Labor Productivity and Work Sampling: The Bottom Line

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Abstract: This paper describes the relationship between labor productivity and direct work as reported in work-sampling studies. Seven data bases, collected primarily from nuclear–power-plant construction projects, are used. Investigations of a 30-project data base show that direct work is better in the winter than during the rest of the year, is best during the start-up and testing phase, and has improved since the Three Mile Island accident. It is concluded that these results are illogical. Using linear regression models, the paper shows that direct work is not related to productivity. This conclusion is based on three assumptions: Reducing wait time leads to increased direct-work time, increased direct-work time leads to better productivity, and better productivity is accompanied by less time spent waiting. Each assumption is tested, and the model statistics show very poor correlations and predictive capabilities. The most reliable data base, consisting of 46 data points, yielded an r_a^2 value of 0.00 and a standard error of the estimate that is equal to the standard deviation of the performance measure. The conclusion is that work-sampling studies show how busy the crafts are, and the results cannot be used to predict labor productivity or to quantify inefficient work hours.

Introduction

Work sampling is a technique that measures the time craftsmen spend in various categories of activities, such as direct work, transporting materials, or waiting. Numerous reports, articles, and texts describe how to conduct a study and illustrate various numerical results (Oglesby et al. 1989; Richardson 1976; Thomas 1991). In three other articles, researchers have reported that the percentage of time spent in direct-work activities is correlated to labor productivity, that is, labor productivity is better as more time is spent in direct-work activities (Liou and Borcherding 1986; Thomas et al. 1984; Handa and Abdalla 1989).

Since the early 1980s, work-sampling results have been used in several electric-utility rate-hearing cases to quantify the number of work hours alleged to have been wasted in the construction of nuclear power plants. In theory, a power plant requires a finite number of work hours to be spent in direct-work activities. A forecast can be calculated using an industry-average curve that shows how the direct-work percentage varies as a function of the percent complete of the facility. This value can be compared to the actual hours spent in direct work based on site-specific work-sampling studies, and the difference represents the inefficient use of labor resources. This approach was adopted by the New York Public Service Commission in the hearing on the Shoreham nuclear facility on Long Island and resulted in the disallowance of over $900 million from the rate base. A similar approach was used in the Seabrook proceedings but rejected at the Millstone Point 3 and Wolf Creek hearings. Considering the enormous sums of money involved, it is

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important that any relationship between direct work and labor productivity be well-founded and based on reliable research procedures and data.

Objectives

The first objective of this paper is to define the fundamental assumptions that need to exist for direct work to be correlated to labor productivity. The second objective is to test the hypothesis that direct-work percentages can be used to predict labor productivity. This paper will demonstrate conclusively that the necessary assumptions cannot be supported and that the two measures are unrelated. Most of the data for this paper were collected from nuclear–power-plant construction projects, because work-sampling studies have not been widely conducted in other sectors of the construction industry. Another advantage of focusing on power-plant construction is that there is general commonality in the procedures used on many sites.

Description of Data

Two primary data sets were used in this investigation. The writer has assembled these data sets over the last 10 years. Several other data bases were also used, as described below. Pertinent information about the data bases is included in Table 1.

Thirty-Project Data Base

The first primary data set consists of 158 work-sampling studies from 30 nuclear–power-plant construction projects. The studies were conducted from 1973 to 1985. As shown in Table 2, the projects are primarily in the eastern United States.

The data base contains information about the plant capacity in megawatts, the date of the study, and the percent complete of the plant when the study was done. Tables 3 and 4 show the distribution of study dates and percent complete. The procedures were available for some studies, and, generally, the procedures were similar with respect to the activity categories, data col-

TABLE 1. Data Base Summary Statistics

Data base (1)	Number of data points (2)	Number of projects (3)	Type of project (4)	Type of data (5)	Craft or activity (6)
30-Project	158	30	Nuclear Power Plants	Biweekly summary	All major crafts, sitewide studies
Three-Project	46	3	Nuclear power plants	Biweekly summary	Carpenters, electricians, ironworkers, laborers, pipefitters
Liou (1984)	21	7	Fossil power plants	Biweekly summary	All major crafts, sitewide studies
Grand Gulf	22	1	Nuclear power plant	Daily values	30 pipefitters installing valves in containment building
Handa and Abdalla (1989)	14	1	Townhouses	Unknown	9–11-person framing crew
Logcher and Collins (1978)	5	5	Commercial	2–5 day summary	Tile-setting activities
Rogge and Tucker (1982)	22	1	Nuclear Power Plant	Biweekly summary	Carpenters, electricians, ironworkers, pipefitters

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TABLE 2. Geographical Distribution of Projects, 30-Project Data Base

Region[a] (1)	Number of projects (2)	Number of studies (3)
Northeast	3	27
Middle Atlantic	7	24
South Atlantic	7	41
East north central	4	18
West north central	0	0
East south central	7	20
West south central	2	17
Rocky Mountain	0	0
Pacific	0	0
Unknown	—	11
Total	30	158

[a]Nuclear Regulatory Commission Region.

TABLE 3. Distribution of Work-Sampling Study Dates, 30-Project Data Base

Year (1)	Number of studies (2)
1973	3
1974	1
1975	2
1976	3
1977	10
1978	13
1979	30
1980	38
1981	20
1982	14
1983	7
1984	4
1985	1

TABLE 4. Distribution of Percent Complete Values, 30-Project Data Base

Percent complete (1)	Number of studies (2)
0–10	9
11–20	19
21–30	13
31–40	13
41–50	18
51–60	21
61–70	15
71–80	22
81–90	19
91–100	7

TABLE 5. Performance Factors and Direct-Work Percentages, Three-Project Data Base

