avoided. Furthermore, the early phase and the start-up phase were not included in the study time frame. Although many changes occur during the start-up phase, this work is typically not conducive to good production, and statistical analyses using these data are very difficult.

Productivity data were collected daily from three active construction projects as shown in Table 1. Each data set represents a single crew. The projects were constructed in the 1989–1992 time frame. A total of 128 weeks of data were collected.

Data-Collection Procedures

Data collection was independent of the cost-reporting system. A procedures manual was developed for this purpose

TABLE 1. Project Features

Data-set number (1)	Description (2)	Craft (3)	Number of weeks (4)
9181	Process plant	Mechanical	13
9182	Process plant	Electrical	14
9185	Paper mill	Electrical	8
9186	Refinery	Mechanical	16
9187	Refinery	Mechanical	15
9188	Refinery	Mechanical	16
9189	Refinery	Mechanical	16
9190	Refinery	Mechanical	15
9191	Refinery	Mechanical	15

(Thomas 1991). Site personnel collected the data. The philosophy and evolution of the procedures manual are explained elsewhere (Thomas et al. 1989). The data-collection effort was organized around the completion of eight forms. Seven forms were completed daily; the other was completed once for each project. The forms solicited information about the crew size and absenteeism, the quantities installed, and the conditions in which the work was done. Selected information requested on each form is as follows:

Form No. 1— Manpower/labor pool: crew size; crew composition (skilled and unskilled); absenteeism.
Form No. 2— Quantity measurement: measured units completed for each subtask.
Form No. 3— Design features/work content: work type; design details.
Form No. 4— Environmental/site conditions: temperature; humidity; weather events.
Form No. 5— Management practices: delays; material, equipment, and information availability; congestion; sequencing; rework.
Form No. 6— Construction methods: length of workday; overtime schedule; working foreman.
Form No. 7— Project organization: size of project work force; other site-support personnel; number of foremen.
Form No. 8— Project features: type of project; approximate cost; approximate planned duration.

The type of data recorded was continuous, integer, and binary. An example of continuous data is the quantity of conduit, i.e., 22.8 m (74.6 ft). Integer data includes the crew size, i.e., nine tradesmen. Binary variables take on values of 0 or 1, depending on whether a particular condition is present. For example, if a measurable portion of the work hours were spent on changed work, 1 would be recorded; if not, the factor would be recorded as 0.

Although the data forms are more detailed than shown here, every effort was made to streamline the data-collection process. Following an initial familiarization period, data collection typically took about 30 min per crew per day.

DATA-PROCESSING PHASE

The purpose of the data-processing phase was to calculate the daily productivity had the crews been installing the same item, screen the data for unusual peculiarities, and normalize the data so that performance is related to a baseline productivity when there were no changes or disruptions to the work.

Calculate Conversion Factors

It is known that the installation of different-sized components require different labor resources. For example, a 101.6-mm (4 in.) conduit requires more work hours per foot to install than a 19.1-mm (0.75 in.) conduit. Differences such as these exist for all the items included in the study. These differences are accounted for by using conversion factors. The logic is as follows.

The first step is to define a standard item. In theory, the choice of an item is irrelevant. In practice, it is usually selected as an item that occurs frequently. In this study, the standard item for electrical work was a 50.8-mm (2 in.) galvanized rigid steel (GRS) conduit, and for piping it was 63.5-mm (2.5 in.), schedule 40, butt-welded, carbon steel spools.

The most accurate estimate of conversion factors should result from measured data; however, experience with productivity data indicates that a very large database is required. In this investigation, unfactored unit rates were obtained from standard estimating manuals. For electrical work, the Means and Richardson manuals plus a manual from a construction company were consulted. For piping work, the Means, Richardson and Page and Nations manuals plus the manual from the same construction company were used. The use of multiple estimating manuals precludes the factors from being influenced by one source.

Using the data from a single estimating manual, conversion factors for each item are calculated as follows:

$$\text{Conversion Factor}_{ij} = \frac{\text{Unit Rate for Item in Question}_{ij}}{\text{Unit Rate of Standard Item}_{j}} \quad (1)$$

where i = item number; and j = manual number. Once conversion factor (CF) values have been calculated for all manuals and items, multiple-regression techniques can be used to develop a mathematical relationship for each grouping of like items. Groups are for conduit, cable, pipe, valves, and so on. The group regression equation can be used to calculate an estimate of the conversion factor for each item in the group.

