Modeling the Variability of Labor Productivity in Masonry Construction

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ABSTRACT

This paper proposes a methodology to model the variability of masonry labor productivity. The theoretical basis of baseline productivity relied upon the analysis of 14 projects sharing similar exogenous conditions and being similar in scope, size of components, specifications, quality requirements and design features. The data were collected using standardized data collection procedures that focused on task-level labor productivity; specifically, the measurement of work accomplished by a single crew in a single shift. Analysis showed that when daily productivity values fall between the control limits, loss of productivity is within normal variation while daily productivity values falling above the upper control limit imply a loss of productivity that is due to the work environment factors as within the normal variation, and in particular to certain significant influential factors that can be cited during that day. These results could have significant implications for construction managers seeking to improve overall project performance.

KEYWORDS: Variability, Baseline productivity, Masonry construction, Work environment factors, Jordan.

INTRODUCTION

Productivity is one of the most important factors affecting the overall performance of any organization, whether large or small. The construction sector has a strategic role in developed and developing countries, employing more than 7% of Europe's work force, the sector is the largest industrial employer in the continent (Proverbs et al., 1999). Similar to Europe, construction industry accounts for some 14% of the gross national product and about 8% of total employment in the US (Thieblot, 2002). The construction industry also involves a large number of variables; the labor intensive work, the unique character and the occurrence of unpredictable events (Choromokos and McKee, 1981; Arditi and Mochtar, 2000; Thomas and Yiakoumis, 1987; Thomas et al., 1990; Horner and Talhouni, 1995; Kaming et al., 1997; Ng et al., 2004; Gulezian and Samelian, 2003; Zayed and Halpin, 2004; Abdel-Razek et al., 2006).

Therefore, the construction process results in relatively high costs (Gambao et al., 2000) and labor becomes a more important input in the production phase. Moreover, the labor cost is somewhere between 20% and 50% of the total project cost (Buchan et al., 1993; Zakeri et al., 1997; Kaming et al., 1998) and the reduction of these costs can be best carried out by improving productivity (Kaming et al., 1998).

In addition, factors affecting productivity may vary from task to task. Although some factors could have

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similar influences on the productivity of a number of tasks, their rate of impact on productivity may vary (Sonmez and Rowings, 1998). The assignment decisions of resources such as labor, equipment and material control the overall duration and cost of a project (Hegazy, 1999). Construction productivity is traditionally identified as one of the three main critical success factors together with cost and quality for a construction project (Nkado, 1995; Walker, 1995). The application of productivity rate which is an indicator of the construction time performance is in the scope of planning and scheduling of the construction, controlling of the cost and worker performance, estimating and accounting.

Labor productivity estimates are often performed by individuals using combinations of analytical techniques and personal judgment (Portas and AbouRizk, 1997); namely, the worker hour estimates are usually obtained through direct interaction with a scheduler, the site manager or related sub-contractors who are knowledgeable enough to reflect the actual conditions of a project and its constituent activities (Arditi et al., 2001). These individuals often have a library of basic productivity rates which are adjusted and recalculated for each project (Proverbs et al., 1998), and always modify their productivity rates for each specific estimate (Christian and Hachey, 1995). On the other hand, differences in these productivity rates are always likely and normal (Kazaz and Ulubeyli, 2004).

Many articles have described, in general terms, the variation in labor productivity and the evidence of complex variability in construction labor productivity (Radosavljević and Horner, 2002), the decline in construction labor productivity (Rojas and Aramvareekul, 2003), trends in construction lost productivity claims (Klanac and Nelson, 2004), benchmarking of construction productivity (Park et al., 2005) and explaining labor productivity differentials (DiGiacinto and Nuzzo, 2006). However, few articles discussed quantitative issues relating the loss of productivity.

The primary objective of this paper is to model the variability of masonry labor productivity. This will be done by analyzing a database consisting of 14 masonry projects to present the theoretical basis of baseline productivity measurements. After the baseline productivity is defined, two major categories of variables that influence labor productivity are introduced: nature of work to be done and work environment factors. The macro-effects of work environment factors on a project as a whole, rather than a specific work activity, are quantified. Due to the difficulty associated with accurately estimating, measuring and predicting a project's labor productivity, quantifying these effects is a significant challenge. Labor is a large portion of the total construction cost and represents the most significant risk to contractors. The completion of this study has led to increased understanding of the impact of work environment factors on productivity and the model described here can assist owners, construction managers, general contractors and specialty contractors to focus their efforts in order to improve labor efficiency.

RESEARCH METHODOLOGY

This research proposes a framework for developing a method to model the variability of masonry labor productivity. Single projects are evaluated by using various project attributes extracted from the data. The following sections present a framework for developing a methodology to assess labor productivity loss in masonry construction.

Data Collection and Processing

Fourteen numerical databases consisting of labor productivity measurements of masonry are used for this theoretical development. Many externalities influence the complexity of the conversion process associated with construction. To reduce this complexity, 14 projects were selected in Amman, Jordan sharing similar exogenous conditions, including: government regulations, economic conditions and sociological and cultural factors. The data were collected using standardized data collection procedures where each project was assigned a 4-digit number, the first 2 digits relating to the year and the last two digits to the project number.

Table (1): Work content scale for masonry (Modified from Thomas and Zavrski, 1998).

Scale	Work Content	Description
1	Low Work Content	Long, straight walls, many greater than 25 ft in length (8m); considerable scope of work for each layout; few openings.
2	Low to Medium	Brick facades with ordinary window and door openings. The openings tend to be at regular intervals, thus minimizing the need for different layouts; reinforced masonry walls; considerable scope of work for each layout.
3	Medium Work Content	Brick facades with numerous window and door openings; numerous short (less than 25 ft) but straight walls; some ornamental work may be required.
4	Medium to High	Interfacing with structural steel structure; numerous cutting of masonry units; some poor design details; walls consisting of multiple size units; extensive ornamental work; some corners are not at 90/.
5	High Work Content	Numerous corners not at 90/; most walls consist of multiple size masonry units; minimal consistent scope of work.

