A FRAMEWORK FOR ESTIMATING LABOR PRODUCTIVITY FRONTIERS

by

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The efficiency of construction operations is typically determined by comparing actual versus historical productivity. This practice is accurate if historical data reflects optimal values. Otherwise, this comparison is a gauge of relative rather than absolute efficiency. Therefore, in order to determine absolute efficiency, one must compare actual versus optimal productivity. Optimal productivity is the highest sustainable productivity level achievable under “good management” and “typical field conditions,” while the productivity frontier is the theoretical maximum achievable under “perfect conditions.”

The productivity frontier is an abstraction useful in the estimation of optimal productivity of construction operations. This research contributes to the body of knowledge by introducing a novel framework to estimate the labor productivity frontier and applying it in a pilot study and a detailed study on the installation of lighting fixtures and the fabrication of sheet metal ducts activities.

The pilot study analyzed data on the fluorescent bulb replacement task up to the action level, collected from a school in Omaha, Nebraska to estimate the labor productivity frontier. Following two approaches–observed durations and estimated durations–the productivity frontier computed from this pilot study was found to be 22.32 stations per hour. The detailed study analyzed both action and movement levels by

collecting data from a workshop at a mechanical specialty constructor in Omaha, Nebraska. The pilot study only analyzed the sequential actions of a single worker. The detailed study analyzed the sequential and parallel actions and movements of crews of multiple workers involved in the fabrication activity. The productivity frontier for this activity computed from the detailed study, following both observed durations and estimated durations, was found to be 2.83 ducts per crew-hour.

Moreover, this research explores advanced automated frameworks using video cameras and a Kinect sensor in order to estimate the labor productivity frontier. One of the advantages of the proposed framework is that constructors, rather than being constrained by historical data, can also estimate the productivity frontier for activities they have never performed. Furthermore, scopes of this research–such as virtual environment development, recombinant synthetic workers development, and ergonomics and safety analysis–are also discussed.

To:

My parents, Dhana Prasad Mani and Shova Mani,

my wife, Lata Shrestha,

my sister, Sarika Mani and brother, Saujanya Mani,

my relatives and friends

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

The construction industry is considered one of the largest industries in the USA with the involvement of over 7.3 million workers and generating more than $1.73 trillion in annual revenue (Statistic Brain, 2015). As many construction operations are labor-intensive, the question of labor productivity becomes paramount especially as higher productivity levels typically translate into superior profitability, competitiveness, and income (Rojas & Aramvareekul, 2003). Labor productivity is becoming the prime factor because labor costs generally account for 30% to 50% of overall project costs in construction (Harmon & Cole, 2006). Unfortunately, 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 and ensure a more effective development of the vital infrastructure that society demands, creating a problem that Drucker (1993) succinctly articulated: "if you can't measure it, you can't manage it."

A project manager generally compares actual with historical productivity for equivalent operations in order to evaluate the efficiency of labor-intensive construction operations. But, this approach of examining productivity only provides a relative benchmark for efficiency. There is currently no systematic approach for measuring and estimating labor productivity (Song & AbouRizk, 2008). The operation may not be efficient even though the actual productivity equals average historical productivity because the operation's efficiency may be well below optimal productivity. This idea

further raises a concern that many factors involved in the processes of construction change overtime–productivity cannot be easily judged by the same data or information that was documented a decade or more ago (Liberda, Ruwanpura, & Jergeas, 2003).

The practice of benchmarking against historical averages will be biased and inefficient unless a standard methodology is implemented to evaluate productivity against an objective standard. This reality calls for an alternative technique to measure labor productivity. In an attempt to achieve this objective, this study introduces the terminology "*labor productivity frontier*" and develops a framework to estimate it. The labor productivity frontier is defined as the theoretical maximum productivity that could be achieved under "perfect conditions" (Son & Rojas, 2010). The perfect condition 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 errors, and precise understanding of the design intent, among others.

Although the labor productivity frontier is an abstraction that represents a production level not achievable in actual practice, it proves helpful in analyzing project conditions. The concept of productivity frontier can be used as an absolute benchmark because it provides a significant input value in order to estimate optimal productivity. Optimal productivity is defined as the highest sustainable productivity achievable in the field under good management and typical field conditions (Son & Rojas, 2010). By comparing actual versus optimal productivity, absolute (unbiased) efficiency can be calculated.

Several studies have been conducted regarding labor productivity, optimal productivity, and overall productivity (Rojas & Aramvareekul, 2003; Son & Rojas, 2010; Thomas & Sakarcan, 1994). However, there has been no research conducted regarding the estimation of the labor productivity frontier. This dissertation first introduces the proposed framework for estimating the labor productivity frontier, its underlying theory, and the methodology necessary for successful implementation. In turn, the estimation of the labor productivity frontier is the first significant step toward developing a process that will allow project managers to determine the efficiency of their labor-intensive operations.

