Construction Baseline Productivity: Theory and Practice

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Abstract: In this paper, the theoretical basis for construction labor productivity measurement is presented. In particular, the theoretical basis for baseline productivity measurements is developed by examining a productivity database consisting of 23 projects involving masonry construction. An important hypothesis is presented showing that as the design becomes more complex, the baseline productivity worsens. It is also hypothesized that higher values of the coefficient of variation indicates a higher variability in management and craft skills and in the use of technology. Two measures are proposed to measure the performance of individual projects: The disruption index and the project management index. These two measures identify the best and worst performing projects. Cumulative probability distributions of the disruption index and the project management index were also developed to evaluate the 23-project database and compare it with other databases. The hypotheses developed from the 23-masonry project database were tested against an 8-project database of concrete formwork and a 12-project database of structural steel erection. Strong support for each hypothesis was found using the two additional databases.

INTRODUCTION

Over the past 25 years, little information has been written to advance the theoretical basis for labor productivity measurements and analyses. The procedures, analyses, and observations in this paper were developed as part of a broader study to develop the theories to support international benchmarking (Thomas and Završki 1998).

OBJECTIVE

The objective of this paper is to model the quantification of construction labor productivity. This will be done by describing the theoretical basis for baseline productivity measurements. After the baseline productivity is defined, a database consisting of 23 masonry projects is used to present the theoretical basis of baseline productivity measurements. Various hypotheses are developed from this database, and two other databases for concrete formwork and structural steel are analyzed next to determine if there are reasons to accept or reject the hypotheses.

Two types of databases are used in this research. The project database is a numerical database of baseline productivity values and other parameters defining the characteristics of the database. The second type is a knowledge base of each project. The knowledge base contains qualitative information about disruptions, craft and management practices, and social and economic factors. The model described herein is applicable to commerical and office structures constructed in normal environmental conditions. The model may not be applicable to projects that undergo severe schedule acceleration.

NUMERICAL PROJECT DATABASES

Three numerical databases consisting of labor productivity measurements of masonry (Db1), concrete formwork (Db5), and structural steel (Db6) activities from 42 construction projects are used for this theoretical development. Pertinent statistics are summarized in Table 1. The work performed in each database was similar in scope. As can be seen, the databases contain data covering 1,997 workdays and 151,624 work hours (wh). For each project, the data were collected using standardized data collection procedures. The data were processed and converted to a standard item of work using conversion factors (Thomas and Raynar 1997). The standard items are as follows: Masonry 20 mm × 20 mm × 41 mm (8 in. × 8 in. × 16 in.) concrete masonry unit; concete formwork-wall formwork system ≤2.44 m (8 ft) high; and structural steel erection—pieces of steel, i.e., beams and columns. Masonry and formwork were measured by the wh/m^2 (wh/ft^2), and structural steel was measured by the work hours per piece. Pertinent statistics about the projects in Db1, Db5, and Db6 are given in Tables 2 and 3.

SINGLE PROJECT EVALUATION

Project performance is influenced by the complexity of the design and by project management. These two categories have been demonstrated to affect labor productivity (UN 1965; Thomas et al. 1990). Single projects are evaluated by using various project attributes extracted from the data and by calculating project performance parameters. These are explained below.

Project Attributes

Variability in Unit Productivity

Experience has shown that where there is good project management and the design complexity [work content (WC)] is relatively consistent, then the daily (unit) productivity is also relatively constant. Each of the projects in the Db1 database was visually examined with respect to its daily productivity variability. When compared with the final cumulative productivity, it was observed that the poorer performing projects had much higher variability than did the better performing projects. High variability on the poor performing projects in this study is caused by disruptions in the work resulting from congestion,

TABLE 1. Database Summary Statistics

Database (1)	Location (2)	Number of projects (3)	Total workdays (4)	Total work hours (5)
Db1: Masonry	Central Pennsylvania and Indiana	23	1,002	82,222
Db5: Concrete formwork	Central Pennsylvania	8	723	58,487
Db6: Structural steel	Central Pennsylvania and Cincinnati, Ohio	11	272	10,915
Total	—	42	1,997	151,624

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TABLE 2. Project Attributes for Masonry, Db1

Project number (1)	WC rating (2)	Baseline productivity [wh/ft^2 (wh/m^2)] (3)	Cumulative productivity [wh/ft^2 (wh/m^2)] (4)	Total workdays (abnormal) (5)	Total work hours (6)
8,602	2	0.085 (0.915)	0.098 (1.054)	18 (0)	399
8701	2	0.080 (0.861)	0.102 (1.098)	27 (6)	2,800
8702	2	0.095 (1.022)	0.092 (0.990)	95 (8)	4,119
8703	2	0.075 (0.807)	0.109 (1.173)	60 (23)	4,807
8704	2	0.080 (0.861)	0.167 (1.797)	63 (39)	6,290
8706	2	0.080 (0.861)	0.085 (0.915)	28 (6)	3,458
8707	4	0.110 (1.184)	0.127 (1.367)	30 (4)	1,737
8708	3	0.095 (1.022)	0.121 (1.302)	61 (20)	4,789
8710	2	0.170 (1.829)	0.295 (3.174)	40 (38)	4,686
8711	1	0.050 (0.538)	0.068 (0.732)	37 (7)	2,141
8801	4	0.105 (1.130)	0.158 (1.700)	63 (31)	4,791
8802	3	0.075 (0.807)	0.098 (1.054)	50 (12)	3,579
8803	3	0.130 (1.399)	0.148 (1.592)	108 (44)	8,482
8804	4	0.115 (1.237)	0.137 (1.474)	16 (6)	750
8805	5	0.170 (1.829)	0.237 (2.550)	110 (74)	8,881
8901	1	0.055 (0.592)	0.074 (0.796)	30 (1)	6,828
8854	3	0.070 (0.753)	0.105 (1.130)	19 (6)	2,022
8861	3	0.080 (0.861)	0.103 (1.108)	39 (8)	3,601
9301	3	0.095 (1.022)	0.129 (1.388)	35 (7)	2,605
9401	2	0.060 (0.646)	0.118 (1.270)	20 (12)	1,287
9501	2	0.095 (1.022)	0.106 (1.141)	9 (3)	169
9601	2	0.080 (0.861)	0.121 (1.302)	21 (8)	3,072
9801	2	0.080 (0.861)	0.093 (1.001)	23 (4)	929

