CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

ESTIMATING PRODUCTIVITY FOR LABOR-INTENSIVE TASK: A CASE STUDY

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Abstract: Traditional approach of evaluating the efficiency of labor-intensive construction operations compares actual with historical productivity, which provides only relative efficiency. As every project is unique in nature, it may not be a reliable and accurate practice because productivity cannot be easily judged by the data that was documented a decade or more ago. Therefore, it is necessary to determine the absolute efficiency. The study of the productivity frontier and optimal productivity presents an innovative frontier approach for measuring efficiency of construction operations by comparing actual versus optimal productivity. The productivity frontier is defined as a theoretical maximum production level per unit of time that could be achieved under perfect conditions, whereas optimal productivity is the sustainable highest level of productivity that may be achieved in the field under good management and typical field conditions. Such a new approach determines absolute efficiency by avoiding accumulation of the relative errors that exists in the traditional practice. The productivity frontier is a construct that acts as a benchmark to estimate optimal productivity. This research contributes to the body of knowledge by introducing a dual approach framework to estimate the labor productivity frontier and applying it in a case study on the “sheet metal duct sealing” task. The theoretical highest labor productivity for this task was 6.88 ducts per crew-hours. This research presents a decision-making framework for project managers that will help to improve the productivity level of labor-intensive operations by avoiding or minimizing the impact due to operational inefficiency factors.

1. INTRODUCTION

Labor productivity is critical and significant metric to the success of the construction industry because it impacts on project cost, schedule, and ultimately profitability of the industry. But, there is currently no systematic approach for measuring and estimating labor productivity (Song and AbouRizk 2008). The lack of reliable means for evaluating the efficiency of labor-intensive construction operations makes it more difficult for the construction industry to improve productivity.

In the existing practice, the efficiency of labor-intensive construction operations is evaluated by comparing actual with historical productivity for equivalent operations (Mani et al. 2016, 2017). Such practice provides a relative benchmark of efficiency. The American Association of Cost Engineers (AACE) (2011) also defines productivity as a “relative measure of labor efficiency, either good or bad, when compared to an established base or norm” (p. 27). Indeed, an operation may not be efficient even though actual productivity equals average historical productivity because the operation’s efficiency may be well below optimal levels (Mani 2015, Mani et al. 2016). This relative measure creates great difficulty in tracing it as an absolute value over time, and there is a possibility of gathering information on the movements of the established base or benchmark values (Allmon et al. 2000). Moreover, every project is unique in nature because there are many factors involved in the construction processes which change over time. Thus, productivity cannot be easily judged by the same data or information that was documented a decade or more ago (Liberda et al. 2003). This reality demands an alternative technique to measure labor productivity.

The proposed research framework can be an alternative technique to measure labor productivity. It estimates the "labor productivity frontier," which acts as a benchmark in order to estimate optimal productivity. The "perfect conditions" is an ideal state where all factors affecting labor productivity are at the most favorable levels, such as good weather, optimal utilization of materials and equipment, highly motivated and productive workers with flawless artisanship, no interference from other trades, no design error, and precise understanding of the design intent, among others. Optimal productivity is defined as the productivity level achievable on a sustainable basis under good management and typical field conditions (Son and Rojas 2011). Mani et al. (2016) presents the relationships among productivity frontier, optimal productivity, actual productivity, system inefficiency, and operational inefficiency as shown in Figure 1. System inefficiencies are loss in productivity due to 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. 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 inefficiency.

Kisi et al. (2014, 2018) explains a top-down approach and a bottom-up approach to estimate optimal productivity. The top-down approach yields the upper level estimation of optimal productivity by deducting system inefficiency losses from the labor productivity frontier. The bottom-up approach yields the lower level estimation of optimal productivity by adding actual productivity with operational inefficiency losses. Kisi et al. (2014, 2018) presents a detailed description on how the productivity frontier is used to estimate optimal productivity. Such a process is outside the scope of this paper. This case study compares performances of three workers and evaluates the feasibility of a dual approach for estimating the productivity frontier for a "sheet metal duct sealing" task.

