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Conceptual Framework of Construction Productivity Estimation

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Abstract

Construction productivity has been generating significant interest in both the construction industry itself and academia. Productivity management is currently recognized as a formal project management process in construction. However, most previous studies focused on defining factors that influence productivity and on measuring limited parts of activities at a micro level to investigate the relationship between factors and productivity. Construction productivity rates differ between projects because of the varying environments, characteristics, and project management efforts for each project. This study performed an extensive literature review on productivity in construction to support the rationale of a proposed conceptual productivity estimation model. The conceptual model is proposed for estimating productivity: expected productivity based on both project environment factors and management efforts. It also presents a comparison between project productivity expected, given the project environment and level of management efforts, and the raw (observed) productivity measure in the field.

Keywords: *productivity, estimation, project management, project environment*

1. Introduction

Because the business environment in construction is highly competitive, the participants in the industry must improve construction productivity performance to survive. Hence, construction productivity has been generating significant interest in both the construction industry itself and academia. Productivity management is currently recognized as a formal project management process in construction (Park et al., 2005). As The Business Roundtable (BRT) Construction Industry Cost Effectiveness (CICE) Project report pointed out, companies need measurement and comparison with others to improve construction productivity (BRT, 1982a). However, most previous studies focused on defining negative factors that influence productivity and on measuring limited parts of activities at a micro level to investigate the relationship between factors and productivity. Construction productivity rates differ between projects because of the varying environments, characteristics, and project management efforts for each project. Therefore, when analyzing construction productivity, one should consider the drivers that cause construction productivity differences between projects (CII, 2001).

This study performed an extensive literature review on productivity in construction to support the rationale of a proposed conceptual productivity estimation model. The literature review focuses on two main areas: construction productivity measurement issues and factors that impact construction productivity. Then the conceptual model is proposed for estimating productivity: expected productivity based on both project environment factors and management implementation. It also presents a comparison methodology between project productivity expected, given the project environment and level of management efforts, and the raw (observed) productivity measure in the field. Differences in expected productivity and raw (observed) productivity can serve as a performance indicator. The proposed model is different from previous productivity models in that previous research focused on limited number of factors: relationship between productivity and weather or change management effort, but this research effort proposes a model that includes all possible factors to accurately estimate productivity.

2. Scope

The term 'construction productivity' in this study is used synonymously with labor productivity, where input includes only labor work hours for an activity. It is because labor is major input for construction and a flexible variable for management than other resources such as materials and equipment.

Also, this paper proposes only a theoretical productivity estimation model rather than validating the model due to lack of data at this time. The model can be validated using enough amount of data in the near future. All environment factors and management efforts can be included in the model. Therefore, environment factors and management efforts that show major correlation with productivity based upon previous research results are included in the estimation model.

3. Definition of Productivity

Back in 1986, Thomas and Mathews (1986) stated that no standardized productivity definition had been established in the construction industry. It is difficult to define a standard productivity measure because companies use their internal systems which are not standardized. Productivity can be simply illustrated by an association between an output and an input. Two forms of productivity were used in previous studies and in the

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industry: 1) productivity = output/input and 2) productivity = input/output. The first form has been widely used in the construction industry and the existing literature and the second form has been usually used for estimating.

In terms of the number of variables in calculating productivity, there are two types of productivity: total factor productivity and single factor productivity. Total factor productivity (TFP) or multi-factor productivity includes multiple factors such as labor, equipment, materials, and capital as inputs. Total factor productivity is usually used in economics studies and not in construction. The equation for TFP is:

$$TFP = \frac{Dollars\ of\ Input}{Dollars\ of\ Output} = \frac{Labor + Equipment + Materials + Capital}{Total\ Output}$$

In contrast, single factor productivity only considers one input to calculate productivity. Labor productivity that considers only labor as an input is commonly used in the construction industry (Woo, 1999). The equation is:

$$Labor\ Productivity = \frac{Input}{Output} = \frac{Actual\ Work\ Hours}{Installed\ Quantity}$$

As shown in the above equation, labor productivity is measured in actual work hours per installed quantity; that is, the number of actual work hours required to perform the appropriate units of work. When defined in this manner, it should be mentioned that the lower the productivity measurement value, the better the productivity performance.