TABLE 3. Project Attributes for Formwork (Db5) and Structural Steel (Db6)

Project number (1)	WC rating (2)	Baseline productivity (3)	Cumulative productivity (4)	Total workdays (abnormal) (5)	Total work hours (6)
(*a*) Concrete formwork (Db5)					
8603	1	0.043 (0.463)	0.076 (0.818)	35 (18)	1,145
8703	3	0.185 (1.991)	0.368 (3.960)	148 (135)	21,276
9102	3	0.115 (1.237)	0.152 (1.636)	64 (41)	3,089
9104	1	0.052 (0.560)	0.055 (0.592)	23 (1)	2,523
9105	2	0.040 (0.430)	0.065 (0.699)	42 (4)	849
9106	3	0.114 (1.227)	0.135 (1.453)	40 (19)	1,905
9502	2	0.070 (0.753)	0.123 (1.323)	265 (149)	25,682
9601	3	0.103 (1.108)	0.102 (1.162)	106 (6)	2,018
(*b*) Structural steel erection (Db6)					
8601	3	1.114	1.73	25 (11)	1,109
8602	4	1.538	1.82	29 (7)	902
8701	3	1.788	3.03	37 (33)	1,096
8702	3	1.022	1.32	22 (7)	526
8704	1	1.905	1.77	5 (3)	152
8801	3	1.092	1.36	28 (6)	998
9001	4	1.546	2.20	21 (8)	891
9101	2	1.244	1.50	12 (5)	544
9102	5	1.867	3.06	24 (14)	889
9201	3	2.230	3.44	47 (41)	3,040
9302	2	1.094	1.45	21 (4)	768

sequencing, lack of materials, etc. This observation leads to the following hypothesis:

> Hypothesis 1—Projects that have good labor performance based on the cumulative productivity also exhibit minimal variability in daily productivity values. Poorly performing projects have high variability. Good and poorly performing projects can be differentiated by the variability in unit productivity values.

This hypothesis is consistent with the statistical approaches used in total quality management, where parameter variation is a measure of consistency and quality. This hypothesis is evaluated numerically later in this paper through the use of disruption indices (DIs).

Baseline Productivity and WC

Disruptions adversely affect labor productivity. It follows that periods where the productivity is best (lowest numerical value) coincide with little or no disruptions. This baseline productivity represents the best performance a contractor can achieve on a particular project. In all but extreme cases, the baseline productivity is unaffected by disruptions.

In studying the projects in Db1, an important hypothesis emerged:

> Hypothesis 2—The baseline productivity is a function of the complexity of the design or WC. As the WC increases (more complexity), the baseline productivity also increases (worsens).

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This hypothesis was tested using the projects in Db1. The baseline for each project was calculated using the following steps:

1. Determine 10% of the total workdays.
2. Round this number to the next highest odd number; this number should not be less than 5. This number n defines the size of (number of days in) the baseline subset.
3. The contents of the baseline subset are selected as the n workdays that have the highest daily production or output.
4. For these days, make note of the daily productivity.
5. The baseline productivity is the median of the daily productivity values in the baseline subset.

Fig. 1 illustrates the workdays used in determining the baseline productivity for Project 8802. As seen, the workdays need not be consecutive. From the knowledge base, Project 8802 was well managed, and this is evident from the daily productivity variability. For this project, using more than 10% of the workdays to define the baseline subset would have little effect on the baseline productivity. However, on more disrupted projects, using more than 10% could distort the baseline productivity value. Thus, 10% is chosen as a reasonable percentage to demonstrate the contractor's ability.

A WC scale ranging from 1–5, with 5 being the most complex, is proposed. The criteria are given in Table 4. Each project was evaluated according to the criteria in Table 4. The baseline productivity and WC values are given in Table 2 and are plotted in Fig. 2. Except for the last project (Project 8710), these data support Hypothesis 2 and the WC scale in Table 4. To mathematically test Hypothesis 2, a linear regression model was developed. The equation and relevant statistics are given below. The t-statistics are given in parentheses below the computed values.