1.2 Theoretical Framework

Figure 1.1 graphically depicts the relationships among several basic labor productivity concepts. The productivity achieved in the field is termed "*actual productivity*," whereas the level achievable under good management in sustainable manner and typical field conditions is called "*optimal productivity*." The difference between optimal and actual productivity is the operational inefficiency. 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 form the operational inefficiency. Operational inefficiency can be minimized by project managers through pre-evaluation of risk factors and by exhibiting unbiased attitude while adopting explicit and systematic methods (Son & Rojas, 2010). However, there are also factors that affect productivity which are not under the control of project managers, such as high temperatures, high humidity, rainfall, and workers' poor

health conditions. The collective effect of these factors constitutes the system inefficiency. If both operational and system inefficiencies are eliminated, then a theoretical maximum productivity could be achieved. The ideal theoretical maximum productivity achievable under "*perfect conditions*" is termed as "*productivity frontier*" (Son & Rojas, 2010). The 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). The point is shown in Figure 1.1 as time T_2.

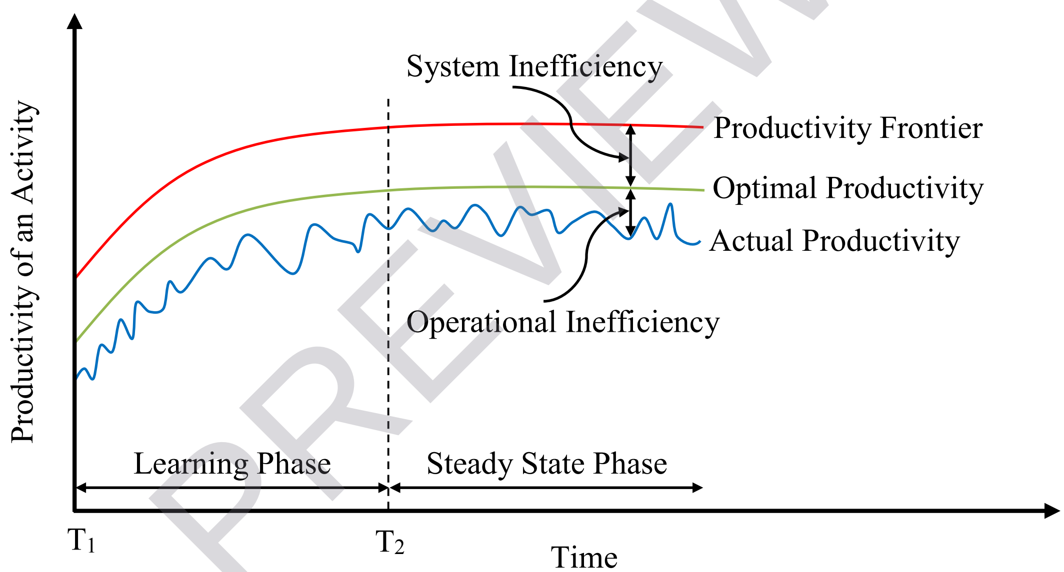

Figure 1.1 : Basic Productivity Dynamics

Out of all the variables shown in Figure 1.1, only actual productivity can be directly measured in the field. Therefore, given this limitation and the theoretical framework explained herein, the main challenges involved in the estimation of labor productivity frontier in labor-intensive construction operations include:

- Classifying the activity, tasks, actions, and movements

- Identifying the contributory and non-contributory actions
- Measuring shortest observed and estimated durations to complete an activity
- Developing the framework to estimate productivity frontier

1.3 Research Objectives

This study proposes the development of a dual approach for estimating the productivity frontier in labor-intensive construction operations. The first approach involves the estimation of the productivity frontier by using observed durations from a time and motion study. The movements of the workers 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 sequences of contributory actions are identified, based on the shortest time taken to complete a task or an activity, and used to determine the productivity as the sum of the shortest durations for each action.

Subsequently, 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 approaches is taken as the best estimate of the productivity frontier.

Building upon the theory, this research specifically established the following objectives:

1. Evaluate the feasibility of the proposed framework for estimating labor productivity frontier for a specific construction activity involving a single worker performing a specific task.
2. Evaluate the feasibility of the proposed framework for estimating labor productivity frontier for entire construction activities involving crews of multiple workers performing parallel and sequential works.
3. Determine the impact of collecting data to the action level of hierarchy in the initial phase and to the lowest hierarchical level (i.e., the movement).
4. Explore automation techniques to facilitate data collection and analysis in order to estimate labor productivity frontier.
5. Explore the application of simulation and visualization techniques (for example, animation in preliminary phase) in order to evaluate the work flow process of a specific task or activity.
6. Explore the feasibility of creating recombinant synthetic workers by aggregating basic movements.