The data collection focused on task-level labor productivity; specifically, the measurement of work accomplished by a single crew in a single shift. Data collection also documented factors that may affect the work of each crew. Measurements were made once daily at the end of the workday, in order to avoid the continuous on-site presence of the researcher. In addition to the practicality of using a day-long unit of time for measurement purposes, the data collection scheme limited the potential impact of the Hawthorne effect that might arise as a consequence of researcher interference during the work day.

A Work Content (WC) scale for the selected construction activity was proposed. Work content is a non-mathematical term referring to the complexity of the design, where the integers from 5 to 1 represent activity complexity in descending order (5 being the most complex, 1 the least complex). Masonry activity that contained both simple and more complex work was ranked based on the complexity of the work content as a whole. Table (1) demonstrates the work content scale for masonry, where the work performed in all fourteen projects was similar in scope, size of components, specifications, quality requirements and design features and was ranked as a low work content of 1 (the least complex).

The data-collection process assured to the greatest possible extent that consistent data were collected, processed and converted to a standard of 20 mm x 20 mm x 40 mm concrete masonry units (Thomas and Raynar 1997). The daily productivity is defined as the work hours per unit of work. It is based on the equivalent quantities and is calculated as follows:

$$\text{Daily Productivity}_t = \frac{\text{Work hours}_t}{\text{Equivalent Quantities}_t}$$

Where t = the time period (e.g., one day), Figures (1), (2) and (3) show plots of the variability in daily productivity for all 14 projects, while their frequency distributions are shown in Figures (4) and (5).

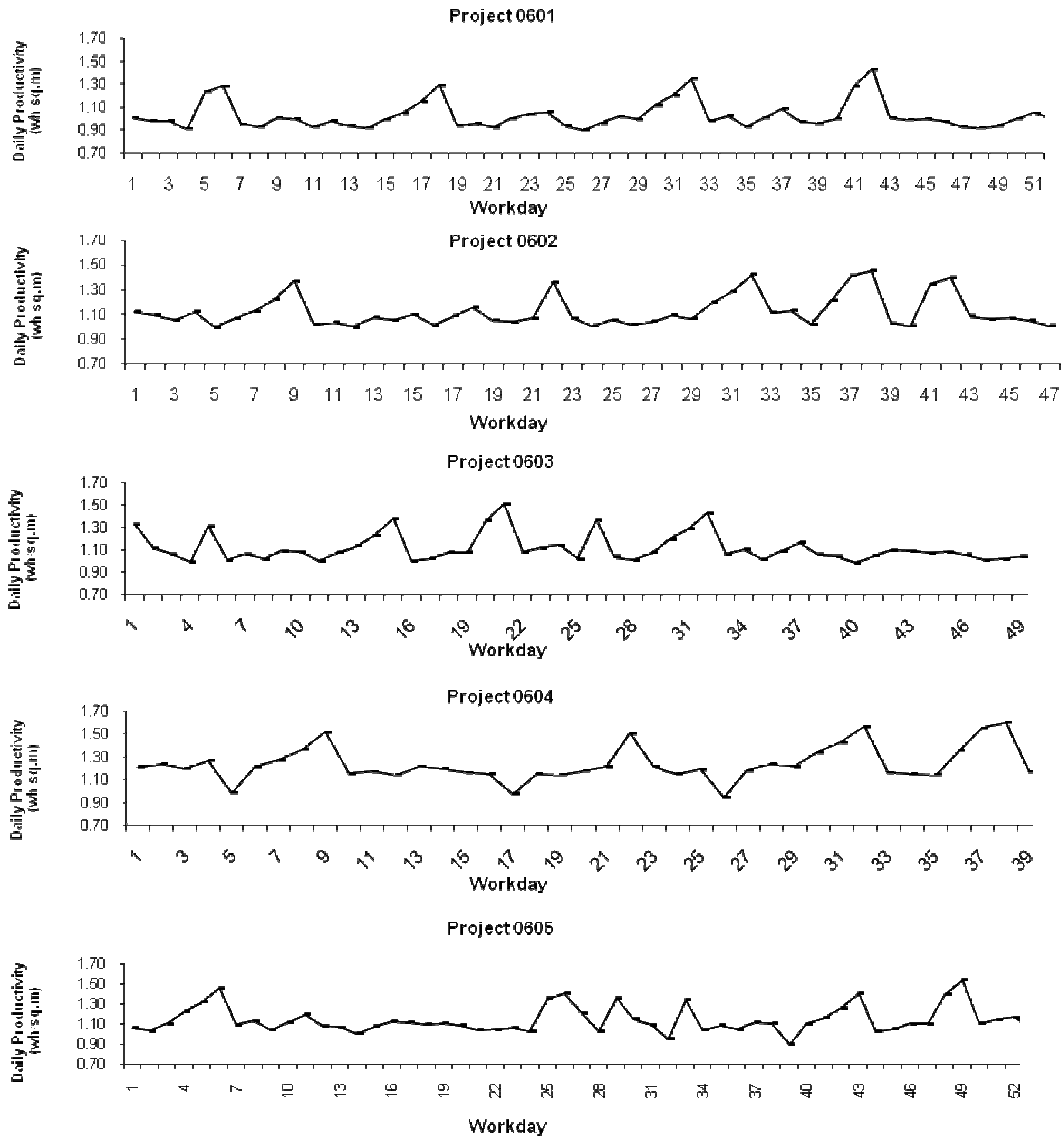

Figure (1): Variability in daily productivity values.

