Estimating Labor Productivity Frontier: A Pilot Study

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ABSTRACT

Labor productivity frontier is the theoretical maximum production level per unit of time that can be achieved in the field under perfect conditions. This level of productivity is an abstraction that is useful in the estimation of optimal productivity for labor-intensive operations.

This paper reports on a pilot study performed to evaluate the feasibility of a dual approach for estimating the productivity frontier for a simple electrical installation. The first approach involves the estimation of the productivity frontier by using observed durations from a time and motion study. The movements of a worker are captured by multiple synchronized video cameras. The actions that make up a particular task are identified from the video frames and categorized into contributory and non-contributory actions. The best series of contributory actions are identified based on the shortest time taken to complete a task, and a synthetic worker model is used to determine the productivity frontier as the sum of the shortest durations for each action. The second approach involves the estimation of the productivity frontier by using estimated durations on the same time and motion study. The probability distributions that best represent action durations are identified and the productivity frontier is defined as the sum of the lowest values from each of the distributions at a 95% confidence interval. The highest labor productivity value from these two strategies is taken as the best estimate of the productivity frontier.

An accurate estimate of labor productivity frontier is the first step toward developing a process that will allow project managers to determine the efficiency of their labor-intensive construction operations by comparing actual vs. optimal rather than actual vs. historical productivity. Toward this end, this paper reviews relevant literature, presents the details of the proposed dual approach, introduces results from the pilot study, and evaluates the feasibility of this methodology for estimating the labor productivity frontier.

INTRODUCTION

Productivity is frequently defined as the ratio of output to input measured at the activity level for detailed estimating and project scheduling (Song and AbouRizk 2008). This productivity at the activity level is frequently referred to as labor
productivity because construction activities are generally labor-intensive. Labor productivity measures the input as labor hours and the output as installed quantities (Dozzi and AbouRizk 1993). Labor productivity is also a prime factor for the analysis of the overall productivity of a project because construction productivity is mainly dependent on labor effort and performance (Jarkas 2012, Liu et al. 2011). As labor costs generally cover 30% to 50% of overall project costs in construction (Harmon and Cole 2006), maintaining consistent and efficient labor productivity can lower costs and keep a project within budget.

The common practice of estimating labor productivity based upon published data or an individual’s experience lacks a systematic approach. Motwani et al. (1995) showed that more than 20% of contractors depend upon estimators’ “gut feelings” and opinions for the majority of their estimates. The lack of consistency in the productivity measurement system and the low quality of historical data may prevent meaningful analyses (Song and AbouRizk 2008). Furthermore, efficiency of construction operations is usually determined by comparing actual vs. historical productivity, a comparative approach that only provides a relative (biased) measure of efficiency. For example, if actual productivity is 95% of average historical productivity, the resulting productivity rate does not necessarily mean that the operation is efficient, but only that the efficiency of the operation is in line with historical averages. In fact, the operation now and then could be significantly inefficient. This reality calls for an alternative technique to measure labor productivity. By defining optimal productivity as the productivity level achievable on a sustainable basis under good management and typical field conditions (Son and Rojas 2010), one could then develop an absolute (unbiased) measure of efficiency by comparing actual vs. optimal productivity. The estimation of optimal productivity is explained in more detail in Kisi et al. (2014).

Figure 1. Main productivity concepts

The productivity frontier is an input to the Kisi et al. (2014)’s model and is defined as the theoretical maximum productivity that could be achieved under perfect
conditions. These perfect conditions refer to ideal situations, such as perfect weather, highly motivated and productive labor with perfect workmanship, optimal materials, optimal equipment, no interferences from other trades, no design errors, and a perfect understanding of design intent, among others. The relationships among productivity frontier, optimal productivity and actual productivity (productivity measured in the field) are illustrated in Figure 1.

A productivity frontier is to be estimated once a construction activity has achieved its steady state phase (i.e. once the learning phase is over and productivity has leveled out). This point is shown in Figure 1 as time $T_2$. The productivity frontier diverges from optimal labor productivity levels due to system inefficiencies—those factors outside the project manager’s purview that affect productivity, including environmental conditions (high humidity, cold or hot temperatures), breaks, workers’ health, absenteeism driven by health or family issues, interference from other trades, and design errors, among others.