4. Productivity Measurement In Construction

A vast number of publications exist on construction productivity, but there is no agreed upon definitions of work activities or a standard measurement system. As productivity researchers have stated, it is difficult to obtain a standard method to measure construction labor productivity because of project complexity and the unique characteristics of construction projects (Oglesby et al., 1989). The uniqueness and non-repetitive operations of construction projects make it difficult to develop a standard productivity definition and measure (Sweis, 2000). Productivity requires a continuous effort to track and manage productivity at the project level and at the company level (Woo, 1999, Halligan et al., 1994). Collected past project productivity data can be used for future estimation processes.

4.1 Productivity Measurement Systems

The CICE project report reviewed construction productivity measurement procedures and then recommended that productivity measurement programs should be established (BRT, 1982a). In 1990, Construction Industry Institute (CII) developed a productivity measurement system that includes a reporting system, an output and input measuring system, and a performance evaluation system to measure site-level productivity (CII, 1990a). Adrian and Boyer (1976) established the Method Productivity Delay Model (MPDM) to measure, predict, and improve the productivity of a given construction method. Weber and Lippiatt (1983) reviewed the methods for measuring single factor productivity and total factor productivity in construction. Thomas and Yiakoumis (1987) described the factor model that contains environmental, site, management, and design factors for structural steel and masonry formwork activities. Sanders and Thomas (1993) further identified factors such as construction methods, design requirements, and weather that affect masonry productivity and investigated the effect of factors using the factor model with data obtained from standardized collection procedures. Another model, the action-response model, also provides a framework for evaluating the causes of productivity loss on projects to mitigate or eliminate the loss of productivity (Halligan et al., 1994). As Liou and Borcherding (1986) determined, productivity measurement is not a one-time task. Continuous measurement and comparison with other projects or companies are the keys to productivity improvement. Thomas and Yiakoumis (1987) stressed the importance of a standardized productivity data collection system to provide reliable analyses.

The productivity measurement research studies mentioned above have focused on how to report, measure, control, evaluate, and improve construction productivity. Furthermore, the existing productivity measurement systems have focused on micro level activities to manage daily or monthly productivity during construction.

4.2 Workstudy

Another aspect of productivity measurement research is “*workstudy*” which identifies how effectively the work was performed. *“Workstudy”* encompasses work sampling, foreman-delay surveys (FDS), group timing techniques, and five-minute rating. Workstudy measures the productive work hours during overall work hours. Thomas and Holland (1980) compared work sampling programs implemented on seven power plant projects and one industrial project. Then, they reviewed the activity categories, data collection techniques, intervals between studies, and data analysis procedures. Tucker et al. (1982) introduced foreman-delay surveys (FDS), which is a method to classify problems resulting in productivity loss with the intent to improve productivity. Foreman-delay surveys were later evaluated and compared to work sampling by Rogge and Tucker (1982). The study found that both FDS and work sampling are effective tools to improve productivity, but FDS provides the benefits of ease of use and economy (Rogge and Tucker, 1982). Thomas and Daily (1983) described and compared three productivity-measuring methods: work sampling, group timing techniques, and five-minute rating using the data from a time-lapse film. They concluded that work sampling describes more valuable information about the characteristics of delays such as waiting for materials and instructions. Researchers have also investigated the relationship between work sampling information and productivity to prove that work sampling can be used as a predicator of construction productivity using statistical techniques like multiple regression and the Pearson correlation coefficient (Liou and Borcherding, 1986, Thomas et al., 1984). However, Thomas (1991) claimed that the direct work from work sampling is not related to construction productivity after examining the variety in the range of data from previous studies. The study contradicts the results of previous studies that proved the relationship between direct work and productivity.

Even though “*workstudy*” is a useful tool to evaluate how effectively work is performed, its purpose is to improve productivity by identifying and reducing non-productive work rather than by measuring and estimating construction productivity.

5. Selected Factors on Construction Productivity

Management and environmental factors and their effects on productivity are areas that have generated a great deal of literature. Literature on factors that influence construction productivity identify both positive and negative impacts. A number of authors have identified the critical factors in management (Fox, 1978; Peltier, 1978; Tucker, 1986). Tucker (1986) determined the reasons causing productivity loss are: the relative influence of labor costs, more sophisticated labor demands, more complex and larger projects, more participants and communication, centralization and specialization, accelerated schedules, increased paper work, and lack of research. Borcherding (1976) listed the adverse factors on productivity in large industrial projects as follows: union, workmen selection, motivation, bureaucracy, scheduled overtime, and change orders. Other factors defined were containing congestion, sequencing, weather, supervision, plant status, information, equipment, tools, materials, and rework (Thomas and Sakarcan, 1994).