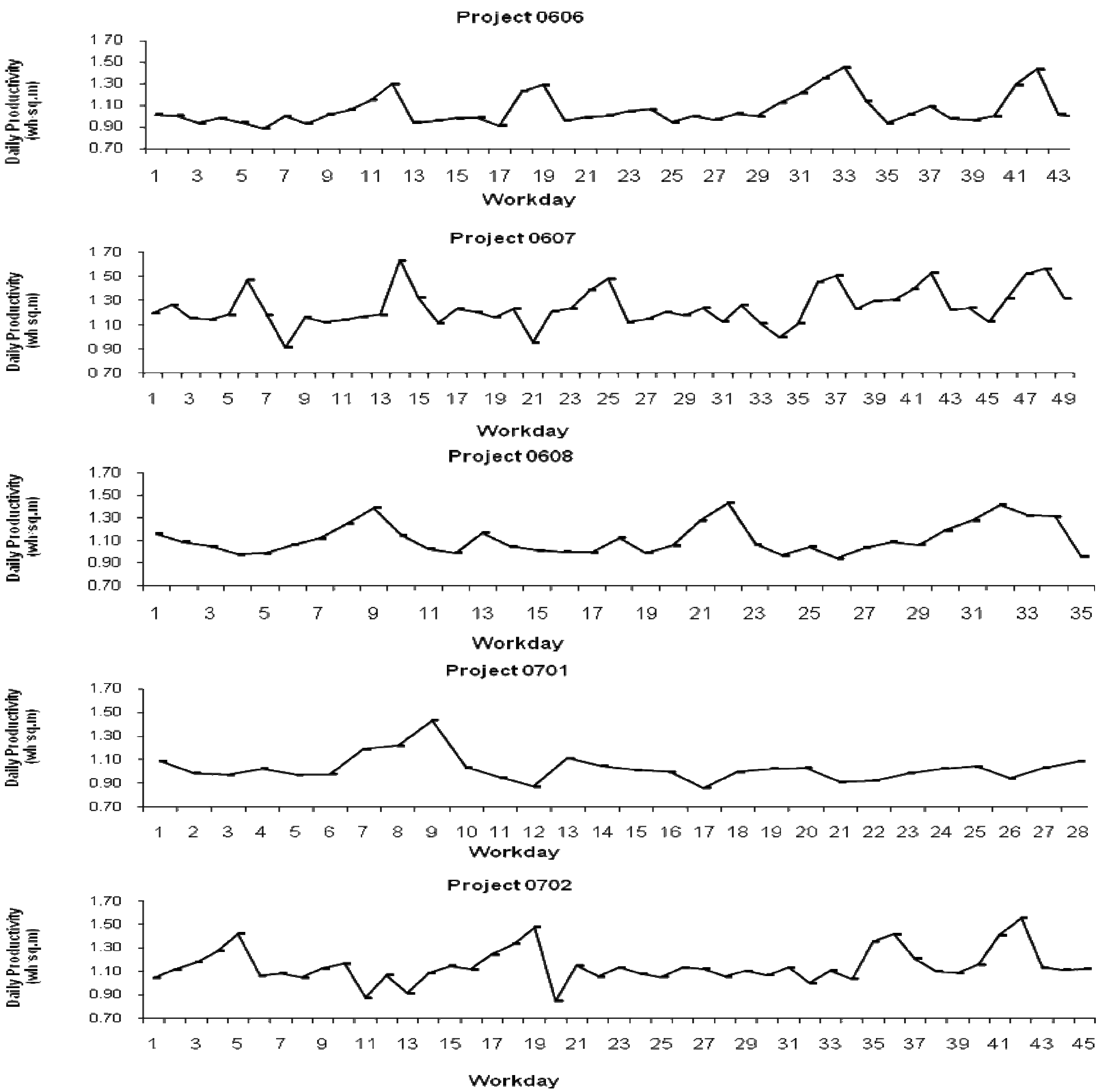

Figure (2): Variability in daily productivity values.

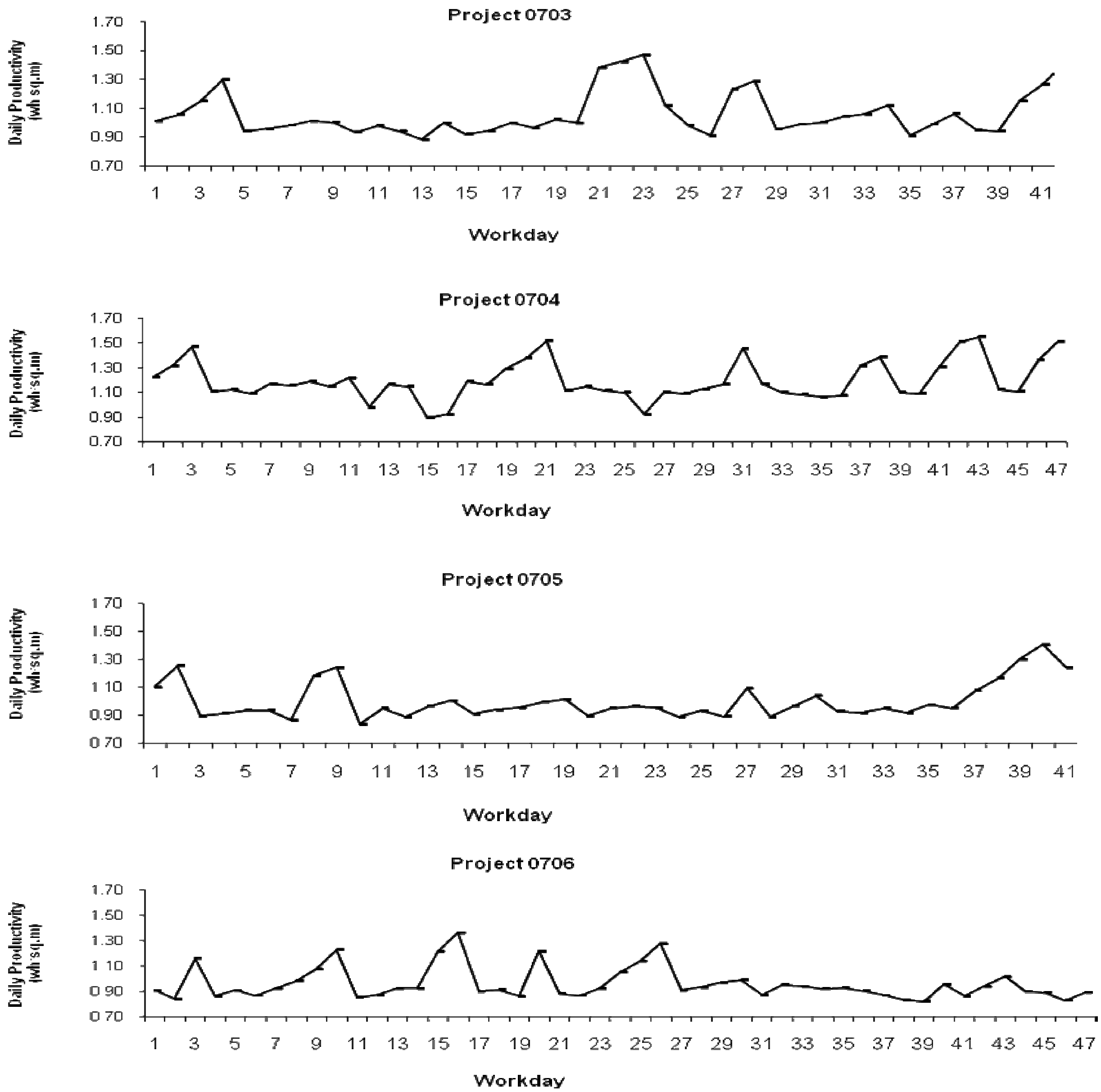

Figure (3): Variability in daily productivity values.