Project (1)	Primary craft (2)	Direct work (%) (3)	PF value (4)
1	Carpenters	30.8	1.03
1	Carpenters	29.7	1.25
1	Carpenters	31.6	1.25
1	Carpenters	37.9	1.54
1	Carpenters	32.2	1.15
1	Carpenters	34.0	1.01
1	Carpenters	33.3	0.65
1	Electricians	21.7	1.05
1	Electricians	24.1	0.72
1	Electricians	31.1	0.83
1	Electricians	29.0	1.23
1	Electricians	36.0	0.95
1	Electricians	25.0	0.78
1	Pipefitters	19.4	1.20
1	Pipefitters	21.4	1.35
1	Pipefitters	23.4	1.15
1	Pipefitters	22.7	1.08
1	Pipefitters	28.8	1.37
1	Pipefitters	24.0	1.12
1	Pipefitters	30.0	1.28
1	Pipefitters	23.0	1.11
2	Electricians	21.1	1.04
2	Electricians	24.4	0.73
2	Electricians	22.9	1.57
2	Electricians	27.3	0.29
3	Carpenters	31.5	1.71
3	Carpenters	26.6	0.77
3	Carpenters	24.3	0.76
3	Carpenters	29.0	0.80
3	Carpenters	44.1	0.79
3	Carpenters	24.0	1.35
3	Electricians	31.3	0.94
3	Carpenters	31.5	0.77
3	Carpenters	30.8	0.57
3	Carpenters	38.7	1.20
3	Carpenters	34.0	1.03
3	Pipefitters	23.2	1.29
3	Pipefitters	18.3	1.02
3	Pipefitters	25.7	1.32
3	Pipefitters	24.0	1.83
3	Pipefitters	42.0	1.29
3	Electricians	24.9	0.93
3	Carpenters	26.9	1.14
3	Pipefitters	17.1	1.10
3	Electricians	40.4	0.64
3	Electricians	33.9	1.24

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lection approach, definition of direct work, crafts and areas studied, and study duration. Most studies covered the major areas of the site, including the major crafts, and typically lasted two weeks. Overall, this is the most comprehensive work-sampling data base on nuclear construction projects known to exist.

Three-Project Data Base

The second primary data base consists of direct-work percentages for specific crafts on three nuclear projects in the northeast. The direct-work value for each craft was matched with the unit rate (work hours per unit) during the same month that the study was done. The unit rates were used to calculate a performance factor (PF) for each craft. The data are summarized in Table 5.

The PF is defined as the estimated unit rate divided by the actual unit rate (Thomas and Kramer 1987). The estimated unit rate and performance factors were available from project records for projects one and three. For project two, the electricians were performing several activities, and because the unit rates for each were known, the PF values were calculated using the concept of earned value. Direct-work percentages must be compatible with the unit rates. Where the PF was reported for a multicraft activity—for example,

TABLE 6. Direct-Work Percentages and PF Values for Pipefitter Study, Grand Gulf Data Base

Direct-Work Percentages		
Narrowly defined (1)	Typical definition (2)	Performance factor[a] (3)
—	42.4	1.04
—	55.5	1.19
—	41.7	0.86
—	31.5	1.36
—	31.5	0.75
—	38.9	1.38
—	34.5	0.95
—	35.0	0.34
—	35.0	0.57
—	40.7	2.55
39.0	41.6	0.09
42.9	42.9	0.65
30.8	30.8	0.85
20.0	35.0	0.32
31.7	50.8	0.93
49.2	52.4	1.51
47.2	47.2	2.15
31.8	34.8	1.40
48.5	53.0	1.52
39.4	45.5	2.19
39.4	39.4	1.71
40.0	46.7	2.51

[a]Earned work hours divided by actual work hours.

TABLE 7. Direct-Work Percentages and Unit Rates for House Framing Study, Handa and Abdalla (1989) Data Base

Direct work (%) (1)	Wait time (%) (2)	Unit rate (min/sq ft) (3)
73.3	4.1	1.270
69.4	8.0	1.072
64.4	12.1	0.888
63.8	8.4	0.982
70.6	4.6	0.879
66.7	9.3	0.615
60.6	12.6	1.278
66.5	8.6	1.023
68.0	6.3	2.704
70.8	6.6	2.085
70.5	7.2	2.517
60.5	14.7	0.469
66.0	9.3	0.449
60.5	14.3	1.208

concrete productivity—the direct-work percentages for the appropriate crafts were averaged. In some instances, the direct-work percentages for the appropriate crafts could not be differentiated. For these cases, a weighted-average PF value was calculated, based on the number of work-sampling observations per craft or craft manning level.

Other Data Bases

Five other data bases also were used in this paper. One is based on the work of Liou (Liou 1984; Liou and Borcherding 1986), who studied both nuclear– and fossil–power-plant projects. The data for the nuclear projects

TABLE 8. Percentages of Time and Productivity of Floor-Tile Operations, Logcher and Collins (1978) Data Base

Category	Job Number				
	1 (2)	2 (3)	3 (4)	4 (5)	5 (6)
(1)					
(a) Work Related					
Productive work	40	48	53	48	42
Layout or measure	3	1	2	3	1
Subsurface floor preparation	2	11	5	1	4
Total work related (%)	45	60	60	52	47
(b) Delay or Wait Time					
Work delays and on-site management or coordination time	16	10	6	8	12
Breaks or non-job-related activities	26	14	19	19	26
Total wait time (%)	42	24	25	27	38
Work hours	67.7	23.8	130.5	187.5	14.9
Productivity (wh/sq ft)	0.040	0.029	0.012	0.004	0.031

TABLE 9. Performance Factors and Wait-Time Percentages, Rogge and Tucker (1982) Data Base

Craft (1)	Wait time (%) (2)	PF value (3)	Craft (4)	Wait time (%) (5)	PF value (6)
Carpenters	18	0.84	Carpenters	15	1.04
Carpenters	16	0.79	Carpenters	14	1.05
Carpenters	10	1.19	Carpenters	12	1.49
Electricians	12	1.15	Electricians	9	0.74
Electricians	6	0.98	Electricians	9	1.21
Ironworkers	26	0.60	Ironworkers	13	0.63
Ironworkers	15	0.53	Ironworkers	14	0.71
Ironworkers	9	0.88	Ironworkers	9	1.04
Pipefitters	15.6	0.90	Pipefitters	15.6	0.96
Pipefitters	19.1	0.74	Pipefitters	13.0	0.91
Pipefitters	14.9	0.79	Pipefitters	11.8	0.89

are included in the 30-project data base. The Liou data base summarized in Table 1 is for the fossil power plants only.