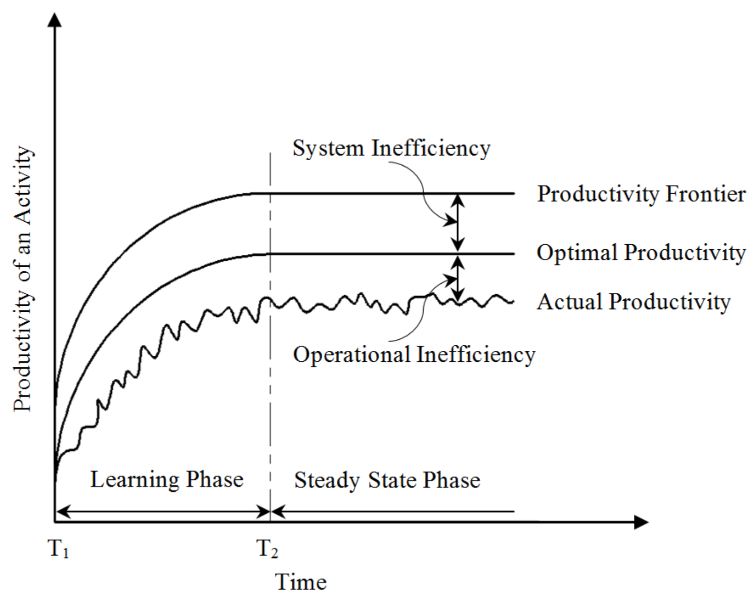

Figure 1: Basic productivity dynamics (modified from Son and Rojas 2011)

In order to estimate the productivity frontier, this research adapts various methods as the theoretical underpinnings of the proposed framework, such as hierarchical analysis, time-and-motion study, and probability distribution analysis.

Hierarchical analysis: Researchers broke down an activity into four level hierarchy of subsystems, such as activity into tasks, tasks into actions, and actions into movements (Mani 2015, Mani et al. 2016). This study goes two levels deeper than Tucker and Guo (1993) classification (area, activity, and task). Ahmad et al. (1995) classified them into five levels: project, division, activity, basic task, and elemental motion.

Time-and-motion study: This study used time-and-motion study to measure observed durations required by workers to perform the "sealing" task. The main objective of time-and-motion study is to set time standards in the production area and to record the incremental times of the various steps or tasks that make up an operation (Meyers 1992, Oglesby et al. 1989). The time and motion study was performed at the action level because, as the lower one moves in a hierarchy, the more variability may be seen among duration values (Mani et al. 2016). Greater variability is preferable because it allows for the identification of the lowest theoretical durations. Mani et al. (2016) presented a detailed information about this concept with relevant examples.

Probability distribution analysis: 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 statistically estimated shortest durations. The statistically estimated shortest duration from the best fitted probability distribution is computed using "Base SAS® 9.2" software. This software defines the shortest value as the lowest threshold parameter and also called "shifted parameter" (Aristizabal 2012) for the shifted probability distribution (Ang and Tang 2004). The maximum likelihood estimation is used to estimate the parameters of the distribution (Ang and Tang 2004).

2. CASE STUDY

This case study compares the "sheet metal ducts sealing" task performed by three workers and evaluates the proposed framework in order to estimate the labor productivity frontier. The "sealing" is a task of the "Fabrication of Sheet Metal Ducts" activity. Mani et al. (2017) compared the "Roll Bending" task performed by two crews. This case study only focuses on the performances of three workers, who were involved in the "sealing" task. The steps involved in this study are described below.

2.1 Data Collection

This study employed multiple Canon XF100 professional camcorders in order to capture video data on the "sealing" task of the "Fabrication of Sheet Metal Ducts" activity at the workshop of the Waldinger Corporation in Omaha, Nebraska. Prior to data collection, those cameras were calibrated and synchronized based upon a mode, frames per second, and initial time (Caillette and Howard 2004). The "Fabrication of Sheet Metal Ducts" activity involves eight tasks: (i) roll bending, (ii) lock forming, (iii) lock setting, (iv) tie-rod installing, (v) flange screwing, (vi) sealing, (vii) packing, and (viii) delivering. The sheet metal duct was manufactured from two plain metal sheets of a standard-sized (80.25 inches x 60 inches x 0.0336 inches). The scope of this study includes labor-intensive operations of the "sealing" task, which was performed by a crew of three workers as shown in Figure 2. This is a critical task because the duct was designed for an exhaust system and it is necessary to prevent from air leakage and exposure from weather corrosion. The sealing task was performed by filling sealer materials on all edges of the duct, screw holes, tie rod joints, and other separations or openings. This task is selected for the study because:

- It consists of a large number of repetitive labor-intensive operations. Also, three workers involved to complete the same task with their own sequence of actions.
- It was a controlled indoor environment and video cameras were able to sit closer to the workstation in order to capture minor movements of workers. However, there were few disturbing factors, such as disturbances by other workers in the workshop, tight working space, and noise generated from heavy manufacturing equipment.
- It consisted of a homogeneous and consistent working environment in terms of work approach, materials used for fabrication, and quality of output.