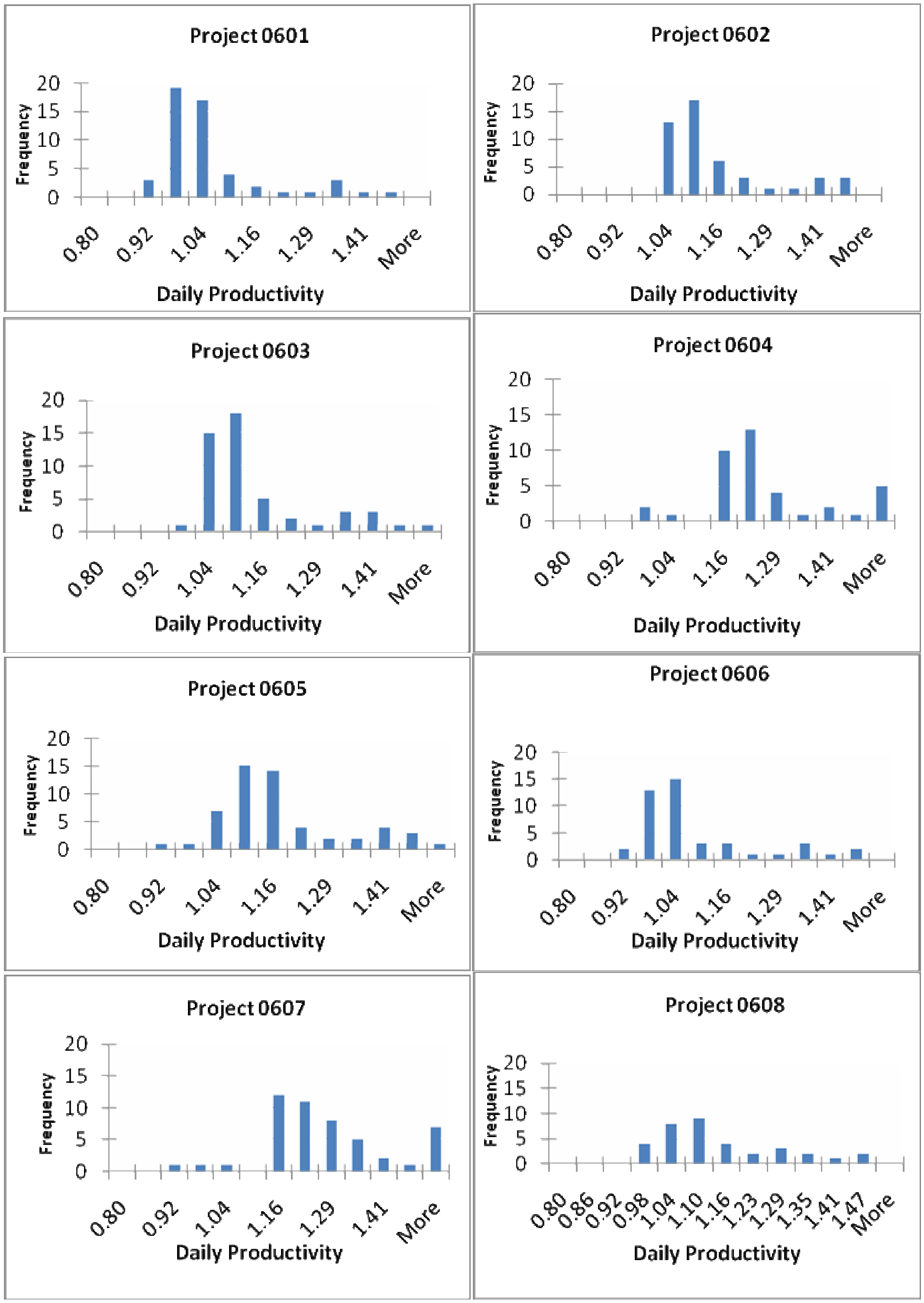

Figure (4): Daily productivity frequency distributions.