Thomas et al. (1984) described a study of 30 pipefitters at the Grand Gulf Nuclear Power Plant. These data, called the Grand Gulf data base, are summarized in Table 6. In this study, two definitions of direct work were used. The first was narrowly defined to include only specific production-related activities. The second definition was typical of the one used in the previously described data bases (see Appendix I).

Handa and Abdalla (1989) presented the results of an eight-week study of a framing crew on a two-story, 30-unit townhouse complex in Ontario, Canada. The data are presented in Table 7. The crew consisted of seven or eight framers and two or three laborers.

Logcher and Collins (1978) studied tile-setting activities in Boston and New York. The data were collected by continuous observation, but were reported in categories that seem consistent with typical work-sampling studies. These data are summarized in Table 8.

The last data base is from a study of four crafts on a single nuclear project by Rogge and Tucker (1982). The study compared delay times from foreman delay surveys and work sampling. The data in Table 9 were extracted from the graphs in Rogge and Tucker (1982).

Factors Affecting Labor Productivity and Direct Work

Many factors can affect both labor productivity and direct-work percentages. These can be categorized in two groups: Project characteristics and work-sampling study procedures. These factors are briefly described in the following. Work sampling is a subjective measure and is prone to many sources of error in addition to statistical sampling error (Thomas 1982). Considering the number and combinations of variables that can affect direct work and productivity, it seems irrational to expect that the two measures will be affected the same way. This is especially true since work sampling only measures the input part of the productivity equation (Thomas et al. 1990).

Project Characteristics

It can be argued that there are many factors affecting productivity, but the major factors appear to be as follows:

Type, Scope, Layout, and Complexity

Nuclear plants are not standardized. Different plant configurations lead to differences in the distribution of crafts used. Also, a larger site requires a larger work force, which is harder to manage, thus resulting in poorer productivity on the larger site (Thomas and Jansma 1985). Work-sampling studies may be harder to conduct on congested, compact sites. The site layout may also affect work-sampling results.

Time Frame

As construction advances on a nuclear project, the work becomes more difficult. The proportion of direct work at 20% complete can be very different from the proportion at, say, 60% complete, even on the same project. The distribution of trades will not be the same.

The vintage of a nuclear facility is another important factor affecting productivity. The evolution in complexity of wall-mounted pipe restraints and stress reconciliation of pipe supports are two examples of situations that have had dramatic consequences on labor-resource requirements. Another uniquely important aspect that differentiates projects of the same vintage is the application of subsection NF, section III, of the American Society of Mechanical Engineers code to pipe component supports. This section of the code requires that welds be incrementally inspected. This requirement was not imposed on earlier projects.

Construction Methods

On-site versus off-site fabrication is one of the principal factors known to affect the number of field labor hours required. There are many other variables.

Weather

Plants constructed in harsh winter environments should require more work hours than those constructed in warmer climates. This is especially true if major concrete operations are scheduled for the winter. Work-sampling studies also can reflect the harsh conditions.

Skill of the Work Force

A skilled work force will be more productive than a less skilled work force. Yet, it does not necessarily follow that the direct-work percentage will be higher. For example, a skilled work force may spend more time in support work and less time in direct work than its less skilled counterpart.

Work Practices

Specific factors affecting productivity and direct work include journeyman-to-apprentice ratios, use of helpers, work schedule, restrictions on the use of preassemblies, use of automatic tools, work methods, scheduled breaks, cleanup time, and so forth. Also, work rules can uniquely affect work sampling and productivity. For instance, on one site the crafts may be required to be at their respective work stations at the start of the shift. On another

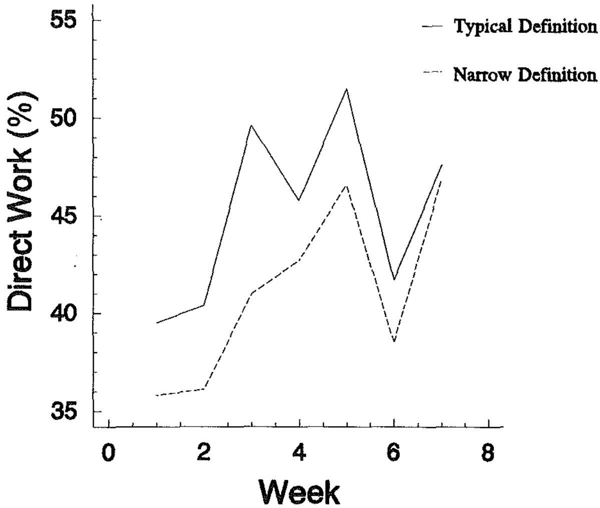

FIG. 1. Influence of Definition on Direct Work Percentage

site, they may be required to have only "brassed in." Havoc has occurred on sites where work rules were not standardized through a project agreement.

Length of Workday

Shorter workdays likely will lead to reduced productivity, because the length of the gearing-up and winding-down periods will remain about the same.

Work-Sampling Study Procedures

The procedures used in work-sampling studies will affect the results (Thomas 1982). The pertinent aspects are as follows:

Activity Categories

The number of activity categories has been observed to range from seven to 28 or more. Activities classified as direct work on one study may be something else on another study.

Activity Definitions

Of particular interest is the definition of direct work. Fig. 1 shows the weekly direct-work percentages of 30 pipefitters installing valves. Two definitions of direct work were used (Thomas et al. 1984). The absolute weekly differences range from 1 to 15%. Even with similar definitions, there can be wide differences because of the interpretive nature of work sampling.

Preference and Biases

Written procedures cannot cover all situations. How these are handled can lead to a lack of uniformity.

Crafts

The work of each craft is unique. It is widely recognized that the direct-work percentages vary appreciably for different crafts.

Site Areas

Not all areas of a site are equally productive. Congestion and quality control are important factors, but there are others.

Shifts

Productivity can vary from one shift to another. Some of the differences can be attributed to the strategy for the second shift. Do the crafts work on different work activities or continue with the day-shift work? The second shift generally has fewer delays from engineering and quality control and less noise and supervision.