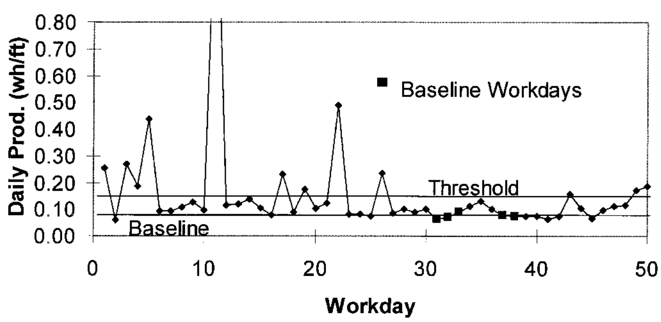

FIG. 1. Daily Productivity of Project 8802 Showing Baseline Productivity and Threshold for Defining Abnormality

TABLE 4. Proposed WC Scale for Masonry, Db1

WC scale (1)	Description (2)
1	Long straight walls, many greater than 8 m (25 ft) in length; considerable scope of work for each layout; few openings
2	Facades with ordinary window and door openings; openings tend to be at regular intervals, thus minimizing need for different layouts
3	Facades with numerous window or door openings; numerous short, straight walls less than 8 m (25 ft); some ornamental work may be necessary
4	Interfacing with structural steel frame, numerous cutting of masonry units; some poor design details, walls consisting of multiple size units; extensive ornamental work, some corners not 90°
5	Numerous corners and walls not at 90°; many walls consisting of multiple size units; minimal consistent scope of work

$$\text{Baseline productivity (wh/ft}^2) = \underset{(4.84)}{0.045} + \underset{(4.58)}{0.016}\ \text{WC} \quad (1)$$

$$r_a^2 = 0.50$$

$$F\text{-ratio} = 20.9$$

$$n = 21$$

In developing (1), two outliers (Projects 8710 and 8805) were excluded. The statistics indicate that this model is satisfactory. The estimated baseline productivity is also shown in Fig. 2 and Table 5.

The last project in Fig. 2 (Project 8710) is worthy of discussion. From the knowledge base, this project experienced significant problems with material management. The superintendent had little experience in supervising masonry construction, and there were other problems as well. On the best of days, the performance of this project never even approached that of the other projects. These observations lead to a third hypothesis:

> Hypothesis 3—Where a project is subject to many disruptions, the baseline productivity will be considerably worse than the estimated baseline productivity, and the project is said to have experienced the ripple effect.

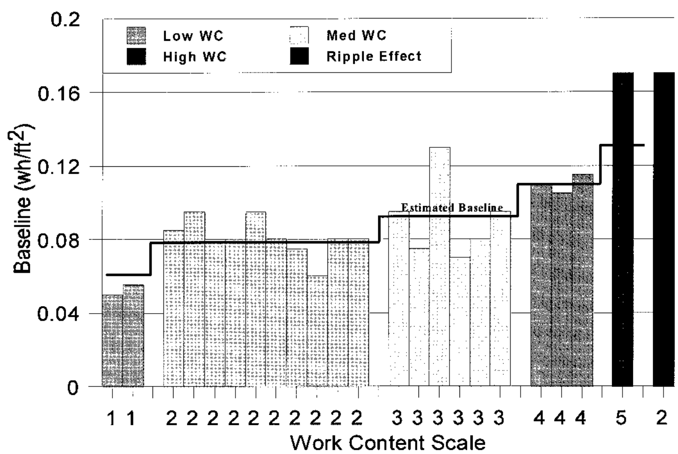

FIG. 2. Baseline Productivity versus WC, Database Db1 (Masonry)

TABLE 5. Estimated Baseline and Threshold Values for Defining Abnormal Workdays, Db1

WC scale (1)	Estimated baseline (2)	Threshold for defining abnormal workdays (3)
	(*a*) Masonry (Db1) [wh/ft^2 (wh/m^2)]	
1	0.061 (0.656)	0.122 (1.313)
2	0.078 (0.839)	0.139 (1.496)
3	0.094 (1.011)	0.155 (1.668)
4	0.110 (1.184)	0.171 (1.840)
5	0.127 (1.367)	0.188 (2.023)
	(*b*) Concrete formwork (Db5) [wh/ft^2 (wh/m^2)]	
1	0.041 (0.441)	0.082 (0.882)
2	0.074 (0.796)	0.115 (1.237)
3	0.107 (1.151)	0.148 (1.592)
4	0.140 (1.506)	0.181 (1.948)
5	0.173 (1.861)	0.214 (2.303)
	(*c*) Structural steel (Db6) (wh/pc)	
1	0.760	1.520
2	1.007	1.767
3	1.254	2.014
4	1.501	2.261
5	1.748	2.508

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The term ''ripple effect'' refers to a highly disrupted project where the work of a crew is affected daily, often by the work of others, and the loss of productivity cannot be related to a specific event. When projects experience the ripple effect, the baseline subset will contain workdays that are disrupted.

Number of Abnormal Workdays

It follows from Hypothesis 1 that high variability in daily productivity is associated with poor labor performance. Thus, an important performance attribute is the number of abnormal or disrupted workdays. The question is: how is an abnormal workday defined? Experience in studying daily labor productivity on many good and poorly performing projects indicates that the random variability in daily productivity values in the absence of disruptons is about twice the baseline productivity. Values exceeding this limit are almost always the result of assignable causes, i.e., disruptions. If the baseline productivity for WC = 1 is 0.656 wh/m^2 (0.061 wh/ft^2), then the range of random variability is up to 1.313 wh/m^2 (0.122 wh/ft^2). As the WC increases, the threshold value for defining abnormality also increases. The threshold values are summarized in Table 5. The threshold for Project 8802 is 1.668 wh/m^2 (0.155 wh/ft^2) and is seen in Fig. 2.

Project Performance Parameters

Selected individual project attributes are used to calculate project performance parameters. These parameters are the DI and the project management index (PMI).