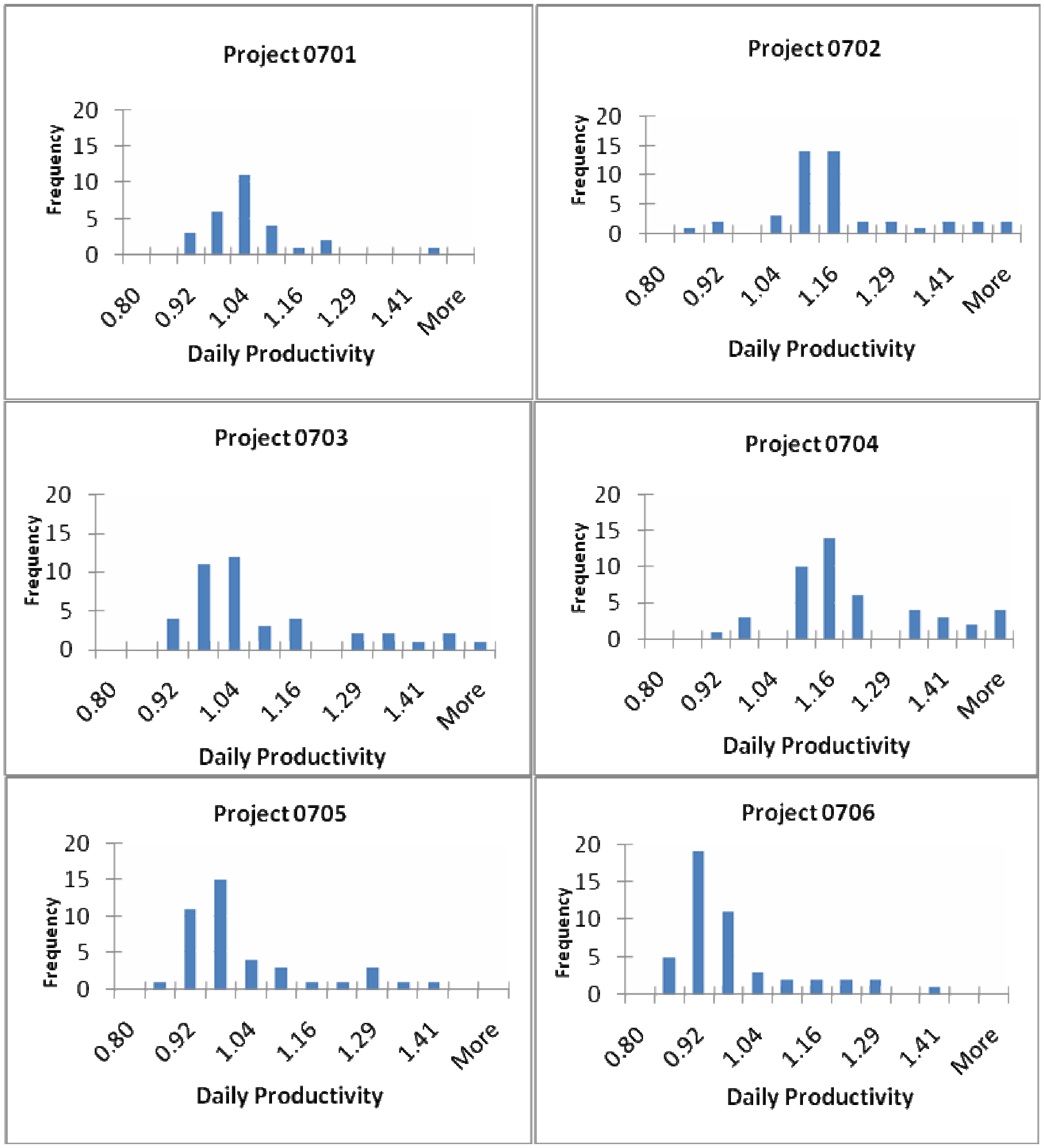

Figure (5): Daily productivity frequency distributions.

Project Evaluation

Single projects were evaluated utilizing a standardized productivity measurement approach for work accomplished by a single crew in a single shift, as well as documentation of the factors that could impact a crew's productivity. Project performance is influenced by the complexity of the design and by project management. These two categories have been demonstrated to affect labor productivity ("Effect" 1965) as shown in Figure (6). The conclusions of the United Nations report have been validated by research conducted at Pennsylvania State University (Thomas et al., 1990). This research has led to the development of the factor model; a detailed representation is shown in Figure (7). The factor model is so named because it is based on the factors that affect labor productivity. The work environment shows 10 influential variables. Although there can be other factors, these 10 are the most common. The work to be done factors were similar in all 14 projects that shared the same size of components, specifications, quality requirements, design features and work scope.

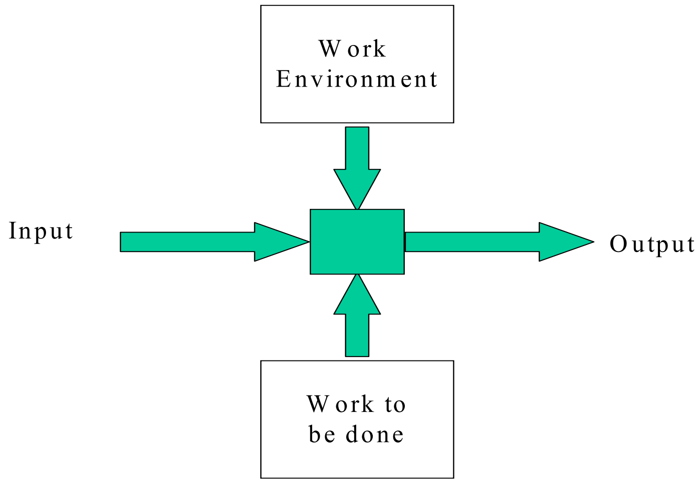

Figure (6): Conceptual representation of United Nations report ("Effect" 1965).