Time of Year

The percentage of time spent on certain activities will be affected by temperatures and rain or snow.

Study Windows

Study windows are times during the day when observations are not made. Because windows cover the least-productive times of the day, e.g., beginning of the shift, coffee breaks, etc., more use of window time will yield higher direct-work values. Percentages should be adjusted to a common base for comparative purposes (Richardson 1976).

Foreman

Direct-work percentages will vary depending on whether the foreman is part of the study and whether the same category definitions are used.

Study Duration

Most studies last about two weeks. Short studies of a week or less are more susceptible to highly variable results caused by rain or other unique events.

Analysis of Patterns of Direct Work

If direct-work percentages and productivity are related, then the direct-work values should mirror trends in productivity. However, before investigating the trends in the 30-project data base, a common baseline needs to be established.

Baseline

It is generally recognized that direct-work percentages on nuclear projects decline as projects progress from start to finish. It would not be correct to directly compare study results at two different stages of completion. The 30-project data base was analyzed, and the following equation was developed to explain the relationship between direct work and percent complete:

$$\underset{}{\text{direct work}} = \underset{(38.55)}{37.174} - \underset{(-5.67)}{0.093}\ (\text{percent complete}) \quad (1)$$

The r_a^2 value was calculated as 0.17, and the standard error was 5.41. The t-statistics are shown in parentheses below each coefficient.

Each observed direct-work percentage in the 30-project data base was di-

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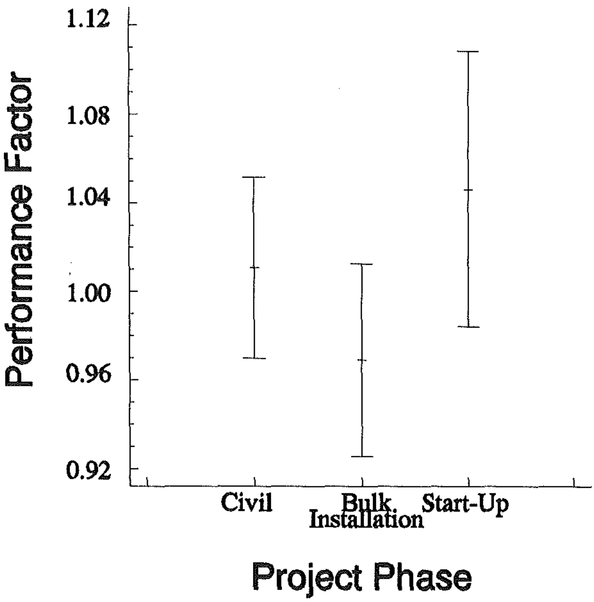

FIG. 2. Factor Means and 95% Confidence Intervals for Relative Direct Work as Function of Phase of Work

vided by the percentage calculated from (1). This yielded a relative direct work, in which a value greater than unity represented a better-than-average percentage. All subsequent analyses of the 30-project data base were based on these relative values.

Phase of Project

It is widely recognized that, on a nuclear project, the work becomes progressively more difficult. To investigate this trend, the data were divided into three groups: 0–50% complete represents the civil phase; 51–80% complete represents the bulk installation phase; and 81–100% complete represents the start-up phase. There were 69, 59, and 29 observations in each category, respectively. An analysis of variance showed the highest relative direct work to be in the start-up phase. The lowest was in the bulk installation phase. Fig. 2 shows the factor mean plot and the 95% confidence intervals.

Winter Weather

To determine the effects of winter weather on direct-work percentages, the data were partitioned into two groups: those studies done in November through February and all others. Forty-two of the studies were done in the winter; 102 were not. An analysis of variance was performed, and it was found that the average relative direct work for the winter months was 1.03. The average for the rest of the year was 0.99. There was no statistically significant difference between the groups. The level of significance was 0.209. A similar analysis was done of studies from projects that were less than 50%

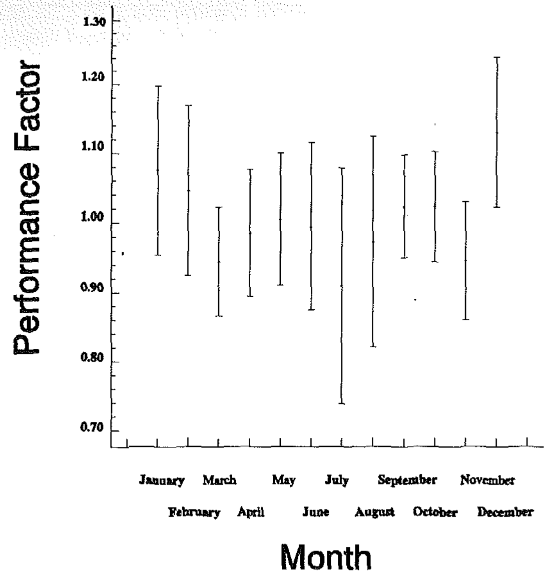

FIG. 3. Factor Means and 95% Confidence Interval for Relative Direct Work as Function of Month of Study

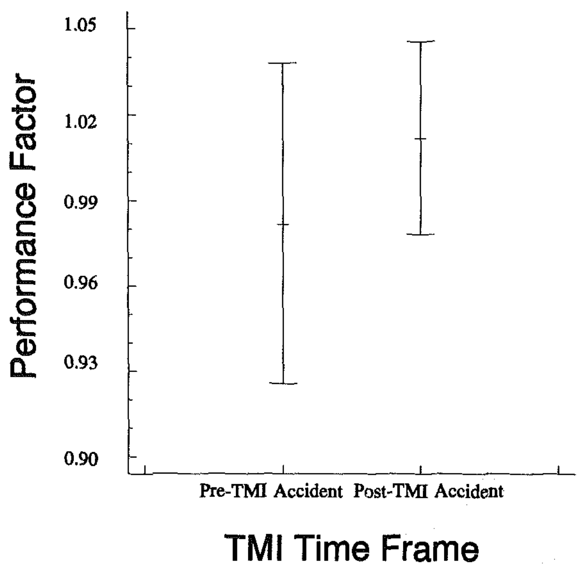

FIG. 4. Factor Means and 95% Confidence Intervals for Relative Direct Work as Function of Three Mile Island Accident

complete, and the conclusions were the same.