In practice, the conversion factor shows how much more or less difficult an item is to install compared to the standard item (Sanders and Thomas 1991). The theory behind conversion factors is that of earned value. It can be easily verified that irrespective of the mix of quantities installed, the conversion factor does not alter the hours earned in a given time frame.

Conversion factors are analogous to monetary exchange rates. For example, a mix of marks, yen, and pounds can be exchanged for an equivalent amount (or value) of pounds or another currency, such as dollars.

The utility of the conversion-factor approach is that the productivity of crews doing a variety of work can have their output expressed as an equivalent output of a single standard item. Thus, the productivity of all crews can be calculated for the same standard item during each time period regardless of the work performed. Likewise, crews from different projects can have their productivities calculated for the standard item, meaning that the data from multiple projects can be combined into a single database because all the productivity values represent installing the same item of work.

To illustrate how the conversion factors are calculated, consider the items listed in Table 2. The standard item is a 50.8-mm (2 in.) GRS conduit. The conversion factors in the last column are calculated using (1), where the unit rate for the standard item is 0.584 work hours/m (0.178 work hours/ft).

Calculate Equivalent Quantities

The equivalent quantities are the number of units of the standard item that will yield the same number of earned hours as was actually earned by installing nonstandard items. Prac-

TABLE 2. Example Listing of Bulk Commodity Items

Item of work (1)	Unit Rate		Conversion factor (4)
	Work hours per meter (2)	Work hours per foot (3)	
19.1-mm (0.75 in.) GRS conduit	0.328	0.100	0.562
25.4-mm (1 in.) GRS conduit	0.403	0.123	0.691
50.8-mm (2") GRS conduit	0.584	0.178	1.000
63.5-mm (2.5 in.) GRS conduit	0.751	0.229	1.287
19.01-mm (0.75 in.) PVC conduit	0.161	0.049	0.275
#6,600 volt cable	0.039	1.200	6.742

TABLE 3. Daily Quantities Installed for Example Crew

Item of work (1)	Quantities Installed		Conversion factor (4)	Equivalent Quantities		Earned hours (7)
	Work hours per meter (2)	Work hours per foot (3)		Work hours per meter (5)	Work hours per foot (6)	
19.1-mm (0.75 in.) GRS conduit	6.1	20	0.562	3.4	11.24	2.0
25.4 mm (1 in.) GRS conduit	—	—	0.691	—	—	—
50.8 mm (2 in.) GRS conduit	7.6	25	1.000	7.6	25.00	4.5
63.5 mm (2.5 in.) GRS conduit	13.7	45	1.287	17.7	57.92	10.3
19.1 mm (0.75 in.) PVC conduit	35.1	115	0.275	9.6	31.63	5.6
#6,600 volt	336	1,100[a]	6.742	22.6	74.16	13.2
Total	—	—	—	61.0	199.95	35.6

[a] This value is divided by 100 to be consistent with the units of clf (100 ft).

tically speaking, it is the most likely estimate of the quantity of the standard item that would have been completed for the same set of work conditions. The equivalent quantity is calculated using the following:

$$\text{Equivalent Quantity}_l = \sum_{i=1}^{k} (\text{Conversion Factor}_i \times \text{Actual Quantity}_{il}) \quad (2)$$

where i = item being installed; and k = total number of items installed during workday 1.

Suppose that on a given day, a crew installs the quantities listed in the first two columns in Table 3. The conversion factors in Table 3 are used in (2) to calculate the equivalent quantities. As shown, the crew did the equivalent of 61.0 m (200 ft) of the 50.8-mm (2 in.) GRS conduit.