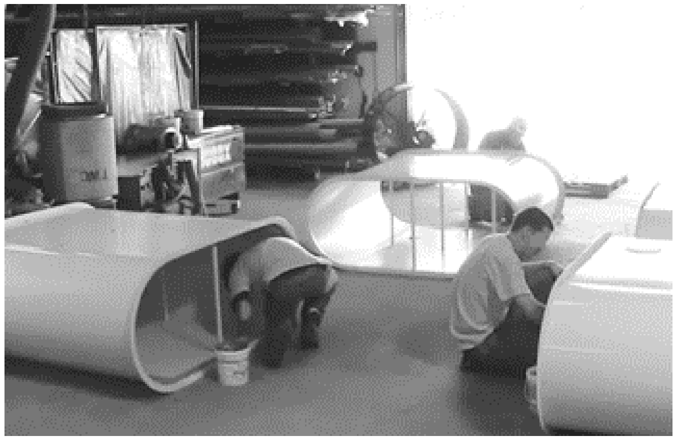

Figure 2: Sheet metal ducts sealing task performed by three workers

2.2 Data Analysis

The "Fabrication of Sheet Metal Ducts" activity was broken down into the four-level hierarchy, such as activity, task, action, and movement. This activity consisted of eight different tasks: (i) roll bending, (ii) lock forming, (iii) lock setting, (iv) tie-rod installing, (v) flange screwing, (vi) sealing, (vii) packing, and (viii) delivering (Mani et al. 2016). This study mainly focuses on the "sealing" task. This sealing task was the sixth task of the activity and was broken down into three actions and eight movements following the hierarchical structure as listed in Table 1. The individual worker performed these actions or movements to accomplish sealing task. All these actions and movements were identified from the video data by converting it into individual images by applying the frame separation algorithm in Matlab (Cai and Aggarwal 1996). At the action level study, data points for the analysis were 351 (117 x 3 = 351). In movement level study, data points for the analysis were 936 (117 x 8 = 936).

Table 1: Actions involved in "Sealing" task

Task	Actions	Movements
Sealing Task	Laying the duct for sealing (A_1)	Lift and move the duct from stacks (M_1) Lay the duct on the ground for sealing (M_2)
	Filling sealer at joints of the duct and flanges (A_2)	Hold a bucket containing sealer (M_3) Hold a paint brush (M_4) Fill sealer on the duct joints and flanges (M_5)
	Stacking the duct (A_3)	Move the duct towards stacks (M_6) Place the duct at stacks (M_7) Move back to the workstation (M_8)

2.3 Action Identification and Classification

Actions were identified by visual inspection (Bai et al. 2008, Wang et al. 2003) and classified into either contributory or non-contributory based upon their impact on work completion. The contributory actions are those which are necessary to accomplish this task. Non-contributory actions are considered non-productive and include actions, such as unscheduled breaks, time spent on attending personal matters (texting, or talking), disturbance by other workers, leaving the workstation for non-related work, and standing for a long time "without doing anything" (idle time). All contributory actions performed individual worker for "Sealing" task are listed in Table 1.

2.4 Productivity Frontier Estimation

During this study, two approaches—observed durations and statistically estimated durations—were established to compute the productivity frontier for the "sealing" task.

2.4.1 Approach 1: Observed Durations

The time and motion study was conducted by reviewing the video data and recorded the durations of the contributory actions for the "sealing" task. Since three workers were performing each action of the sealing task individually, the duration to complete this task was evaluated based on the performance of an individual worker. Therefore, three sequential datasets were classified and analyzed separately for each action. The shortest possible duration for this task was estimated by adding up the shortest durations observed for each action based on sequence of actions performed by an individual worker because the task was made up of actions in a specific sequence. Among available shortest durations for each sequential set of task, the shortest of the shortest duration is considered as the shortest observed duration for that task.