Even though a comprehensive list of factors has been identified, a data collection effort on the various factors has not been consistent. Most existing literature collected data on one or two factors to establish the relationship between productivity and the identified factor(s). More detailed review on selected factors that have been frequently researched was performed and the findings are discussed in the following sections.

5.1 Scheduled Overtime

The BRT (1986) reported that productivity decreases as the number of work hours per week increases. This means that scheduled overtime has a negative impact on productivity. CII has summarized previous studies concerning the effects of scheduled overtime on construction productivity (Thomas, 1990). Thereafter, CII investigated productivity loss caused by scheduled overtime and showed that the use of overtime may cause an average of 15 percent productivity loss (Thomas and Raynar, 1994). The reason for productivity loss from scheduled overtime was defined as disruption generally caused by resource problems (Thomas and Raynar, 1994). While most studies pointed out the negative impact of scheduled overtime, CII indicated that productivity does not unavoidably decrease during overtime and emphasized management efforts to overcome productivity loss from scheduled overtime (CII, 1988). In another study, Woo (1999) developed a simulation model to quantify and assess the impact of scheduled overtime on productivity and schedule.

5.2 Change Orders

Change orders have a significant impact not only on cost and schedule performance (CII, 1990b), but on construction productivity as well. Thus, CII has funded research to explore the impact of change orders on construction productivity (Hester et al., 1991, Thomas and Napolitan, 1994). The CII research shows an average 30 percent productivity loss caused by change orders, but finds that the early identification of change may reduce productivity loss (Thomas and Napolitan, 1994). Predictive models that quantify the negative effects of changes on productivity were developed using data from electrical and mechanical construction (Hanna et al., 1999a; Hanna et al., 1999b). The important finding from the models is the impact of the timing of the change orders. That is, the later a change order is initiated in the project life, the greater the adverse influence on productivity. This confirmed the results of previous research (Hanna et al., 1999a, Hanna et al., 1999b).

5.3 Materials Management

Materials issues like waiting for material, tools, or equipment are the major non-productive categories found in work sampling and foreman delay surveys. Consequently, the use of effective materials management would potentially benefit construction productivity (CII, 1986; Thomas et al., 1989). The different impacts of construction resources and methods on productivity were examined in high-rise in-situ concrete construction operations (Proverbs et al., 1999). Thomas and Sanvido (2000) claimed that productivity loss ranged from 5.4% to a high of 56.8% and was caused by materials management problems that included late or out-of-sequence deliveries and fabrication or construction errors based on three case study projects.

5.4 Weather

Most activities in construction are performed outside. Accordingly, construction work is adversely influenced by unexpected bad weather. Even though weather is an 'Act of God', the impact of weather on project performance should be considered in the planning phase to minimize the adverse impact of weather in the construction phase. Therefore, comprehensive studies regarding the impact of weather on productivity have been performed.

Temperature and humidity were identified as adverse factors on productivity (Koehn and Brown, 1985; Sanders and Thomas, 1991). According to Koehn and Brown (1985), it is difficult to achieve efficient performance under extreme weather conditions (below -10° F and above 110° F). Another research reports that about 30 percent of productivity loss occurred due to winter climate in steel erection construction (Thomas et al., 1999). A decision support system that quantifies the impact of rainfall on the productivity of highway construction was developed to estimate the activity schedule based on historical data and a knowledge base (El-Rayes and Moselhi, 2001).

5.5 Human Factors

As has been discussed previously, many factors influence construction labor productivity. However, the labor force itself is also another factor influencing labor productivity (Maloney, 1983). Lemna et al. (1986) identified productive foremen and determined their characteristics including planning, communication, and material and equipment management. Another approach regarding the human effect on productivity is to consider psychological factors that motivate workers. Motivation has received attention as a means to improve construction productivity (Borcherding and Oglesby, 1974; Borcherding, 1976). The study by Khan (1993), comprehensively reviewed how management implemented various motivation theories to improve productivity in the construction industry. Borcherding and Oglesby (1974) investigated the relationship between job satisfiers and construction productivity. Their influence on construction productivity were further determined using data collected through interviews and questionnaires (Borcherding et al., 1980; BRT, 1982b).