The work hours earned are determined by multiplying the quantities installed by the unit rate from Table 2 (Thomas and Kramer 1987). For the actual installed quantities in Table 3, the crew earned 35.6 work hours. If the earned hours are calculated based on the equivalent quantity of 61.0 m (199.95 ft), the unit rate of 0.584 work hours/m (0.178 work hours/ft) for the standard item [a 50.8-mm (2 in.) GRS conduit] from Table 2 is used and the earned work hours are also equal to 35.6. Therefore, the value of the work in terms of earned hours is the same, it is simply expressed in a different way. If a different standard item is chosen, the earned work hours will still be 35.6.

Screen Data Set

The 128-week data set was examined for abnormalities that would confuse the analysis process. These data were removed from the data set. Included as abnormalities were days when no work hours were recorded or unusually large quantities were installed. All days with more than 300 work hours were deleted, because this would be analogous to an exceptionally large crew size. The latter portion of data set 9185 was incomplete, and these data were also deleted. In the screening process, the database was reduced from 522 to 372 daily records.

Determine Baseline Productivity

A baseline productivity was calculated for each data set by determining the work hours and quantities installed on days when there were no changes or rework, disruptions, or bad weather reported. Table 4 shows the data used in this calculation.

Calculate Performance Ratios

The emphasis in this study is on the effect of changes on labor productivity. The daily departure of the actual productivity from the baseline in Table 4 is calculated using the following:

$$\text{PR}_{lm} = \frac{\text{Actual Productivity}_{lm}}{\text{Baseline Productivity}_m} \quad (3)$$

where l = workday being considered; and m = the project data set. PR values were calculated for each of the 372 data values in the database. A PR value greater than unity means that based on the daily quantities, more work hours were required that day than on the average baseline day; that is, the productivity was worse than the baseline productivity.

The individual project baseline productivity values in Table 4 were used in (3). In doing so, the departure from normality was assessed uniquely for each project. This approach negated the influence of unique project design, management, and labor aspects.

DATA ANALYSES: HOW MUCH

The analysis of the quantitative effect of changes on labor efficiency is based on average values derived from the database. The principal analysis techniques are analysis of variance (ANOVA) and multiple regression.

TABLE 4. Data Used in Calculating Baseline Productivity

Data-set number (1)	Number of data points (2)	Work hours (3)	Quantities		Baseline Productivity	
			Meters (4)	Feet (5)	Work hours per meter (6)	Work hours per foot (7)
9181	26	5,171	1,207	3,958	4.26	1.30
9182	24	4,518	510	1,672	8.85	2.70
9185	12	1,716	365	1,198	4.49	1.43
9186	16	1,820	337	1,106	5.41	1.65
9187	2	180	30	97	6.10	1.86
9188	7	764	369	1,211	2.07	0.63
9189	10	914	637	2,089	1.44	0.44
9190	12	1,215	557	1,826	2.20	0.67
9191	7	655	38	124	17.28	5.27

Distribution of Performance Ratios

An investigation of performance ratios indicates that when changes occur, the impacts can be quite severe (PR values > 1.0). Also, it is possible to perform change work without negatively impacting performance ($PR \leq 1.0$). Most of the low PR values occurred when the crews performed work on pipe hangers. As will be shown in the next section, these days are randomly distributed within the database and are not correlated to any of the other variables considered. Their presence has no impact on the data analysis because the writers are evaluating the influence of various factors, not developing a predictive model.

Correlation between Performance and Other Factors

The initial investigation was an analysis to identify the relationship between various factors. The factors selected for this analysis and the level of significance, which ranges between 0.000 and 1.000, are shown in Table 5. If it is hypothesized that an independent variable produces statistically significant differences in a dependent variable, then the level of significance is the calculated α-value at which the null hypothesis H_0, that there is no difference, would be rejected (Devore 1991, 315). In simpler terms, the level of significance is the maximum probability that chance or randomness produced the observed differences when, in fact, the null hypothesis is true. The level of significance is also called the p-value; a value near 0.000 means a highly significant relationship. The use of level of significance highlights the difference between the approaches of theoretical or classical and applied statistics. A brief discussion is provided in Appendix I.

The analysis shows that changes work is highly correlated to the performance ratio, rework, and disruptions. Rework is also highly correlated to disruptions. Weather events are highly correlated to the length of the workday, and work on pipe supports is significantly correlated to the performance ratio.