DI

The DI measures the variability within a single project. It is a measure of the extent to which the project experienced abnormal workdays. The following definition is applied:

$$\mathrm{DI} = \frac{\text{Number of disrupted workdays}}{\text{Total number of workdays}} \tag{2}$$

The value of DI ranges from 0.0 to 1.0. The higher the DI, the more the project experienced abnormal workdays. The DIs for the projects in Db1 are shown in Fig. 3. Overall, the DI results are consistent with known observations and data collected at each site and support Hypothesis 1.

PMI

The cumulative productivity includes influences from design and project management. However, the influence of design is determined from (1) and can be subtracted to yield a measure of the influence of project management. This measure is the PMI, which is defined mathematically in (3)

$$\mathrm{PMI} = (\text{Actual cumulative production} - \text{Estimated baseline productivity}) \div \text{Database baseline productivity}_{(\mathrm{WC}=1)} \tag{3}$$

The PMI is a dimensionless parameter that reflects the contribution of project management to the cumulative labor performance on the project. The lower the PMI, the better the influence project management had on overall labor performance. Higher numbers are indicative of poor labor performance.

The PMI values for each project in Db1 are also summarized in Fig. 3. The results were evaluated against the knowledge base for each project. For instance, it is known that Projects 8704 (No. 5), 8710 (No. 9), 8801 (No. 11), 8803 (No. 13), and 8805 (No. 15) were poorly managed, and the PMI values in Fig. 3 are consistent with this knowledge. These projects also showed high variability in the daily productivity graphs. Projects 8702 (No. 3), 8706 (No. 6), 8707 (No. 7), 8711 (No. 10), 8802 (No. 12), 8901 (No. 16), 8854 (No. 17), and 8861 (No. 18) show good performance in Fig. 3 and also had low variability in daily productivity.

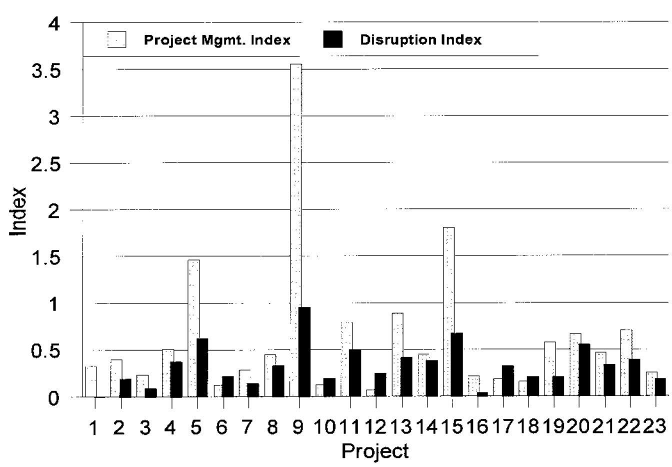

FIG. 3. DIs and PMIs, Database Db1 (Masonry)

SINGLE DATABASE EVALUATION

During the evaluation of database Db1, it was observed that the variability in the baseline productivity within a single database was affected by the misuse of technologies, variations in craft skills, and the quality of site management. As a measure of the variability in the baseline measurements, an average error of estimation was calculated. The average error of estimation is the average value of the residuals. The residual is the absolute difference between the estimated baseline productivity for each project using the regression equation (Table 5) and the actual baseline productivity. The average error of estimation is calculated using (4)

$$\text{Average error of estimation} = \frac{\sum |\text{Estimated baseline} - \text{Actual baseline}|}{\text{No. of projects}} \tag{4}$$

For the projects in Db1 (excluding Projects 8710 and 8805), the average error of estimation was computed to be 0.118 wh/m^2 (0.011 wh/ft^2). Because the average error is a function of the absolute value of the baseline productivity and is comparable with other databases only if the database baseline values are the same, the coefficient of variation (CV) is calculated in (5)

$$\mathrm{CV} = \frac{\text{Average error of estimation}}{\text{Estimated productivity baseline}_{(\mathrm{WC}=3)}} \times 100 \tag{5}$$

The CV for masonry was calculated as 11.5. This value will be used to compare Db1 with other databases.

EVALUATION OF OTHER DATABASES

The hypotheses presented above were tested using two other databases consisting of concrete wall formwork (Db5) and structural steel (Db6). These evaluations are detailed below.

Concrete Wall Formwork, Db5

Database Db5 contains concrete wall formwork data from eight projects constructed in and around State College, Pa. Pertinent data are found in Table 3. The knowledge base revealed that one was known to have experienced significant deficiencies in material management, housekeeping, and safety. Several were also well managed. Three of the projects

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were underground parking garages where the slabs were constructed on a slope. Several projects also had significant amounts of wall penetrations, i.e., doors and pipe sleeves, and blockouts, i.e., corbels, ledges, and pilasters. The design on two projects was very simple.

Determine Project Attributes

The variability of the daily productivity values was examined visually, and the results support Hypothesis 1, which states that good and poorly performing projects can be differentiated by the variability in the daily productivity values.

To determine the WC rating, each project was rated on a scale of 0–5 for eight factors pertaining to the work complexity. The factors are listed in Table 6. The rating is based on the linear footage of the wall affected by the factor compared with the total footage of the wall. The following scale was proposed for determining the rating: <5%—rating = 0, 5–14%—rating = 1, 15–30%—rating = 2, 31–50%—rating = 3, >50—rating = 4, and severe or unusual—rating = 5. The rating of 5 is reserved for extreme conditions associated with irregularities in size, shape, and complexity. The rating for each factor was multiplied by a weighting factor to yield a score for that factor. The weighting factors are also given in Table 6. The sum of the eight individual scores yields a total score. The larger the score, the greater the WC or the more complex the project. The WC rating is based on the following score: score 0–10, WC rating = 1; score 11–25, WC rating = 2; score 26–40, WC rating = 3; score 41–55, WC rating = 4; and score >56, WC rating = 5.