Let, the first worker W_1, second worker W_2, third Worker W_3, and Actions A_1, A_2, and A_3 of sealing task (T), then the shortest duration to complete the sealing task was computed for each dataset using Equations 1, 2, and 3. The shortest observed duration to complete the "sealing" task for one duct for the first worker was 601 seconds, for the second worker was 608 seconds and that for the third worker was 563 seconds as shown in Table 2. The minimum value among three sets was taken as the shortest observed duration to complete the sealing task (T). Thus, the shortest observed duration to complete this task was found to be 563 seconds. The number of ducts sealed was divided by this observed shortest duration in order to compute the equivalent productivity. The resulting equivalent productivity was 6.39 ducts per crew-hour.

[1] $T\text{-}A_1\text{-} W_1 + T\text{-}A_2\text{-} W_1 + T\text{-}A_3\text{-} W_1$
[2] $T\text{-}A_1\text{-} W_2 + T\text{-}A_2\text{-} W_2 + T\text{-}A_3\text{-} W_2$
[3] $T\text{-}A_1\text{-} W_3 + T\text{-}A_2\text{-} W_3 + T\text{-}A_3\text{-} W_3$

2.4.2 Approach 2: Statistically Estimated Durations

The probability distribution for each action involved in the task was obtained with the application of the "Input Analyzer" tool in the "Arena Simulation Software." Based on the best-fit probability distribution for each action obtained from the "Arena Input Analyzer," the threshold parameter (shortest duration) for that distribution was estimated using "Base SAS® 9.2." The shortest duration of the contributory actions for this task were estimated from the distribution, which were evaluated at a 95% confidence level, and values were recorded in the Excel spreadsheet. The shortest estimated duration for each action was estimated for each task. Using Equations (1), (2), and (3), the shortest duration to complete the sealing task was computed for each dataset. The shortest estimated durations for the first, second, and third datasets were 591 seconds, 523 seconds, and 548 seconds for Workers W_1, W_2, and W_3, respectively as shown in Table 2. The minimum value among these three sets was taken as the shortest estimated duration to complete the sealing task (T). Therefore, the shortest estimated duration was found to be 523 seconds. The number of ducts sealed was divided by this estimated shortest duration in order to compute the equivalent productivity. The resulting equivalent productivity was 6.88 ducts per crew-hour.

The estimated value of the labor productivity frontier was obtained by choosing the highest productivity from these two approaches-observed and estimated durations. For the "sealing" task, the productivity frontier computed from this study was found to be 6.88 ducts per crew-hour.

Table 2: Shortest observed and estimated durations of actions performed by three workers for the "Sealing" task (durations are in seconds)

Worker	Actions	Lowest Observed Durations	Lowest Estimated Durations	Distribution
W_1	A_1	7	7	Gamma
	A_2	590	581	Exponential
	A_3	4	3	Gamma
W_2	A_1	9	9	Lognormal
	A_2	591	506	Weibull
	A_3	8	8	Weibull
W_3	A_1	10	9	Gamma
	A_2	546	532	Weibull
	A_3	7	7	Gamma
Total Shortest Durations for Sealing Task		563	523	

* (Note: SOD = Shortest observed duration; SED = Shortest Estimated Durations)

3. RESULTS

When comparing results obtained from the research, this study identified the following differences in the performances of three workers.

- The first worker completed 37.6% of the total work of the "Sealing" task (44 out of 117 ducts), whereas the second worker accomplished only 18.8% of the total work of that task (22 out of 117 ducts). The third worker sealed 43.6% of the total sealing work (51 out of 117 ducts).
- There were three datasets classified based on the sequence of actions performed by three workers. All of them accomplished "sealing" in the sequential order: (i) laying the duct for sealing, (ii) filling sealer at joints of the duct and flanges, and (iii) stacking the duct.
- The shortest observed duration taken by the first worker to complete the "sealing" task was 601 seconds, for the second worker was 608 seconds and that for the third worker was 563 seconds. Thus, the shortest observed duration to complete this task was found to be 563 seconds. The number of ducts sealed was divided by this observed shortest duration in order to compute the equivalent productivity. The resulting equivalent productivity was 6.39 ducts per crew-hour.
- The shortest estimated duration by the first worker to complete this task was 591 seconds and that for the second worker was 523 seconds, and that for the third worker was 548 seconds. Therefore, the shortest estimated duration was found to be 523 seconds. The number of ducts sealed was divided by this estimated shortest duration in order to compute the equivalent productivity. The resulting equivalent productivity was 6.88 ducts per crew-hour.
- From two approaches—observed durations and statistically estimated durations, the productivity computed for the "sealing" task were 6.39 ducts per crew-hour and 6.88 ducts per crew-hour, respectively. The highest productivity between them gives the labor productivity frontier for the "sealing" task, which was 6.88 ducts per crew-hour.