Significance of Individual Factors

Of particular interest is the influence on the performance ratio of changes, rework, disruptions, and weather. An ANOVA test was done for each factor selected one at a time. PR was the dependent variable. The length of the workday was not analyzed because the reason for essentially all shortened workdays was attributable to bad weather, and is, therefore, already considered.

The results of the analysis are shown in Table 6. As can be seen, there is a significant relationship between the PR values and the presence of changes at $\alpha = 0.086$. The other variables do not show strong significance.

Another by-product of the ANOVA analysis is the average performance ratio for the conditions being examined. These PR averages can be used to compute an efficiency for that condition using the following equation:

TABLE 5. Significance Matrix

Factor (1)	PR (2)	Changes (3)	Rework (4)	Disruptions (5)	Weather (6)	Pipe supports (7)
Changes	0.018					
Rework	0.789	0.000				
Disruptions	0.913	0.017	0.000			
Weather	0.378	0.841	0.362	0.395		
Pipe supports	0.002	0.326	0.510	0.828	0.466	
Length of workday	0.564	0.738	0.908	0.234	0.000	0.973

TABLE 6. Significance of Various Factors on Performance Ratio

Factor (1)	Level of significance (2)	Efficiency (3)
Changes	0.086	0.71
Rework	0.387	0.84
Disruptions	0.164	0.74
Weather	0.203	0.74

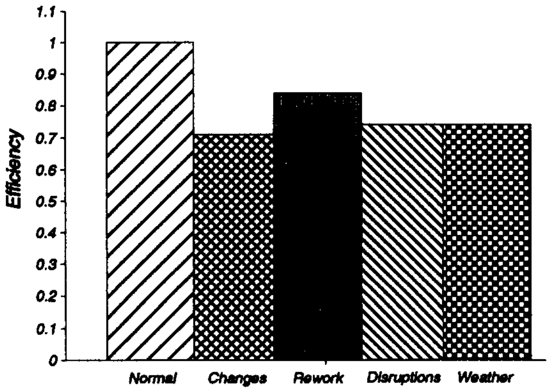

FIG. 2. Efficiency as Function of Various Factors Taken One at a Time

$$\text{Efficiency} = \frac{\text{Average Performance Ratio with Factor Present}}{\text{Average Performance Ratio under Normal Conditions}} \tag{4}$$

These efficiencies are shown graphically in Fig. 2. As is evident, when only one factor is considered at a time, there is a degradation in performance when any of the factors are present.

Multivariant Analysis

There is always some uncertainty in performing single-variable analyses because the dependent variable, in this case PR, may be influenced by some other factor. For this reason, a multivariant-regression model was developed. Each of the variables in Table 6 was a candidate for the model.

Four multivariant-regression models were developed using combinations of changes, rework, disruptions, and weather. The choice of the best model was based on the standard error, and the mean absolute error. There were minor differences between the four models; therefore, the simplest model was selected and is shown as follows:

$$PR = 2.57 + 1.07 \times \text{Changes Indicator} \tag{5}$$

Based on (5), the PR value when the changes indicator is present is $2.57 + 1.07 = 3.64$, compared to a PR value of 2.57 when the indicator is not present. Using (4), the efficiency is 0.71, or a loss of efficiency of about 30%. The loss of efficiency when changes were present for each of the equations tested was calculated. The efficiencies ranged from 0.69 to 0.75.

DATA ANALYSES: WHY

The data analyses into why changes negatively impact labor performance address the issue of causation. Because disruptions are highly correlated with changes, the analyses focused on an examination of the frequency and nature of disruptions. The disruptive events that are evaluated are material, tool, equipment, and information availability; out-of-sequence work; and rework and fabrication errors. Weather events were excluded because they are beyond the control of management.

Congested situations were not considered because almost all the work on the three projects was done in a congested environment.

Disruption Frequency

The data set was partitioned as shown in Table 7, and the percentage of days when there were disruptions and rework were calculated for the no-change and the change conditions. Table 7 shows that when change work is done, there is a significant increase in the frequency of occurrence of rework and disruptions. This outcome is shown graphically in Fig. 3. When no-changes work was performed, rework and disruptions occurred on 20% and 100% of the days, respectively. These percentages increased to 82% and 26%, respectively, when work on changes was performed. From Fig. 3, it is clear that changes are linked to more rework and disruptions.