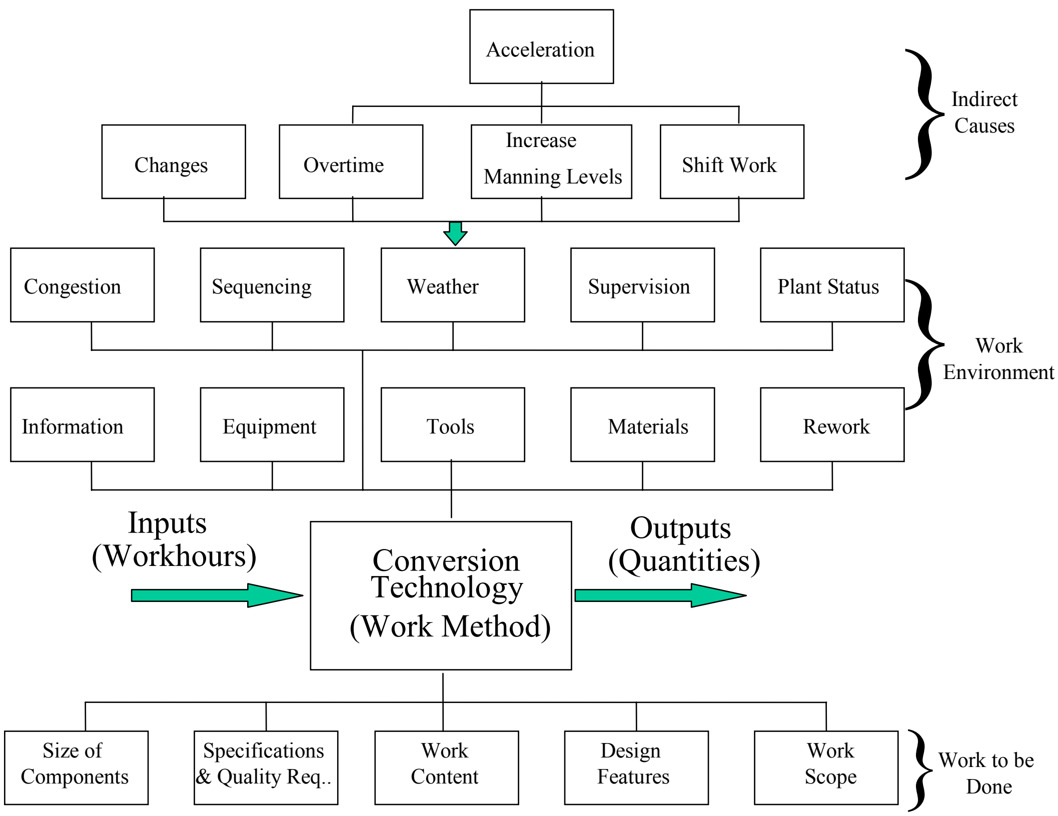

Figure (7): Factor model (Thomas et al., 1990).

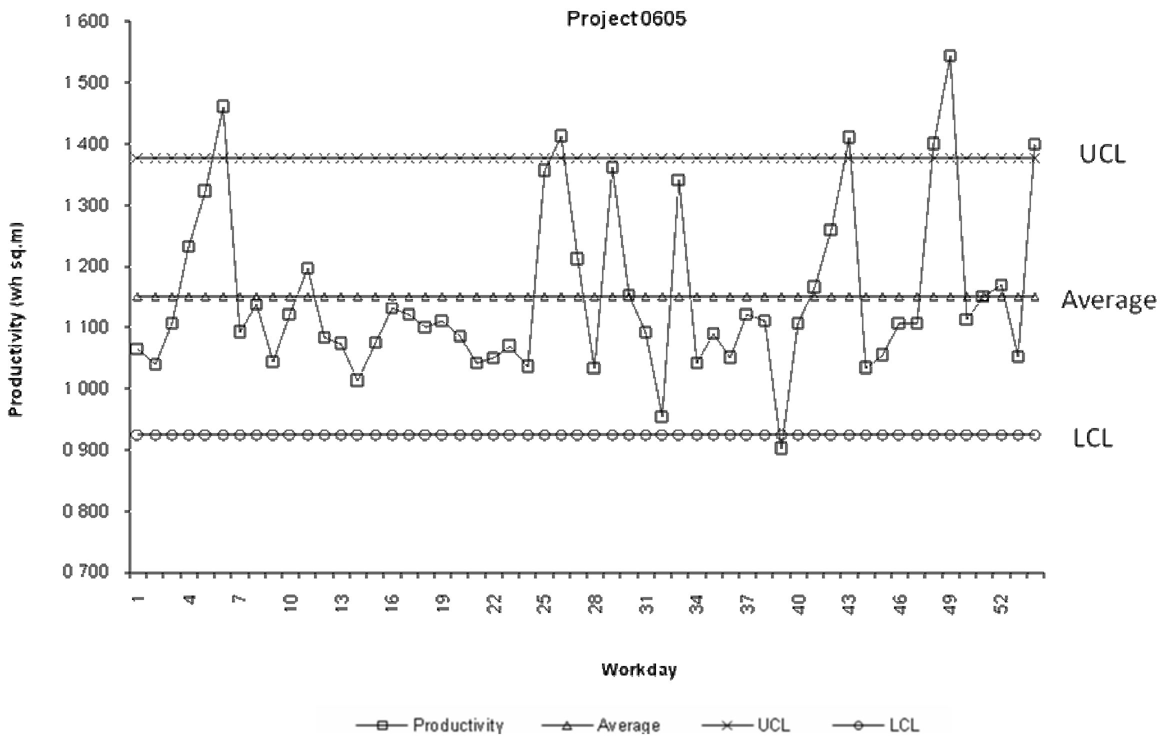

Figure (8): Project 0605.

Baseline productivity is a numerical measure that reflects the best productivity value that a contractor can achieve on a particular project when there are few or no disruptions. From previous studies, disruptions are associated with lower productivity; however, the baseline is unaffected by disruptions. The baseline productivity for each project was calculated by determining the range of random variability in daily productivity values when a project is satisfactorily managed. The boundaries for this range are the Upper Control Limit (UCL) and the Lower Control Limit (LCL). The UCL and LCL can be calculated by applying the following steps:

1. For each project, calculate the average for the daily productivity values. Call this average X.
2. Calculate the difference between consecutive data points for the daily productivity values. Call each difference range R.
3. Determine the median of the ranges. Call this median M.
4. Multiply the median M of the ranges by 3.14 (Nelson, 1984).
5. Add that result to the average X to get the UCL, and subtract it from the average X to get the LCL (Nelson, 1984).

Based on the above criteria, an abnormal workday is defined as any workday where the daily productivity statistic value exceeds the UCL; thus, abnormal workdays refer to days with significantly below average productivity. Productivity that is below the LCL has the highest daily production or output. The baseline productivity for each project is the average of the daily productivity values that falls below the LCL. Pertinent project statistics are summarized in Table (2) and a sample plot for project 0605 is shown in Figure (8).