4. LIMITATIONS AND DISCUSSION

The estimated duration was obtained by estimating the lowest threshold parameter of each probability distribution in the "Base SAS® 9.2" software. Sometimes, it is difficult to plot best fitted probability distribution in this tool. For example, the SAS cannot plot the Erlang distribution. In such a scenario, the second best-fit distribution obtained from the "Arena Input Analyzer" was taken into account on the basis of a square error and p-value. The test shows that the lower the p-value when compared with the level of significance (α = 0.05), the poorer the fit in the probability distribution is (Kelton et al. 2010, Rockwell Automation 2013). During this analysis, only the best-fit curve having higher p-value is considered. Then, the threshold parameter is estimated for that probability distribution in the “Base SAS® 9.2” software. This software not only tests the best-fit probability distribution, but also shows its parameters including the lower threshold parameter with corresponding p-value for each test.

This paper is mainly focused on the estimation of the productivity frontier. The estimation of optimal productivity is outside the scope of this paper. Kisi et al. (2018) presents a detailed description on how the productivity frontier is used to estimate optimal productivity following top-down and bottom-up approaches as shown in Figure 3. The top-down approach yields the upper level estimation of optimal productivity by deducting system inefficiency losses from the productivity frontier. The bottom-up approach yields the lower level estimation of optimal productivity by adding actual productivity with operational inefficiency losses. Though the productivity frontier is a theoretical level of productivity and is not achievable in real practice, upon minimizing losses due to operational inefficiencies, the productivity of the task could be improved to nearly the productivity frontier. In addition, this research approach helps project managers to identify critical scenarios in a project’s lower hierarchical levels and address those problems on time in order to improve productivity (Mani et al. 2017). Also, this research shows the significance of the study of system and operational inefficiencies factors for the specific project.

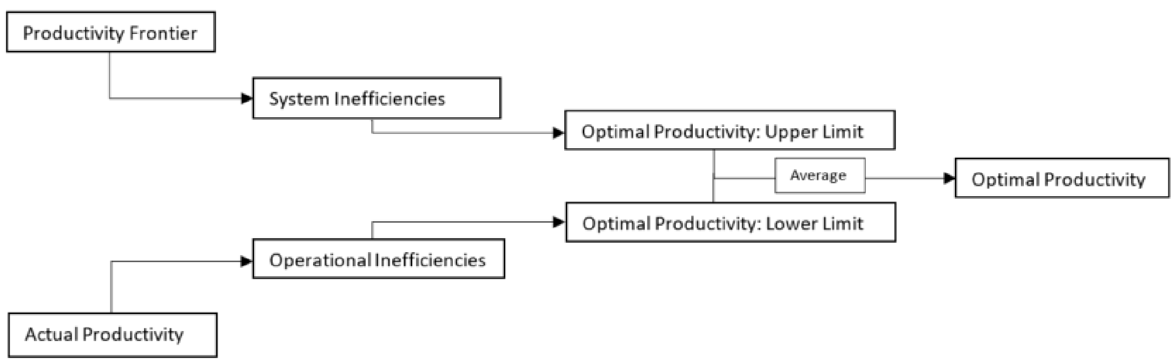

Figure 3: Framework for estimating optimal productivity

5. CONCLUSIONS

This research brings an innovative approach of analyzing productivity in construction engineering and management domain. It presents a research framework that estimates the productivity and evaluates the efficiency in the project level. This study reports the results of a case study for the “sealing” task by comparing performances of three workers. The maximum productivity that could be achieved for the “sealing” task is 6.88 ducts per crew-hour, which is the labor productivity frontier for this task. This labor productivity frontier acts as a benchmark to estimate optimal productivity. Estimating the accurate labor productivity frontier is the first step toward allowing project managers to determine the absolute efficiency of their labor-intensive construction operations by comparing actual versus optimal rather than actual versus historical productivity. Moreover, this research framework helps project manager to improve the level of productivity by avoiding or minimizing the impact due to operational inefficiency factors.

ACKNOWLEDGEMENTS

The authors acknowledge the assistance of the Waldinger Corporation and express their special gratitude to the manager, site supervisor, and workers for providing access to their manufacturing workshop. Without their support, this case study would not have been possible.

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