Disruption Frequency by Type

The database was partitioned according to the presence of change work, and the frequency of occurrence of disruptions by type expressed as a percentage was calculated. The results of this analysis are shown in Table 8. The most obvious statistic is the significant increase in material-availability difficulties. Although the percentages of the other disruption types are small, there are increases in all categories.

TABLE 7. Percentage of Days

Condition/factor (1)	Rework (2)	Disruptions (%) (3)
Normal (no changes)	20%	11
Changes performed	82%	26

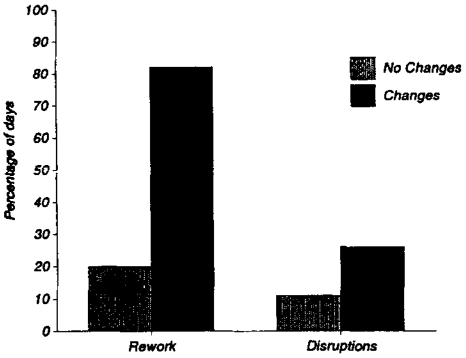

FIG. 3. Increase in Percentage of Days as Function of Rework and Disruptions

TABLE 8. Percentage of Disrupted Days by Type

Disruption type (1)	Percentage of days when there were no changes (%) (2)	Percentage of days when there were changes (%) (3)
Material availability	9	26
Tool availability	1	2
Equipment availability	1	2
Information availability	1	1
Sequencing	1	2

TABLE 9. Quantitative Effect of Disruptions

Disruption type (1)	Efficiency (2)
Material availability	0.74
Tool availability	1.06
Equipment availability	1.05
Information availability	0.53
Sequencing	0.71

Quantitative Effect of Disruptions

The quantitative impact of disruptions by type on labor efficiency was examined by developing a multiple-regression equation in which the performance ratio is the dependent variable and the disruption types are the independent variables. Efficiencies were then calculated by (4). To use (4), the average PR when a disruption is present, say subpar material availability, is divided by the average PR when no disruption is present. Table 9 shows the efficiency values: when materials are not available, the crew output was 74% of normal. Lack of materials reduced performance by 26%. As can be seen, out-of-sequence work and lack of materials and information are particularly acute, even though the disruption type may have occurred infrequently. These disruption types suggest that the principal factor affecting labor efficiency is the timing of the change.

Based on the results in Tables 5–9, there is little doubt that disruptions cause a loss of efficiency and that as changes occur there is a greater frequency of disruptions.

CONCLUSIONS

The effect of construction on labor efficiency is documented. On average, there is a 30% loss of efficiency when changes are being performed, although it is possible to perform many changes without a loss of efficiency. The key variable affecting efficiency is believed to be the time of the change.

Lower labor performance is strongly related to the presence of change work, disruptions, and rework. As change work is performed, there is almost a three-fold increase in the percentage of disrupted days. The most significant types of disruptions are the lack of materials and information and having to perform the work out-of-sequence. These disruptions result in a daily loss of efficiency in the range of 25–50%.

Because disruptions are related to losses of efficiency and change work is related to an increased occurrence of disruptions, change work and disruptions are also correlated. These observations are consistent with the factor model. Because disruptions are the root cause of loss of efficiency, it is concluded that to manage change work for improved efficiency, it is important to avoid disruptions. Based on the data in this paper, lack of materials is the most serious disruption.

ACKNOWLEDGMENT

This work was sponsored by the Construction Industry Institute under the guidance of the Changes-Impact Task Force. Their support and assistance in this research is gratefully acknowledged and appreciated.

APPENDIX I. THEORETICAL VERSUS APPLIED STATISTICS

The classical or theoretical approach to hypothesis testing is to define an acceptable level of significance or α-value a priori; use the data set to compute an F-ratio and α-value; and reject the null hypothesis, H_0, if the computed α-value exceeds the preselected value. This approach may be inadequate because it says nothing about whether the computed value of the test statistic just barely fell into the rejection region or exceeded the critical value by a large amount.