The baseline productivity was also determined as described earlier, and the relationship between the baseline productivity and WC for formwork is shown in Fig. 4. The concrete formwork data in Db5 supports Hypothesis 2, that the baseline productivity is a function of the complexity of the design or WC.

A regression model was developed excluding Project 8703. The following relationship resulted. The estimated baseline values are also shown in Fig. 4 and Table 5.

$$\text{Baseline (wh/ft}^2) = \underset{(0.56)}{0.008} + \underset{(5.40)}{0.033}\ \text{WC} \quad (6)$$

$$r_a^2 = 0.83$$

$$F\text{-ratio} = 29.2$$

$$n = 7$$

The variability in the eight baseline productivity values was determined not to be related to technology issues. For instance, on three projects (Projects 8603, 9104, and 9105), hand set forms were used and the technology seemed appropriate in each instance. On two other projects (Projects 9102 and 9106), steel panel forms were used. These were among the more complex projects, and the technology also seemed correctly applied. The effect of the steel panels on these two projects appears to be minimal. However, five projects (Projects 8703, 9102, 9104, 9106, and 9502) were done by general contractors, and three projects (Projects 8603, 9105, and 9601) were done by specialty contractors. The latter three projects were all better than the estimated baseline productivity. It would appear that management and craft skills may be more of a determining factor leading to the variability in Db5. These observations lead to another hypothesis:

> Hypothesis 4—The variability in individual project baseline productivity values in a single database is related to the correct use of technologies, and variable craft and project management skills.

The average error of estimation was calculated as 0.108 wh/m^2 (0.010 wh/ft^2), and the CV was calculated as 9.3. Project

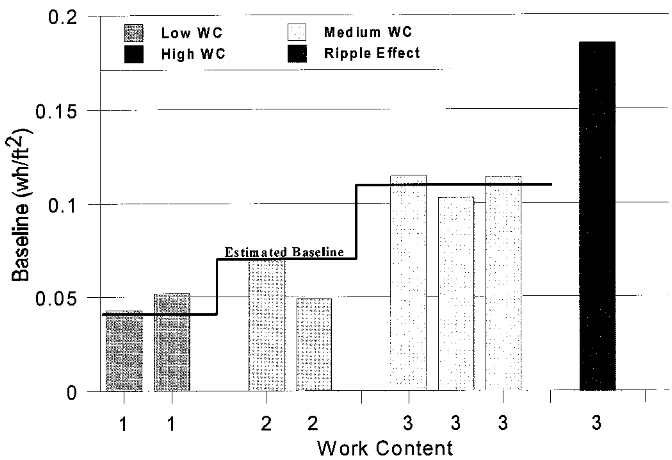

FIG. 4. Baseline Productivity versus WC, Database Db5 (Concrete Wall Formwork)

TABLE 6. Proposed WC Factors and Rating, Concrete Formwork, Db5

Factor/weighting factor (1)	Description (2)	How determined (3)
Sloped walls and irregular heights (excluding boxouts); weight = 2	Walls supporting slabs on slope; wall heights that are variable (variable heights constructed using besets are not included in this factor) that require dimensions of panel to be altered	Linear footage of wall affected
Panel modifications: pilasters, corbels, ledges, variable width, etc.; weight = 2	Details requiring planar face of panel to be modified	Linear footage of wall affected
Numerous sizes and shapes, curved walls; weight = 2	Relates to need to construct and stockpile numerous sizes and shapes, includes curved walls	Linear footage of wall affected
Finish requirements limiting reuse of panels; weight = 1	Higher than normal finish requirements that limit reuse of panels	Use rating of 0 for underground work where finish is of no concern, 1 for normal, exposed finish, and higher rating where greater or unique architectural finishes are specified
Boxouts, penetrations, pipe sleeves; weight = 2	Penetrations, door and window openings that do not require modification to the panel face	Linear footage of wall affected
Restricted access: tight quarters, exterior walls; weight = 4	Tight spaces with less than 3 m (10 ft) of space in which to operate and exterior walls	Linear footage of wall affected
Integral columns; weight = 3	Columns that are integrated into wall that require change in formwork width	Linear footage of wall affected
Alignment tolerances; weight = 4	Tolerances that are greater than normal industry practice	Linear footage of wall affected

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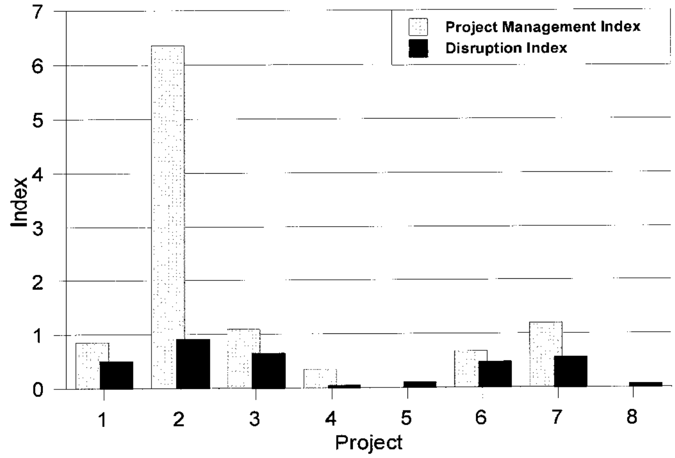

FIG. 5. DIs and PMIs, Database Db5 (Concrete Wall Formwork)

8703 was excluded in this calibration because the knowledge base showed this to be a highly disrupted project.