Another analysis of variance was done using the month of the year as the independent variable. Fig. 3 is a factor mean plot showing the 95% confidence intervals. As can be seen, the time of year is not a factor. For instance, the average relative direct work in December is 1.13, compared with 0.91 in July.

Three Mile Island Effect

Lastly, the data were examined to determine if they reflected any deterioration after the March 1979 accident at the Three Mile Island nuclear plant. There were 38 studies done before the accident and 108 studies afterward. The results shown in Fig. 4 indicate that the relative values increased after the accident. The average relative direct work improved from 0.98 to 1.01.

Synopsis

If one accepts the hypothesis that direct-work percentages can be used to predict labor productivity, then, based on the preceding analyses, productivity is no different in winter than in the rest of the year (perhaps best in December). Productivity is best during the start-up phase and has improved since the Three Mile Island accident. Of course, these statements are contrary to scientific research, common industry knowledge, documented industry statistics, and common sense. Thus, one is likely persuaded to accept the null hypothesis that direct-work percentages cannot be used as predictors of labor productivity.

Fundamental Assumptions

The hypothesis that direct-work percentages from work sampling can be used to predict labor productivity is based on the following three assumptions (Thomas et al. 1990):

- Reducing the amount of time spent waiting leads to more time spent in direct-work activities.
- If more time is spent in direct-work activities, the productivity will be better.
- If the first two assumptions are true, it follows that reducing waiting time will lead to improved productivity.

Each of these assumptions is evaluated in the following section.

Testing of Assumptions

The foregoing assumptions were tested using the data bases listed in Table 1. Various regression models were developed, and the model statistics were evaluated. Because direct work is being examined for its predictive capabilities, the most appropriate statistic is the standard error of the estimate. Table 10 summarizes the model statistics. The standard error should be compared with the mean and standard deviation of the dependent variable. Comparatively large standard errors indicate poor predictive capabilities.

Wait Time versus Direct Work

The first assumption is that wait time and direct work are inversely pro-

TABLE 10. Parameters for Various Statistical Models

Source (1)	Number of data points (2)	Dependent Variable: Description (3)	Dependent Variable: Mean value (4)	Dependent Variable: Standard deviation (5)	Model Statistics: Standard error of estimate (6)	Model Statistics: r_a^2 (7)
		(a) Direct Work versus Wait Time				
30-Project Data Base	127	Direct work (%)	32.3	5.91	5.90	0.11
Liou (1984)	21	Direct work (%)	37.7	7.69	5.67	0.48
Handa and Abdalla (1989)	14	Direct work (%)	66.5	4.18	1.62	0.85
		(b) Productivity versus Direct Work				
Grand Gulf	12	Performance factor (narrow definition of direct work)	1.22	0.69	0.70	0.23
Grand Gulf	22	Performance factor (typical definition of direct work)	1.22	0.69	0.66	0.13
Handa and Abdalla (1989)	14	Productivity (min/sq ft)	1.25	0.71	0.67	0.09
Logcher and Collins (1978)	5	Productivity (productive time)	0.023	0.015	0.011	0.59
Logcher and Collins (1978)	5	Productivity (total work-related time)	0.023	0.015	0.015	0.23
3-Project Data Base	46	Performance factor	1.07	0.30	0.31	0.00
		(c) Productivity versus Wait Time				
Rogge and Tucker (1982)	22	Performance factor	0.91	0.23	0.17	0.41
Logcher and Collins (1978)	5	Productivity	0.023	0.015	0.012	0.50
Handa and Abdalla (1989)	14	Productivity (min/sq ft)	1.25	0.71	0.67	0.09

portional. To test this assertion, the 30-project data base was examined. Fig. 5 shows the relationship between direct-work and wait-time percentages. The two measures are, at best, weakly related. A linear regression model with direct work as the dependent variable yielded an r_a^2 value of 0.11. The standard error of the estimate was calculated to be 5.90. The standard error is interpreted to mean that, given the wait time, the true value of direct work can be predicted to within ± 1.96 (5.90), or $\pm 11.56\%$, and the estimate will

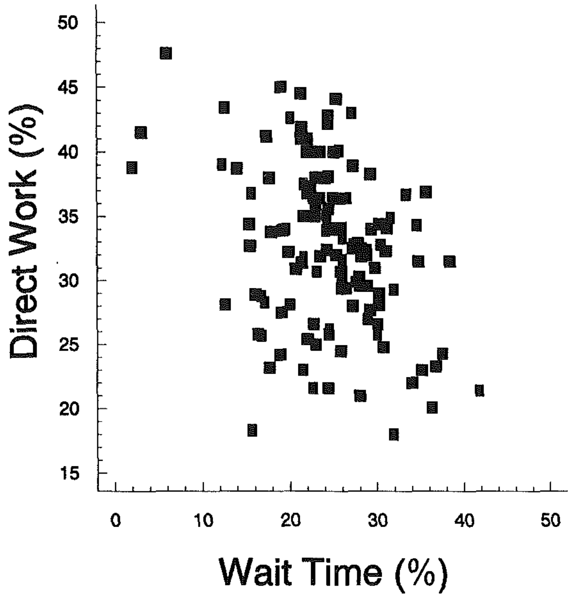

FIG. 5. Relationship between Direct Work and Wait Time, 30-Project Data Base

be within this range 95 times out of 100. Obviously, the predictive capabilities of this model are quite poor.

Other literature was investigated to determine if data were available to support the assumption. Liou examined 39 work-sampling studies from 12 nuclear power plants and 21 studies from 7 fossil power plates (Liou and Borcherding 1986). Using the data from the fossil power plants, it can be shown that direct work and wait time are somewhat correlated (see Fig. 6). A linear regression model with direct work as the dependent variable yielded an r_a^2 value of 0.48. The standard error of the estimate was calculated to be 5.67. Although some correlation exists, the standard error is almost as large as the standard deviation of direct work. Thus, the variable wait time provides only marginal predictive capabilities. This observation is consistent with Fig. 5. The 39 data points from the nuclear plants are included in the 30-project data base described earlier and were not analyzed separately.