1.4 Significance of Research

1. If the proposed framework were found to be scalable, practical, and reliable for estimating productivity frontier in complex construction activities, then a novel and validated tool would be available to project managers to estimate optimal labor productivity as well as to evaluate the efficiency of their construction operations.

2. If the benefits of collecting movement data for the proposed framework were to outpace the costs, then the additional effort required to move beyond the action level would be justifiable.
3. If data collection and analysis of the proposed framework could be automated, then the cost of implementation would decrease significantly.
4. If a simulated and animated construction environment could be developed, then it would be helpful to project managers or other laborers to understand work flow process of a specific task or activity and also helpful to validate the working procedures.
5. If independent movements could be recombined in a simulated environment to create synthetic workers and crews, then the productivity frontier of any construction activity could be determined. One of the advantages of the proposed framework is that constructors, rather than being constrained by historical data, can also estimate the productivity frontier for activities they have never performed.

1.5 Research Hypothesis

1. The proposed framework for estimating labor productivity frontier is applicable to complex construction operations with crews of single or multiple workers performing both sequential and parallel processes.
2. The costs of collecting movement data for the proposed framework for estimating labor productivity frontier outpace the benefits of moving beyond the action level.

3. Data analysis and collection activities can be automated for the proposed framework for estimating the labor productivity frontier.
4. The simulated and animated work flow process of an activity and a task is applicable to validate the working procedure.

1.6 Dissertation Structure

This dissertation consists of eight chapters. It is a compilation of documents in a single report describing the background of the research, the significance of the research, methodology followed to conduct the research, a description about the data acquisition, pilot study, detailed study, analytical results obtained from time and motion study, as well as probability distribution analysis, formation of models and their validation, and a discussion about the limitations of the research as well as recommendations for future research. The structure of the dissertation with its components is described briefly as follows:

Chapter 1 Introduction: This chapter consists of problem statement, theoretical framework, research objectives, significance of this research, and the research hypotheses.

Chapter 2 Literature Review: This chapter covers the foundation and guidelines of research. It discusses background of labor productivity by reviewing previously published papers and books, before analyzing the labor productivity frontier, such as existing definitions of labor productivity, labor productivity benchmarking and metrics, critical analysis of various methodologies implemented to evaluate performance of

construction activities, existing techniques to estimate labor productivity, and identified impediments to the achievement of high productivity levels.

Chapter 3 Research Methodology: This chapter first defines the theoretical underpinnings of the proposed framework to achieve research objectives. Then it thoroughly describes each step of the basic framework of this research, history of data collection, and statistical background. Moreover, it briefly discusses advanced framework to estimate the labor productivity frontier.

Chapter 4 Pilot Study: The preliminary study (pilot study) results appear in this chapter. The pilot study is conducted in order to determine the feasibility of proposed manual framework while estimating the labor productivity frontier considering a simple electrical bulb replacement task performed by a single worker. This chapter includes field data collection, data analysis, action identification, action classification, model development, model validation, and productivity frontier estimation following two approaches: observed duration and estimated duration. Finally, limitations of this research are also discussed in this chapter.

Chapter 5 Detailed Study: The detailed study describes extended research on labor-intensive manufacturing operations during fabrication of sheet metal duct at a workshop of the Waldinger Corporation in Omaha, Nebraska. The evaluation of the feasibility of the proposed basic framework (manual framework) for estimating labor productivity frontier is conducted for the entire manufacturing activity involving crews of multiple workers performing parallel and sequential works. The reason behind selection of this activity, working environment, video data collection, data extraction, data analysis, action and movement identification and classification, observed and estimated

durations determination, labor productivity frontier estimation, comparison between performance of multiple crews on the specific task, comparison between hierarchical action and movement levels analysis, and limitations of this research are also discussed in this chapter.

Chapter 6 Conceptual Exploration of an Automated Framework: As basic framework (manual framework) to estimating labor productivity frontier is more time consuming and laborious, this chapter explains an exploration of an automated advanced framework with its scope in the construction engineering and management domain. It explains two separate frameworks: (a) using multiple video cameras and (b) using a Kinect sensor during data collection stage. Various stages involved in this automated framework–such as workers pose modeling and tracking, action identification and classification, database development, model development and validation, and productivity frontier estimation–are discussed in this chapter. Moreover, limitations of this framework and possible obstacles are also discussed in this chapter.

Chapter 7 Conclusions and Recommendations: This chapter discusses a comparison between the pilot study and the detailed study. Conclusions and limitations of the research are discussed in this section. In addition, potential research areas are also recommended in this section.

Chapter 8 Future Research: This section introduces new terminology, "*recombinant synthetic workers*," and discusses its possible applications with a brief explanation about virtual environments in construction engineering and management domain. The usability of the labor productivity frontier for estimating optimal productivity is also discussed briefly in this chapter.