Calculate Project Performance Parameters

The criteria for abnormal workdays is given in Table 5. Fig. 5 summarizes the disruption indices. For Db5, the DI correctly identified the best and the poorest performing projects. This information is consistent with the knowledge about each project. As with Db1, the data support Hypothesis 1. The PMIs are also shown in Fig. 5. The best and worst performing projects are correctly identified. It was observed that generally, the best projects were performed by specialty contractors, and the poorer performing projects were performed by the general contractors.

STRUCTURAL STEEL ERECTION, Db6

Database Db6 contains daily productivity data on 11 projects involving structural steel erection. Pertinent statistics are found in Table 3. One project (Project 8704) lasted only 5 days and consisted of less than 100 pieces of steel. Two of the nine remaining projects (Projects 8701 and 9201) were poorly managed, but several others were well managed. The character of the buildings varied. Most were multistory buildings requiring both meticulous vertical and horizontal alignment. One project (Project 9102) was a 35-story building. Two structures (Projects 9101 and 9302) were single-story, post and beam construction with web joists and roof deck. One of these single-story projects was rather complex with a sloped roof, wind screen, many small, uniquely sized pieces, and moment connections. Of the multistory buildings, one had precast slabs (Project 8602). The erection of the slabs needed to be integrated with the steel erection. All other buildings had slabs of joist, deck, and concrete construction.

Technology is not a significant factor in steel erection as there are limited choices relative to the way steel is erected. On most projects, one truck-mounted crane was used with boom sizes ranging from 18.3 to 30.5 m (60 to 100 ft). A greater factor influencing the labor performance of steel erection is the skill of the craftsmen, particularly the foreman. Six of the projects were known to have been performed by specialty contractors, whereas two others (Projects 8701 and 8704) were known to have been performed by a prime contractor. These latter two projects were two of the worst three projects in the database. On both of these projects, there seemed to be lack of familiarity with steel erection. On one project (Project 8701), there was considerable difficulty in vertical alignment.

Determine Database Attributes

The variability of the projects was evaluated, and it was determined that as per Hypothesis 1, the worst performing projects showed higher variability than the better performing projects.

Each project was categorized according to its WC using the scale described in Table 7. The baseline productivity was determined and is shown in Fig. 6. Some variability is noted. This may be partly a function of the skill of the contractor because the three projects with WC = 3 were done by specialty contractors. Each is below the estimated baseline productivity. The two prime contractors are above the estimated baseline. Thus, there is additional support for Hypothesis 4. Another factor to consider is that some of the projects experienced fabrication errors. Three of the four are worse than the estimated baseline. Nevertheless, the data tend to be supportive of Hypothesis 2: That the baseline is a function of design complexity or WC.

A linear regression model (excluding Projects 8701, 8704, and 9201) was developed and resulted in the following:

TABLE 7. Proposed WC Scale for Structural Steel, Db6

Scale (1)	WC (2)	Description (3)
1	Low WC	Pre-engineered, light, single-story structures; post and beam construction; flat root construction; minimal alignment tolerances
2	Low to medium	Engineered single-story structures; post and beam construction; flat roof construction using joists and decking or precast decking; ordinary vertical alignment tolerances required
3	Medium WC	Multistory structures requiring meticulous vertical and horizontal alignment; joist and decking construction for floors and roof
4	Medium to high	Multistory structures requiring meticulous vertical and horizontal alignment; floor and roof construction requiring interfacing with steel erection (i.e., precast floors); architectural details requiring installation of uniquely sized pieces
5	High WC	Multistory structures greater than 10 stories requiring meticulous vertical and horizontal alignment; extensive floor and roof construction interfaced with steel erection (i.e., precast floors); extensive architectural details requiring uniquely sized pieces; welded and moment connections; larger diagonal bracing

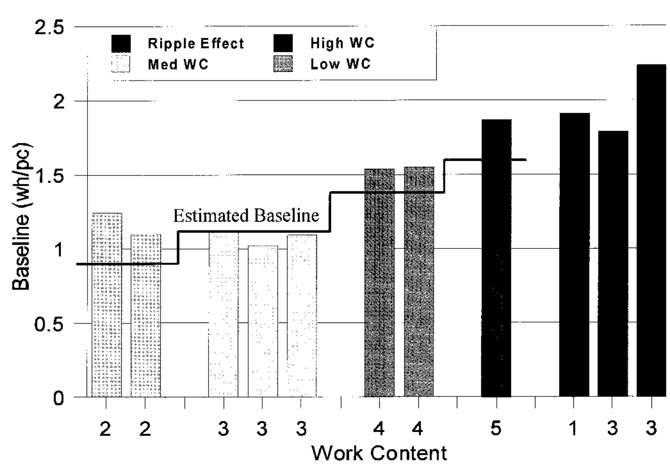

FIG. 6. Baseline Productivity versus WC, Database Db6 (Structural Steel Erection)