The data from Handa and Abdalla (1989) were also examined and the statistics showed a high r_a^2 value of 0.85. This result is possibly because the direct-work percentage is rather large and limits the variability of the other variables. Also, there are only 14 data points.

Direct Work versus Productivity

Three published articles have suggested that labor productivity is related to work sampling. The first is by Liou and Borcherding (1986). They investigated the relationship between direct work and concrete productivity (unit rate) and reported several equations that they claimed could be used to predict productivity. Their analysis was based on 41 data points from 10 nuclear and three fossil projects.

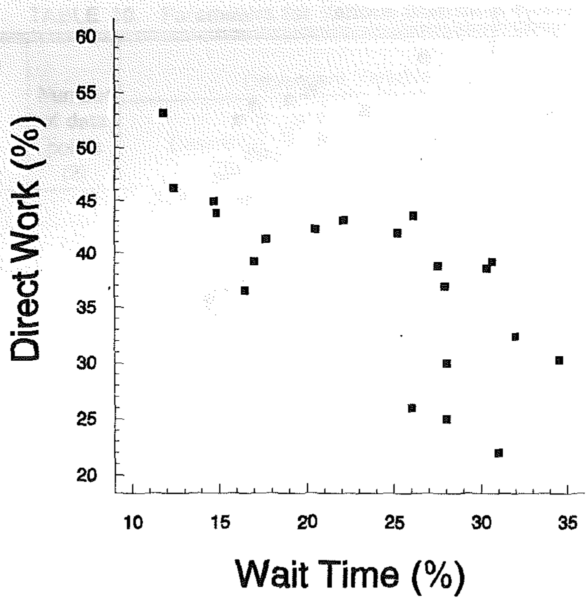

FIG. 6. Relationship between Direct Work and Wait Time, Liou Data Base

A careful review of their work, including the source document (Liou 1984), reveals several flaws with respect to the data. Liou requested unit rate data from electric utilities via a questionnaire that specified that the unit rate should include direct and indirect craft labor. Unfortunately, the questionnaire did not request that the unit rate data be limited to the same month in which the work-sampling study was done. A careful review of the data indicates that all of the concrete data are cumulative unit rates [see Table 4, column one, in Liou and Borcherding (1986)]. For example, on one project, the unit rate of 22.36 wh/cy was matched with work-sampling studies done at 30, 55, 70, 71, and 75% complete. It is incorrect to correlate cumulative unit rate data with the work-sampling studies (point estimates), because a work-sampling study typically lasts two weeks, whereas the unit rate may cover three to five years.

The questionnaire also asked for the percent complete of the facility at the time of the survey (presumably the work-sampling survey). A review of the data indicates that of the 14 studies, 23 were done when the facility was 50% complete or more, long after the major concrete work was finished. These projects were into the mechanical and electrical phases, and studies done during these phases were heavily oriented toward the piping, electrical, sheet metal, boilermaker, and millwright crafts. It is incorrect to compare concrete productivity to work-sampling studies done when there was no concrete work in progress.

The flaws in the data are reflected in the study results. For instance, Liou and Borcherding (1986) reported an equation (see Table 3) with the following independent variables: Direct work, material handling, breaks, and late start and early quit percentages. The model shows that direct work is the least significant variable (t-statistic of -1.81). If the critical value for the t-

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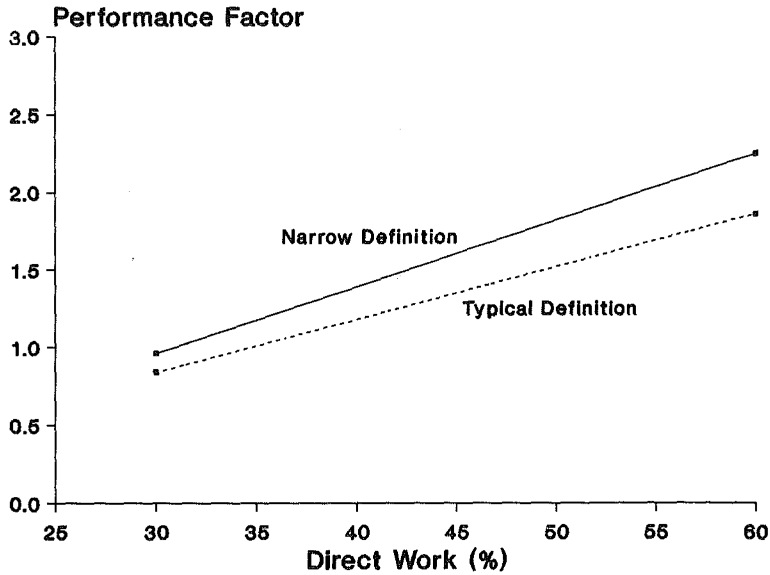

FIG. 7. Performance as Function of Direct Work Definition, Grand Gulf Data Base

statistic of 1.96 were applied, as suggested by Liou, the variable direct work would have been excluded from the model. The most significant variables are material handling and the late-start–early-quit percentages. The model also shows that productivity improves with increasing percentages of break time. Because of the flaws in the data, Liou's work is not included in Table 10 and was not used to test the assumptions about direct work and productivity.

In a 1984 article, the writer described a study of 30 pipefitters installing valves in the containment building at the Grand Gulf Nuclear Power Plant (Thomas et al. 1984). The study compared the use of a typical definition of direct work to a more narrowly defined definition. The typical definition is comparable to the definitions used in the 30-project, three-project, Liou, and Handa data bases. However, many of the conclusions were based on the narrowly defined definition. Fig. 7 shows the influence of definition.

The study was very different from the others presented in this paper. The crew output was measured on a micro scale; specifically, the measured tasks were: Cut pipe, fit up, weld preparation, and complete weld. The data were collected by focusing on specific crews rather than collecting observations during general sitewide tours.