As shown in Figure 1, actual productivity generally manifests as suboptimal productivity. In theory, actual productivity and optimal productivity can be identical in a few instances. However, the difference between optimal and actual productivity is the operational inefficiencies. Poor sequencing of activities, inadequate equipment or tools, mismatch between skills and task complexity, excessive overtime, and poor lighting conditions are examples of factors that may combine to make up the operational inefficiencies. Operational inefficiencies can be minimized by project managers through pre-evaluation of risk factors and by exhibiting unbiased attitudes while adopting explicit and systematic methods (Son and Rojas 2010).

Given these definitions, one can state that productivity is optimistically forecasted when the estimated values are higher than the optimal productivity and is conservatively forecasted when the estimated values are lower than the optimal productivity. Of course, managers do not purposely forecast at these levels. They just assumed that these levels are reasonably attainable in the field based upon historical averages and personal judgment. Son and Rojas (2010) argue that both optimistic and conservative assumptions end up negatively affecting actual productivity in the field.

Based upon these theoretical definitions, the challenge resides in properly estimating the value of optimal productivity. Kisi et al. (2014) explain how this estimation can be achieved by using two independent but complementary approaches, one of which requires the estimation of the productivity frontier. Therefore, this pilot study focuses on the estimation of the productivity frontier as an input to the Kisi et al. (2014) model.

This paper introduces, via a pilot study, a framework for the estimation of construction labor productivity frontier based on two complementary approaches.

THEORETICAL FRAMEWORK

Time and motion studies (Oglesby et al. 1989) are generally conducted to collect and analyze site data (Shahidul and Shazali 2011). They are useful in determining the time required to accomplish a specific task (Oglesby et al. 1989) by a qualified and well-trained person working at a normal pace. Information acquired through these studies includes the actual time worked by laborers, the actual volume
of production, and the rates of output over the course of a shift (Finkler et al. 1993). These studies are helpful in documenting and improving inefficient methods, eliminating or reducing avoidable delays in the workplace, and developing time standards. Time and motion studies are also used to exactly tally the time spent on each type of task and are typically used in the analysis of body motions employed while doing a job in order to find the most efficient method in terms of time and effort. The pilot study described in this paper used a time and motion study of a simple electrical installation as the basis of analysis for estimating the productivity frontier of the operation.

Construction activities can be broken down following a hierarchical structure. Tucker and Guo (1993) classified construction activities into area, activity, and task, whereas, Ahamad et al. (1995) classified them into five levels: project, division, activity, basic task, and elemental motion. For the purposes of this pilot study, and depending upon the complexity of a project, activities are broken down into tasks, tasks into actions, and actions into movements.

The time and motion study was performed at the action level, as the lower one moves in a hierarchy, the more variability may be seen among duration values. Greater variability is preferable because it allows for the identification of the lowest theoretical durations. For example, one can assume that after many observations, the lowest recorded duration for an activity in the field is X. If that activity were divided into several tasks and the minimum duration for each task measured, then the total duration of the activity calculated by reassembling its tasks would be X’, where X’ < X. Analogously, if each task were broken down into its constituent actions and the minimum duration for each action measured, then the total duration for the activity calculated after reassembling actions into tasks and tasks into the activity would be X”, where X” < X’ < X. Applying the same logic, if one goes to the movement level, then X”’ < X” < X’ < X. This reduction in durations is due to two different effects. The first one resides in the fact that higher hierarchical levels “hide” the variability of its constituent parts since one only “sees” the variability of the aggregated whole. By breaking down a process into its elemental components, one makes visible previously “hidden” variability. The second effect is the fact that non-contributory tasks, actions, and movements are eliminated from the analysis as lower levels of the hierarchy are employed. For example, if one measures the duration of an activity from beginning to end, non-contributory tasks could be embedded in such a measure. However, if one calculates the duration of an activity by aggregating the durations of its constituent tasks, only direct and contributory work would be considered as all non-contributory tasks would be eliminated because they do not form part of the value-added hierarchy.

Even though X”’ would be based on actual observations, it should not be interpreted as an actual duration associated with the actual productivity; rather, X”’ should be interpreted as a synthetic measurement of a theoretical duration associated with a theoretical productivity.

Once durations are determined, productivity may be calculated by dividing the production rate by the observed shortest durations for the activity. However, since observed durations may not include the lowest possible duration for a task, action, or movement, probability distributions are fitted to the data to obtain estimated shortest
durations. Productivity is again calculated by dividing the production rate by the estimated shortest durations for the task. We recommend taking the highest productivity from these two techniques—observed durations and estimated durations—as the value for the labor productivity frontier.