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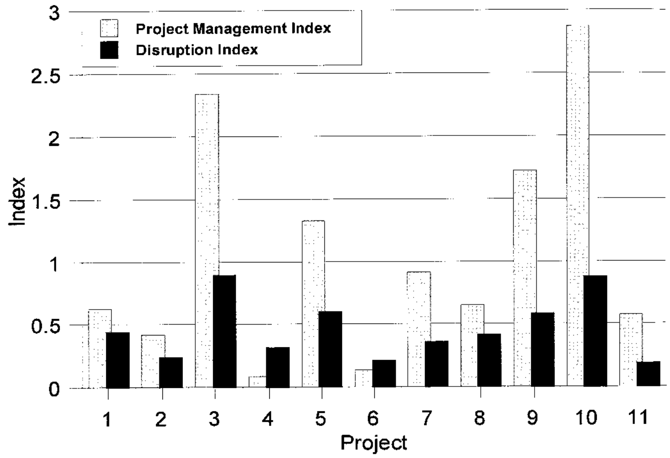

FIG. 7. DIs and PMIs, Database Db6 (Structural Steel Erection)

$$\text{Baseline (wh/pc)} = \underset{(2.38)}{0.513} + \underset{(3.89)}{0.247}\ \text{WC} \tag{7}$$

$$r_a^2 = 0.67$$

$$F\text{-ratio} = 15.1$$

$$n = 8$$

The estimated baseline productivity values using (7) are summarized in Table 5.

The average error of estimation was computed (excluding Projects 8701, 8704, and 9201) as 0.132 wh/pc, and the CV was calculated to be 10.6.

Calculate Project Performance Parameters

Other parameters describing each project are included in Table 3. The DI values were calculated and are summarized in Fig. 7. The DI values correctly identified the three worst projects. Thus, these data support Hypothesis 4. The PMI values are also shown in Fig. 7. The PMI correctly identified the worst three projects and the two best projects. All projects are consistent with the knowledge-base information about the projects.

DATABASE COMPARISONS

This section compares the masonry (Db1), wall formwork (Db5), and structural steel (Db6) databases. The goal of these comparisons is to evaluate the various hypotheses that have been presented and to determine if there is consistency between the various activities.

Data Variability

Hypothesis 1 stated that it was possible to differentiate good and poorly performing projects by the variability of the daily productivity values. All 42 projects, which included both good and poorly performing projects, were visually evaluated, and no reason was found to reject Hypothesis 1. Hypothesis 1 was analytically evaluated using the DIs. As the performance degraded, the DI worsened (increased). Thus, the DI results add further support for Hypothesis 1.

Baseline Productivity

Hypothesis 2 stated that the baseline productivity was a function of the complexity of the design. As the WC increases, the baseline productivity worsens. The relationship between the baseline productivity and the WC for each database is shown in Figs. 2 (masonry), 4 (wall formwork), and 6 (structural steel). Regression models were developed to describe the relationship in each database. The model statistics, particularly the t-statistics and the F-ratio, showed strong relationships for each database. The r_a^2 ranged from 0.50 to 0.83. This parameter is not considered a particularly reliable indicator because the slope of the regression models is relatively small. Each database shows trends that support Hypothesis 2. These data show a twofold or more increase in the baseline productivity from low (WC = 1) to high (WC = 5) complexity. Even though the analysis is somewhat limited by the lack of observations in the lower and higher WC categories, there is no reason to reject Hypothesis 2.

Hypothesis 4 stated that the variability in baseline productivity values in a single database is related to a number of factors, including the correct use of technologies, and variable craft and management skills. The variability within the three databases was compared by computing the CV. The CV values were 11.5 for masonry, 9.3 for formwork, and 10.6 for structural steel. The labor-intensive activity (masonry) had the highest variability. For wall formwork and structural steel, the specialty contractors performed better than the prime contractors, suggesting that craft and management skills affected the variability. Technological issues were not a factor in the three activities. Although only three databases are included in the assessment of Hypothesis 4, no reason to reject Hypothesis 4 was identified.

Ripple Effect

Hypothesis 3 stated that the baseline productivity is affected by the presence of many disruptions, i.e., the ripple effect. This effect was evaluated using graphs of the DI versus PMI. In all three databases, a nonlinear relationship began at a DI in the range of approximately 0.40–0.60. The data for the three databases were combined and are plotted in Fig. 8. These data show strong support for Hypothesis 3.

DI

The DI was evaluated as a performance indicator. The DI generally identified the worst and best performing projects for all three databases. The cumulative probability distributions were computed for all three activities and are shown in Fig. 9. These showed similar trends. The median DI values (50th percentile) are 0.30, 0.48, and 0.39 for masonry, concrete formwork, and structural steel, respectively. The median concrete formwork project experienced more disruptions than the median masonry or structural steel project. This observation is consistent with the relative complexity and variety of formwork construction and the need to coordinate with other trades,