Using the narrowly defined definition, the writer presented an equation that showed a relationship between direct work and performance. Unfortunately, that relationship was developed using seven-day moving-average data, and this approach yielded an artificially high correlation. Also, the standard error of the estimate was not reported. For this paper, the relationship was recalculated using unaveraged data and is as follows:

$$PF = \underset{(0.34)}{-0.34} + \underset{(1.75)}{4.32 \times 10^{-2}} x_n \quad \text{(2)}$$

where PF = the ratio of the earned work hours divided by the actual work hours; and x_n = the percentage of time when direct work is narrowly defined. Eq. (2) is based on 12 data points. The r_a^2 value was 0.23, and the standard error was 0.70. The t-statistics are less than 1.96. A similar equation was calculated using the typical definition of direct work. Based on 22 data points, the equation is

$$PF = \underset{(0.23)}{-0.19} + \underset{(1.76)}{3.42 \times 10^{-2}} x_t \quad \text{(3)}$$

where x_t = the percentage of time when the typical definition of direct work is applied. The r_a^2 was 0.13, and the standard error was 0.66. The t-statistics indicate that the coefficients are not very reliable. Eqs. (2) and (3) are shown in Fig. 7.

Both equations show very poor correlations and very high standard errors. Compared to the PF values, the standard error suggests that the variable direct work operates as a random variable. The slope of the curve is also of interest. Using (2), an increase in the PF of 25%, a substantial improvement, is accompanied by an increase of about 5% in direct work. Thus, direct work appears to be somewhat insensitive to productivity—a conclusion that is supported by the previous statistics. Overall, it appears likely that the earlier results reported by the writer were misleading, because of the narrowly defined definition, microscopic measurement of output, and moving-average data.

Handa and Abdalla (1989) described the results of an eight-week study of a framing crew on a townhouse complex. The study was similar to that by the writer described earlier, in that the quantities were measured in a detailed manner. In Handa and Abdalla, quantities were tracked in 15 categories. Using the data in Table 7, they reported that the unit rate was correlated to direct work. The article stated a r^2 value of 0.35, but when it was adjusted for the number of degrees of freedom, the r_a^2 value was 0.24. The standard error was not reported, but was calculated by the writer as 0.62. This statistic should be compared with the standard deviation of 0.71 for the unit rate. The equation presented by Handa and Abdalla included two terms, the percentage of direct work and the combined percentages for the personal time, breaks, and late-start–early-quit categories. A careful review of the equation indicates that the t-statistic for direct work was -0.06. This low value indicates that direct work contributes almost nothing to the predictive capabilities of the equation. Thus, it would appear that Handa and Abdalla have greatly overstated the predictive capabilities of the variable direct work.

Using their data, a linear regression equation was calculated relating the unit rate to the percentage of direct work. The r_a^2 value was 0.09 and the standard error was 0.67. These statistics are included in Table 10 and show that direct work is not correlated to productivity.

Logcher and Collins (1978) described the study of five projects involving the placement of floor tile. The data are included in Table 8. Two regression models were developed using the unit rate as the dependent variable and productive work and total work-related percentages as independent variables. The r_a^2 values were 0.59 and 0.23, respectively, and the standard errors were 0.011 and 0.015, respectively. The data support their observations that productive time was not related to productivity.

The three-project data base provides the best insight into the relationship

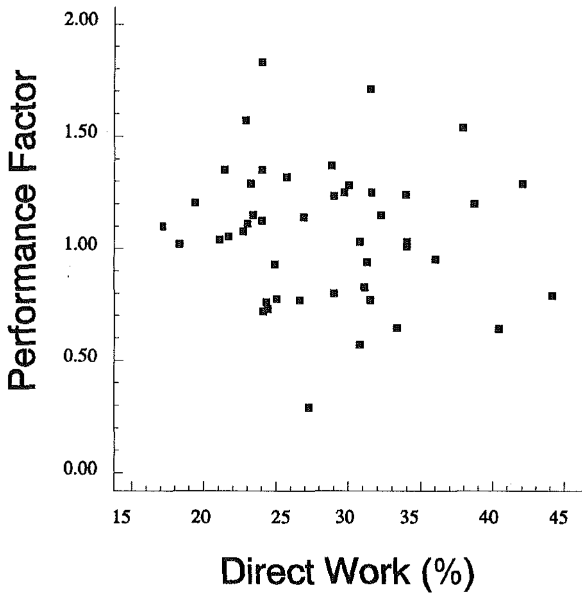

FIG. 8. Performance Factor as Function of Direct Work Percentage, Three-Project Data Base

between productivity and direct work because: (1) There are a large number of data points; (2) the data are not subject to the same variability as daily data; (3) the performance factors are monthly statistics, not cumulative; and (4) the direct-work percentages and performance factors cover the same crafts during the same time frame. The data are plotted in Fig. 8. A regression model was calculated using dummy variables to account for differences in the data sources and crafts. The r_a^2 was determined to be 0.00, and the standard error was 0.31.

The statistics using the three-project data base are consistent with the other data sets in that the correlation is very low and the 95% confidence interval for the predictions is quite large. For the models listed in Table 10, the standard deviation of the dependent variable is about the same as the standard error of the model. These results confirm that direct work as determined by work sampling is merely a random variable and is unrelated to productivity.

Productivity versus Wait Time

Handa and Abdalla (1989) reported the unit rate of a framing crew and the combined percentages of wait time and unexplained idle time. A regression model shows the r_a^2 value to be 0.09 and the standard error 0.67.

Rogge and Tucker (1982) compared delay times from foreman delay surveys to wait time from work-sampling studies. He also presented performance-factor data over the same time frame. Using the data from their article, performance factors for carpenters, electricians, ironworkers, and pipefitters were correlated to wait time from the work-sampling studies. The regression model using dummy variables yielded an r_a^2 value of 0.41 and a

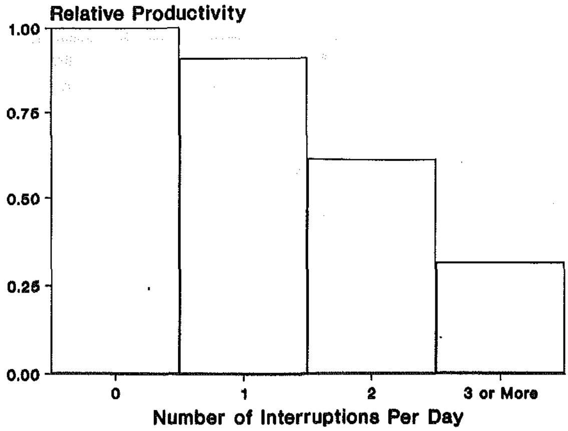

FIG. 9. Impact of Interruptions on Productivity Based on Time Actually Working

standard error of 0.17. A similar model was created using data from Logcher and Collins (1978) and yielded an r_a^2 value of 0.50 and a standard error of 0.012.