PILOT STUDY

A pilot study was conducted to evaluate the proposed framework in order to determine the feasibility of estimating labor productivity frontier in construction. This pilot study analyzed data captured during the replacement of electrical lighting fixtures at Omaha South High Magnet School. The steps involved in this framework are described below.

Data collection and analysis

Three Canon XF100 professional camcorders were used to collect video data. These cameras were calibrated using the “Camera Calibration Toolbox” in Matlab (Bai et al. 2008). Prior to data collection, the cameras were synchronized based upon mode, frames per second, and initial time (Delamarre and Faugeras 1999, Caillette and Howard 2004). The scope of this electrical lighting installation project included the replacement of old T12 with new T8 fluorescent bulbs and ballasts. Data captured included different events involved in bulb replacement, such as material delivery to site, material storage, material unpacking and transportation to the work station, equipment and tools preparation, removal of the old T12 fluorescent bulbs, replacement by T8 fluorescent bulbs, and collection of old bulbs for recycling.

Depending upon site conditions, single or multiple cameras were used (Bai et al. 2008, John et al. 2009, Sigal et al. 2010). One moving camera was used to capture materials and equipment delivery activities (dynamic background). Two or three fixed cameras were used to capture electrical lighting installation processes depending upon space availability at the site of installation (fixed background). For small rooms, only two fixed cameras were used, whereas for the larger rooms, three cameras captured movements from different angles.

Two electrical workers from Commonwealth Electric Company, a veteran and a novice, participated in the project. However, this pilot study focused exclusively on analyzing the activities performed by the veteran worker given his level of experience performing similar operations. Video was recorded in three different school zones: classrooms, lockers, and corridor/hallways.

To facilitate data analysis, the activity “Lighting Replacement” was selected because of its homogeneity across the construction project. The activity was broken down into four tasks: (1) Site Preparation, (2) Fluorescent Bulb Replacement, (3) Waste Management, and (4) Documentation. Each task was then broken down into actions and each action into movements. For the pilot study, detailed data was collected for the task “Fluorescent Bulb Replacement.” Durations were measured at the action level for this task because actions produced enough data for a preliminary analysis without creating an unnecessary burden for data processing. This task was broken down into eight actions: (1) Glass Frame Opening, (2) Old Bulb Removal and Storage, (3) Ballast Cover Removal, (4) Old Ballast Removal, (5) New Ballast Installation, (6) Ballast Cover Closure, (7) New Bulb Installation, and (8) Glass
Frame Closure. As with any work breakdown structure, the number of levels and categories within a level were selected based on the analyst’s judgment and experience. These actions were identified from the video data by converting it into individual images thanks to the frame separation algorithm in Matlab (Cai and Aggarwal 1996). This study analyzed data of about 30 stations completed by the skilled worker at the actions level.

Visual inspection was used to classify each action into contributory (direct and indirect work) and non-contributory based upon their influence to activity completion (Bai et al. 2008). Contributory work (direct and indirect) is the work necessary to accomplish the task. Non-contributory work deals with non-productive situations such as workers being idle, texting, talking, or taking unscheduled breaks etc. (Oglesby et al. 1989).

**Model development and validation**

Several researchers have developed sophisticated human models (Badler et al. 1979, Calvert et al. 1993, Sengupta and Das 1997). Since such level of sophistication was not necessary for this pilot study, a simplified, AutoCAD-developed skeleton view of a worker illustrated the worker’s movement. This model was found to be accurate enough for the purposes of identifying and classifying actions according to the proposed framework. Figure 2 shows an instance of this skeleton view model in which each frame shows a specific action as listed below (video frame numbers in parenthesis):

(i) Glass Frame Opening (7106)
(ii) Old Bulb Removal and Storage (7255)
(iii) Ballast Cover Removal (7653)
(iv) Old Ballast Removal (8507)
(v) New Ballast Installation (9442)
(vi) Ballast Cover Closure (10427)
(vii) New Bulb Installation (10966)
(viii) Glass Frame Closure (11646)

![Figure 2. Skeleton view of worker on rolling scaffold](image)

These frames were animated using Windows Movie Maker in order to validate the process workflow. Five experts evaluated the movements of the worker in the model.
Productivity frontier estimation

The productivity frontier was computed for the “Fluorescent Bulb Replacement” task from the time and motion study following two approaches as explained earlier in this paper: (1) observed durations and (2) estimated durations.