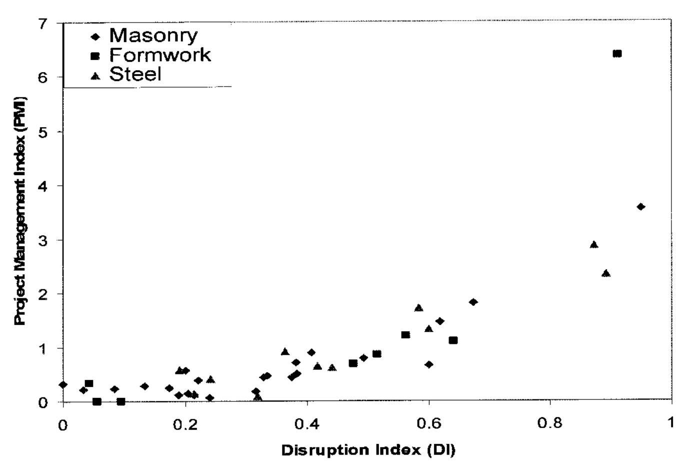

FIG. 8. PMIs versus DIs, Databases Db1, Db5, and Db6

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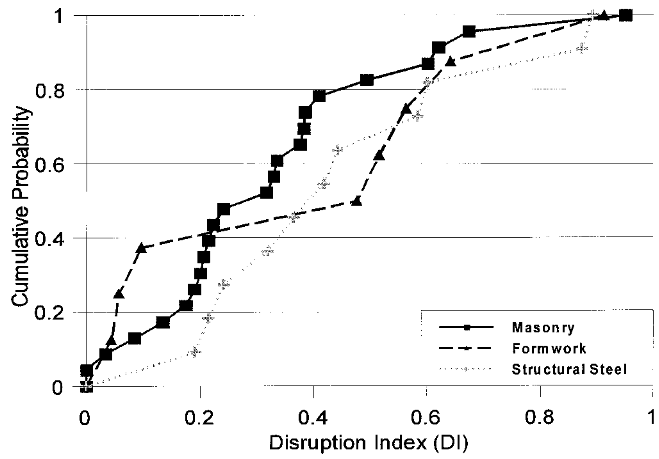

FIG. 9. Cumulative Probability Distribution of DI

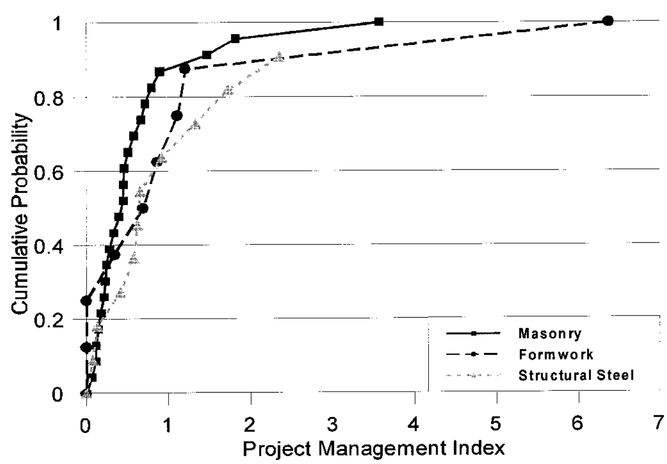

FIG. 10. Cumulative Probability Distribution of PMI

mainly ironworkers. Frequently, the formwork activity may have to share crane service.

PMI

The PMI was also evaluated as a performance indicator. The PMI correctly identified the worst and best performing projects for all three activities. The order of the projects from best to worst is consistent with the knowledge of the projects. The cumulative probability distributions are shown in Fig. 10. The trends are similar. The median PMI values (50th percentile) are 0.42, 0.68, and 0.63 for masonry, concrete formwork, and structural steel, respectively. Fig. 10 shows that the median formwork and steel projects were more adversely affected by management than was masonry. This is intuitively correct for formwork because there are more requirements for coordination. The structural steel work may be affected by craft skills and fabrication errors.

CONCLUSIONS

Variability in the daily productivity data was found to be an important delineator between good and poorly performing projects in all three databases (a total of 42 projects). Poorly performing projects have much higher variability than do projects that perform well.

The baseline productivity was found to be a function of the design complexity in all three databases. A WC scale was proposed for each activity, and this scale was found to model satisfactorily the relationship between the baseline productivity and the complexity of the design. The r_a^2 values range from 0.50 to 0.83. The relationship between the baseline productivity and the WC was found to be more pronounced for concrete formwork than the other activities. This finding is intuitively correct because of the need to integrate technology with high craft and management skills and to apply these to a more diverse WC.

The CV was calculated to measure the variability in the baseline-WC relationship. The CV for masonry, formwork, and structural steel was calculated as 11.5, 9.3, and 10.6, respectively. It is hypothesized that where technologies are incorrectly applied or where there is a wide range of craft skills, there is greater variability in the baseline productivity. A lower CV indicates a more consistent application of technologies and craft skills.

The DI and PMI were found to have correctly identified the best and worst performing projects. Both are considered to be reliable indicators of project performance. The ratings were very consistent with the knowledge-base information about each project. The relationship between the PMI and DI was investigated and found to consistently identify those projects subject to the ripple effect.

The cumulative probability plots showed consistent trends, but also showed distinct characteristics for each database. The median DI values showed that concrete formwork was more prone to disruptions than was masonry and structural steel. Concrete formwork had the highest PMI, indicating that on average, concrete formwork may be more difficult to manage.

APPENDIX I. DEFINITIONS

- Baseline productivity—The baseline productivity is based on the 10% of workdays that have the highest production (output). When describing a project, the project baseline is the best and most consistent productivity that the contractor achieved on that project. When used to describe a database, the database baseline is the best baseline productivity that was achieved for that database. In almost all cases, the baseline productivity is unaffected by disruptions.
- DI—The DI is the ratio of the number of disrupted workdays divided by the total number of workdays.
- Labor productivity—The work hours required to perform items of work divided by the quantity of work performed. The higher the labor productivity, the worse the performance.
- PMI—The PMI is a normalized measure of the management influence on the total cumulative productivity for a project. Mathematically, the PMI eliminates the productivity influence of complex designs.
- Ripple effect—A phenomenon describing a highly disrupted project where the work of a crew is affected daily, often by the work of others. In this case, the baseline productivity, even on days where there are no reported disruptions, is measurably worse than would be expected. When the ripple effect is present, the baseline subset contains workdays that are disrupted.
- WC—A term referring to the complexity of the design. A component with a higher WC is more complex to construct than a component with a lower WC.

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APPENDIX II. REFERENCES

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