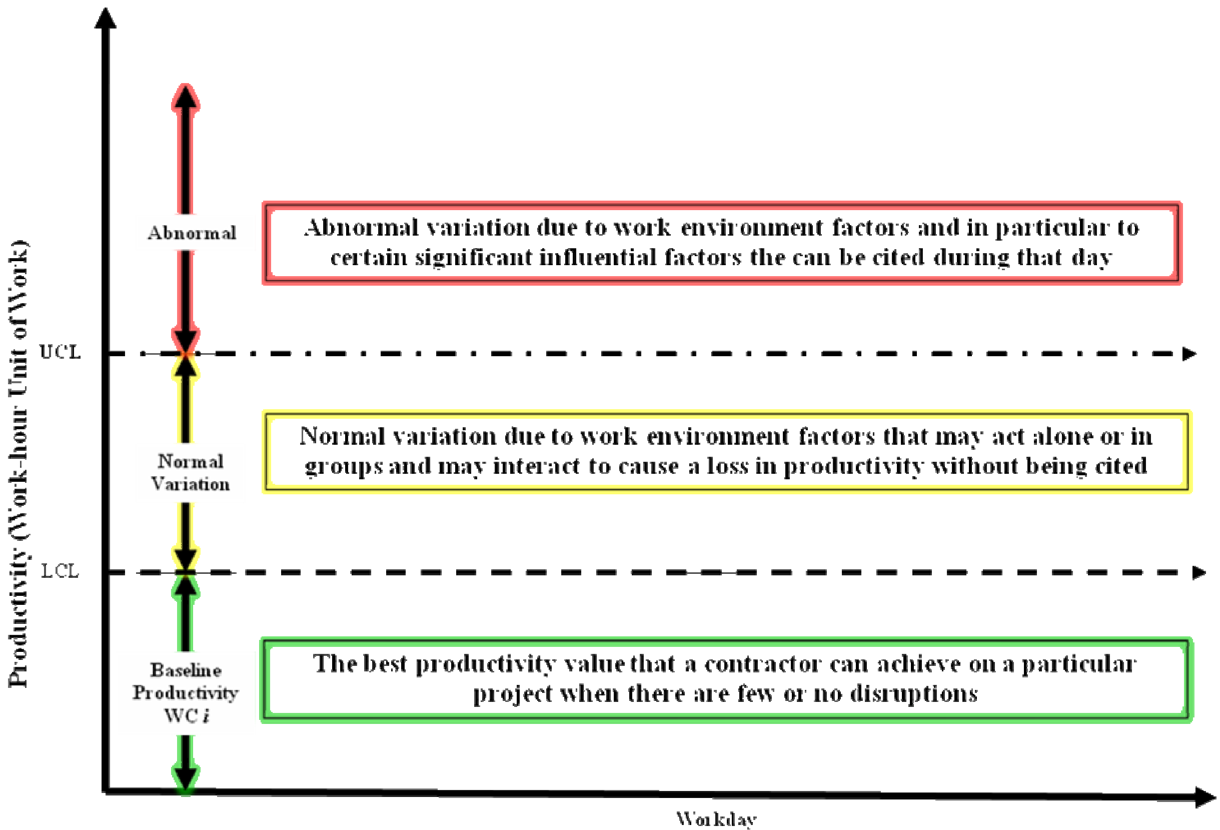

Figure (9): Conceptual representation of the loss of labor productivity.

PRODUCTIVITY CHART: UNDERLYING THEORY

The theory underlying the masonry labor productivity model is that in general the work of a crew is affected by a number of factors that might lead to a loss in potential productivity. Figure (9) is a conceptual representation of the loss of labor productivity for a specific work content of masonry I, where I ranges from 1 to 5.

Baseline productivity reflects the best productivity value that a contractor can achieve on a particular project in a case where there are few or no disruptions. Difference in baseline productivity values from one database to another is due mainly to work method and skills used (Sweis et al., 2007). Productivity that is below the lower control limit has the highest daily production or output. The baseline productivity for Jordan's database representing the chart's lower control limit of (0.876 Wh/sq.m) is the average of the productivity values that represent the lower control limits of all 14 projects.

Daily productivity that falls between the LCL (0.876 Wh/sq.m) and UCL (1.314 Wh/sq.m) is within normal variation due to work environment factors. A variety of work environment factors may lead to a loss of labor productivity. The authors could not possibly detect a review or study that could address all possible factors or combination of causes. However, the work environment factors frequently cited as causing loss of productivity include adverse weather, unavailability of material, lack of equipment and tools, out-of-sequence work, congestion, dilution of supervision, rework and fatigue due to scheduled overtime.

According to Drewin (1985), the open conversion system associated with construction is complex, influenced by many factors. The work environment factors will always be present, may act alone or in groups and may interact to cause a loss in productivity without being cited. The chart proposes that daily productivity that falls between the LCL and UCL is within normal variation, and construction managers don't need to panic since this random variation is part of the open conversion system. Nonetheless, variability in the daily productivity data was found to be an important delineator between good and poor performing projects in Jordan's databases (a total of 14 projects). Poor performing projects have much higher variability (range of normal variation above baseline) than well-performing projects do.

Table (2): Jordan's database parameters.

Project Number	Work Content Rating	Baseline Productivity (Wh/sq.m)	Average Productivity (Wh/sq.m)	Median Productivity (Wh/sq.m)	Range of Normal Variation above & below Average (Wh/sq.m)	Range of Normal Variation above Baseline (Wh/sq.m)	Upper Control Limit (UCL) (Wh/sq.m)	Lower Control Limit (LCL) (Wh/sq.m)
0601	1	0.921	1.030	0.998	0.182	0.364	1.212	0.848
0602	1	0.993	1.124	1.073	0.214	0.427	1.338	0.911
0603	1	1.001	1.116	1.078	0.207	0.414	1.324	0.909
0604	1	0.985	1.235	1.197	0.229	0.458	1.464	1.006
0605	1	1.032	1.151	1.108	0.226	0.452	1.377	0.925
0606	1	0.931	1.056	1.000	0.214	0.427	1.269	0.842
0607	1	0.998	1.246	1.211	0.356	0.713	1.359	0.889
0608	1	0.975	1.114	1.061	0.286	0.571	1.399	0.828
0701	1	0.872	1.027	1.018	0.201	0.402	1.228	0.817
0702	1	0.913	1.142	1.117	0.250	0.499	1.392	0.893
0703	1	0.921	1.064	1.000	0.182	0.364	1.246	0.881
0704	1	0.981	1.192	1.149	0.229	0.458	1.421	0.963
0705	1	0.883	0.999	0.949	0.207	0.414	1.206	0.792
0706	1	0.833	0.961	0.921	0.196	0.393	1.158	0.765
Average		**0.946**	**1.104**		**0.227**	**0.454**	**1.314**	**0.876**

Based on the chart, an abnormal day is where the daily productivity value falls above the UCL. In this case, the loss of productivity is due to the work environment factors as within the normal variation, and in particular to certain significant influential factors that can be cited during that day. This is where the construction manager should focus to identify the major work environment factors that led to the loss and take action to reduce their future impact.