If productivity is correlated to wait time, then the productivity based on the time spent actually working (total time less wait time) should remain unchanged. An earlier article by the writer (Thomas et al. 1990) described the experiences of Horner, Hester, and Smith, stating that as the delay time

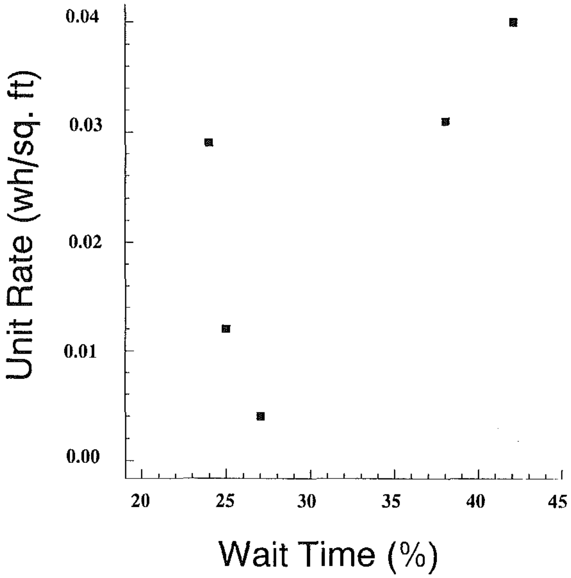

FIG. 10. Productivity as Function of Wait Time, Logcher Data Base

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increased, the productivity based on the time working actually worsened. Fig. 9 shows the effect of interruptions on the productivity (based on actual working time) of a crew of insulators. As the number of interruptions per day increased, the output was reduced by 69%.

Logcher and Collins (1978) also reported that the time spent on breaks and non-job-related activities was only weakly correlated to productivity, and that productive time decreased more than the corresponding increase in delay time. Fig. 10 shows change in productivity based on the time spent working as a function of the waiting time.

Synopsis

Considering all the evidence, one cannot accept the hypothesis that direct work can be used to predict labor productivity. The data in Table 10 consistently show weak correlations and exceedingly poor predictive capabilities. The r_a^2 values show that, in most cases, more than 50% of the variability of the data is not explained by the model. For most models, the amount of unexplained variability exceeds 75%. The standard deviation of the dependent variable is of the same order of magnitude as the standard error of the model for all the models considered. Thus, it is concluded that, as it relates to productivity, direct work is merely a random variable. Work sampling indicates how busy the crafts are, not if they are being productive.

Value of Work Sampling

A logical question is: What value does work sampling have if it is not related to productivity? The results of a study can serve an important communication function on a large, complex project like a power plant. The results of a study often stimulate discussions among managers that can lead to improvements in the flow of information or methods of work. However, it is unlikely that subsequent work-sampling studies will show the effects of any corrective action.

Conclusions

This paper examined the hypothesis that direct-work percentages from work-sampling studies can be used to predict labor productivity measured as the work hours per unit of output. Data and observations from five technical articles and two other comprehensive data bases were examined. Overall, the published articles have presented misleading results, have failed to report the most relevant model statistics, have overstated the predictive capabilities, or have reported conclusions based on incorrect data and methodologies.

The overwhelming conclusion of this investigation is that direct work cannot be used to predict labor productivity. This conclusion is based on coefficient of determination and standard error calculations. In all cases, the correlations are weak and the predictive capabilities are unreliable at a 95% confidence interval. The three-project data base contains the best available data. An analysis of these data showed an r_a^2 value of 0.00 and a standard error of the estimate that is equal to the standard deviation of the performance measure. The conclusion is that work-sampling studies show how busy the crafts are, but the results cannot be used to predict labor productivity or quantify inefficient work hours.

Appendix. References

Handa, V. K., and Abdalla, O. (1989). "Forecasting productivity by work sampling." *Constr. Mgmt. Econ.*, 7, 19–28.

Liou, F. (1984). "A statistical study on work sampling and unit rate productivity for power plants," thesis presented to the University of Texas, at Austin, Texas, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Liou, F., and Borcherding, J. D. (1986). "Work samling can predict unit rate productivity." *J. Constr. Engrg. Mgmt.*, ASCE, 112(1), 90–103.

Logcher, R. D., and Collins, W. C. (1978). "Management impacts on labor productivity." *J. Constr. Div.*, ASCE, 104(4), 447–461.

Oglesby, C., Parker, H., and Howell, G. (1989). *Productivity improvement in construction*. McGraw-Hill, Inc., New York, N.Y.

Richardson, W. (1976). *Cost improvement, work sampling, and short interval scheduling*. Reston Publishing Company, Inc., Reston, Va.

Rogge, D. F., and Tucker, R. L. (1982). "Foreman-delay surveys: Work sampling and output." *J. Constr. Div.*, ASCE, 108(4), 592–604.

Thomas, H. R. (1981). "Construction work sampling." *Business Roundtable*, Oct.

Thomas, H. R. (1982). "Games people play with work sampling." *J. Constr. Div.*, ASCE, 108(1), 13–22.

Thomas, H. R., Guevara, J. M., and Gustenhoven, C. T. (1984). "Improving productivity estimates by work sampling." *J. Constr. Engrg. Mgmt.*, ASCE, 110(2), 178–188.

Thomas, H. R., and Jansma, G. L. (1985). "Quantifying construction productivity losses associated with an accelerated schedule." Burns & Roe, Inc., Oradell, N.J., Jul.

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

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

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