The applied statistician approaches the hypothesis testing problem in a slightly different way. No pass/fail α-value is selected in advance. Instead, the data are analyzed, and the smallest α-value at which the null hypothesis, H_0, would be rejected is computed. This statistic is called the *p*-value or level of significance. The *p*-value conveys much about the strength of evidence against H_0 and allows an individual decision maker to draw a conclusion without imposing a particular α on others who might wish to draw their own conclusions.

The level of significance has other practical implications as well. The level of significance is the maximum probability that chance or randomness produced the observed differences when, in fact, the null hypothesis, H_0, is true. If the level of significance is near zero, then it is more probable that the observed differences were truly the result of the influence of the independent variable being considered.

APPENDIX II. REFERENCES

Brown, D. W. (1988). *Influences on cost of construction changes and forward change pricing report.* Constr. Education Inst., the Frisby Group, Greenville, S.C.

Construction Industry Institute. (1988). "The impact of changes on construction cost and schedule." *Rep. of Cost/Schedule Task Force*, Austin, Tex.

Dellon, A. L., and Dellon, I. J. (1988). "Documentation and verification in the change order process." *Trans.*, Am. Assoc. of Cost Engrs., C.7.1–C.7.5.

Devore, J. L. (1991). *Probability and statistics for engineering and the sciences.* Brooks/Cole Publishing Co., Pacific Grove, Calif.

Dieterle, R. A., and Maziarz, S. J. (1991). "Substantiation of costs in construction claims." *Cost Engrg.*, 33(3), 9–12.

Hester, W. T., Kuprenas, J. A., and Chang, T. C. (1988). "Changes during construction and their impact: a review of the literature and development of management techniques." *Draft Rep.*, to Constr. Industry Inst., Austin, Tex., 26.

Leonard, C. A. (1987). "The effect of change orders on productivity." (1987). *Revay Rep.*, Revay and Associates, Ltd., Montreal, Canada, 6(2), 1–3.

Sanders, S. R., and Thomas, H. R. (1991). "Factors affecting masonry productivity." *J. Constr. Engrg. and Mgmt.*, ASCE, 117(4), 626–644.

Thomas, H. R. (1991). "Procedures manual for collecting productivity and related data on the effects of changes on industrial construction projects: electrical and piping." *Final Rep.*, Pennsylvania Transp. Inst., Pennsylvania State Univ., University Park, Pa.

Thomas, H. R., Maloney, W. F., Smith, G. R., Sanders, S. R., Horner, R. M. W., Handa, V. K. (1990). "Productivity models for construction." *J. Constr. Engrg. and Mgmt.*, ASCE, 116(4), 705–726.

Thomas, H. R., and Napolitan, C. L. (1993). "The effects of changes on labor productivity: why and how much." *Rep. to the Constr. Industry Inst.*, Austin, Tex.

Thomas, H. R., and Kramer, D. F. (1987). "The manual of construction productivity measurement and performance evaluation." *Rep.*, Constr. Industry Inst., Austin, Tex.

Thomas, H. R., and Sakarcan, A. S. (1994). "Forecasting labor productivity using factor model." *J. Constr. Engrg. and Mgmt.*, ASCE, 120(1), 228–239.

Thomas, H. R., Smith, G. R., Sanders, S. R., and Mannering, F. L. (1989). "An exploratory study of productivity forecasting using the factor model for masonry." *Rep. No. 9005*, Pennsylvania Transp. Inst., Pennsylvania State Univ., University Park, Pa.

United Nations. (1965). "Effect of repetition on building operations and processes on site." United Nations Committee on Housing, Build., and Plng., *Rep. ST/ECE/HOU/14*, New York, N.Y.

Yanoviak, J. J. (1987). "Improving project management for claims reduction." *Trans.*, Am. Assoc. of Cost. Engrs., Morgantown, W.Va., H.2.1–H.2.5.

Zietoun, A. A., and Oberlender, G. D. (1993). "Early warning signs of project changes." *Source Document 91*, Constr. Industry Inst., Austin, Tex.

Zink, D. A. (1990). "Impacts and construction inefficiency." *Cost Engrg.*, 32(11), 21–23.