Approach 1: observed durations

The time and motion study reviewed video data of the skilled worker replacing the florescent bulbs. The durations of the contributory actions for the “Fluorescent Bulb Replacement” task were recorded in an excel spreadsheet. Since this task comprised of actions in a serial fashion, the shortest possible duration of the task was estimated by adding up the shortest durations observed for each action. The shortest total observed duration for the bulb replacement was 182 second. The equivalent productivity could then be computed by dividing the number of units produced by this observed shortest duration, which resulted in 19.78 stations per hour. Given that the probability of actually observing this level of theoretical productivity in the field is infinitesimal, we propose that this value be taken as an estimate of the productivity frontier. For example, if (1) 100 observations are recorded during a construction task, (2) the task includes five actions, (3) the lowest duration recorded for each action occurs only once, and (4) the duration of each action is independent from the duration of all others; then the probability of observing the duration of the task being equal to the sum of the shortest durations of the actions would be one in 10 billion.

Approach 2: estimated durations

Given the low likelihood of observing the lowest possible duration for each action in a single case study, probability distributions were fitted to the data to obtain estimated shortest durations. The best-fitted probability distribution for each action was determined from “Arena Input Analyzer” (Takus and Profozich 1997), while the lowest threshold parameter (lowest duration) for each distribution was estimated using “Base SAS(R) 9.2”, evaluated at a 95% confidence interval (Stephens 1974). The estimated lowest durations of the contributory actions for this task were recorded in an excel spreadsheet. Then the shortest possible duration was estimated by adding up the shortest durations estimated for each action. The shortest total estimated duration was 178 seconds. The equivalent productivity could then be computed by dividing the number of units produced by this estimated shortest duration, which resulted in 20.23 stations per hour.

The highest productivity from these two approaches—observed and estimated durations—yielded the estimated value of the labor productivity frontier. Thus, the productivity frontier computed from this pilot study for the “Fluorescent Bulb Replacement” task is 20.23 stations per hour.

CONCLUSION

Even though the productivity frontier is not achievable in practice, it is a valuable concept for estimating optimal productivity of labor-intensive operations. Optimal productivity, in turn, is necessary to develop an unbiased means of calculating the efficiency of construction operations since actual productivity is
compared against an objective measure rather than historical values.

This paper illustrates a dual approach for the estimation of the productivity frontier by conducting a pilot study for a lighting replacement activity. This study was conducted to illustrate and justify the proposed framework and make sure that this research had significant importance in the future.

The validity of taking the theoretical productivity estimated using this framework as the productivity frontier may be questioned given that field data is used for the analysis. In essence, the productivity frontier is an abstraction that cannot be measured in the field. Therefore, using actual field data to estimate its value may seem counterintuitive. However, deductive logic can be used to justify this choice. First, this research defines optimal productivity as the productivity “under good management” and “normal field conditions.” Therefore, if the recorded durations occurred in a project without negative management issues and under normal operations, then they would represent at least optimal productivity. Second, in order for these durations to represent the productivity frontier, one would have to eliminate all system inefficiencies that could have been present during the data collection period. Even though this elimination is impossible in practice, if a concerted effort is made to minimize system inefficiencies, then the theoretical productivity calculated following these procedures would be somewhere in between the optimal productivity and the productivity frontier. Third, given that this methodology focuses on the instantaneous highest values of labor productivity recorded, the probability of actually observing this level of theoretical productivity in the field is infinitesimal. For example, if (1) 100 observations are recorded during a construction task, (2) the task includes five actions, (3) the lowest duration recorded for each action occurs only once, and (4) the duration of each action is independent from the duration of all others, then the probability of observing the duration of the task being equal to the sum of the shortest durations of the actions would be one in 10 billion. Fourth, part of the adopted definition for optimal productivity included “on a sustainable basis,” which dismisses a productivity level that happens once in 10 billion observations. Therefore, this value can be taken as an estimate of the productivity frontier.

Although this research examines data from a simple electrical activity, this methodology can be implemented in more complex operations. However, most of the manual steps used in the pilot study would have to be automated in a more complex activity in order to determine the productivity frontier. Research efforts are currently underway to develop automated tools to apply the proposed framework.

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