The same model can be applied to any construction activity if:

1. All quantities and productivity calculations are standardized such that the values represent the same size component and type of work across all projects being compared; and,
2. An appropriate Work Content (WC) rating for the selected construction activity is determined, where WC is a non-mathematical term referring to the relative complexity of various work designs compared across a single one.

CONCLUSION

This research proposed a framework for developing a method to model the variability of masonry labor productivity. Single projects were evaluated by using various project attributes extracted from the data. The data were collected using standardized data collection procedures, and the work performed was similar in scope, size of components, specifications, quality requirements and design features. The findings of this research are discussed below emphasizing the theory underlying the variability of masonry labor productivity.

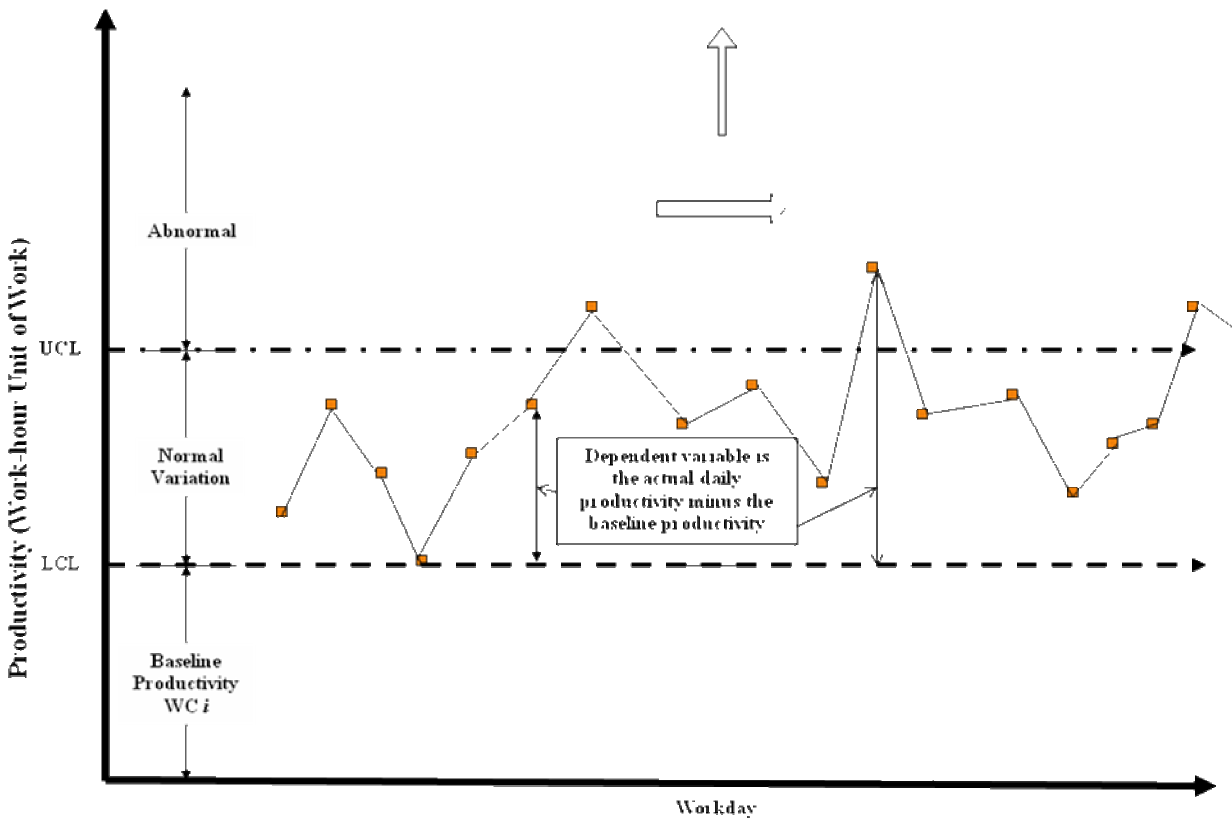

Figure (10): Quantification of work environment factors.

The baseline productivity was calculated for the Jordan's database where all fourteen projects shared a low work content of 1 (the least complex). The daily productivity values that fall between LCL (0.876) and UCL (1.314) indicate a loss of productivity within normal variation due to work environment factors that may act alone or in groups and may interact to cause a loss in productivity without being cited. Hence; construction managers don't need to panic since this random variation is part of the open conversion system and the range of this variation can be an important indictor between good and poor performing projects where poor performing projects have much higher variability (range of normal variation above baseline) than well-performing projects do.

When daily productivity values fall above the UCL, the loss of productivity is due to the work environment factors as within the normal variation, and in particular to certain significant influential factors that can be cited during that day. This is where the construction manager should focus to identify the major work environment factors that led to the loss and take action to reduce their future impact.

Most significantly, this study made its most important contribution in the application of a methodology that reliably quantifies comparable measures of productivity. The strength of this approach lies in its ability to compare productivity level and the impacts of contributing factors among projects.

IMPLICATIONS AND FUTURE RESEARCH AND DEVELOPMENTS

As mentioned in the previous section, the top two blocks in Figure (9) represent the loss of productivity due to work environment factors. The use of data collection techniques that focus on task-level labor productivity (specifically, the measurement of work accomplished by a single crew in a single shift), as well as the daily documentation of factors that may have affected the work of each crew, enables the assessment of work environment factors.

To quantify the influence of work environment factors, a multiple regression model can be developed in which the dependent variable is the actual daily productivity minus the baseline productivity as shown in Figure (10). The independent variables are the cited work environment factors such as lack of material, lack of equipment and tools,… etc. The independent variables are treated as binary variables and the constant term in the multiple regression model represents the average variation in the daily productivity from the baseline. The coefficient of any particular independent variable represents the rate of productivity lost as a result of that specific factor during the period in which it was present. Moreover, the number of hours lost due to that factor can be calculated by multiplying that specific factor coefficient by the units of work accomplished during the period when the factor was present.

Although the environment in which this research has been carried out is limited to Jordan, the methodology proposed can be applied to any construction activity in developed or developing countries.

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