6. Estimation of Productivity

Literature cites a number of productivity models that describe factors and estimate productivity based on data collected. Contractor companies usually track construction productivity information and use their own historical productivity data to estimate future projects. This estimate can be used as a baseline for productivity and can be obtained by using historical data from similar projects (Sweis, 2000).

The regression model is the most frequent statistical technique used to estimate productivity (Sander and Thomas, 1993, Smith, 1999, Thomas and Završki, 1999). This technique enables one to identify the impact of various factors and establish productivity estimates based on actual productivity data. Hanna et al. (1999a) employed regression models to examine the impact of change orders on productivity for electrical and mechanical construction. Koehn and Brown (1985) established non-linear equations to explain weather effects on construction productivity.

The learning curve also is an important factor in productivity. The learning curve theory states that the productivity of the same repetitive work will be continuously improved as a result of greater familiarity with the activity, better management, and more efficient use of tools and equipment (Oglesby et al., 1989). Mathematical learning curve models have been developed to predict productivity (Thomas et al., 1986; Thomas and Yiakoumis, 1987).

7. Conceptual Productivity Estimation Model

7.1 Raw Productivity and Baseline Productivity

This study proposes the productivity estimation model that considered the effects of project environment factors and management efforts. Raw productivity is defined as an observed value during construction. It includes the effects of project environment and management efforts performed by a project team. Therefore, raw productivity is not an absolute productivity value. For example, same workforce may produce different productivity rates in same work on different construction sites due to different environment even though their management efforts are same. It means one needs to detect the impacts of project environment and management efforts to calculate absolute productivity called by baseline productivity in the paper. Baseline productivity is pure productivity rates for each work. The previous study defined baseline productivity as the best productivity can be achieved and is unaffected by disruptions (Thomas and Završki, 1999). Previous study considered only negative impact of project management in means of disruptions. Therefore their baseline productivity is the best performance. However, the rationale of this framework is that project management may also have positive impact on productivity. The concept of baseline in the paper is silmilar with adjusted productivity (Thomas et al., 1999). It enables to estimate expected productivity during a project planning phase. Fig. 1 illustrates the conceptual relationship between baseline productivity, raw productivity, and productivity estimates.

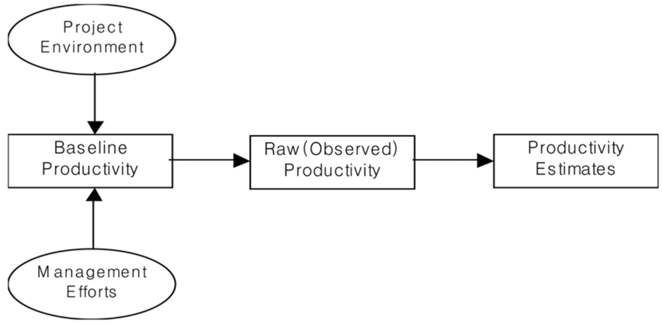

Fig. 1. Conceptual Framework of Productivity Estimation Model

7.2 Impact of Project Environment Factors

An earlier productivity study identified work environment and project characteristics variables that may impact construction productivity (Thomas and Sakarcan, 1994). This paper proposes 14 project environment factors based on comprehensive literature review: weather, labor skill, labor availability, materials availability, site conditions, project complexity, regulatory requirements, project team experience, project team turnover, detailed engineering design location, business market conditions, absenteeism, technology use, and human factor. It also proposes use of these 14 environment factors to calculate expected productivity.

An ordinal scale can be used to measure project environment factors. This scale ranges from highly negative to highly positive. As shown in Fig. 2, it assesses whether environment factors adversely or positively affected construction productivity beyond the conditions for which companies planned.

7.3 Impact of Management Efforts

Productivity differences among projects may be influenced by the degree of management efforts. This paper includes eight practices recommended by CII that may impact on productivity: pre-project planning, change management, constructability, materials management, zero accident techniques (safety), quality management, team building, and automation/integration technology. Practice use is scored from 0 to 10 (10 indicating fully use).

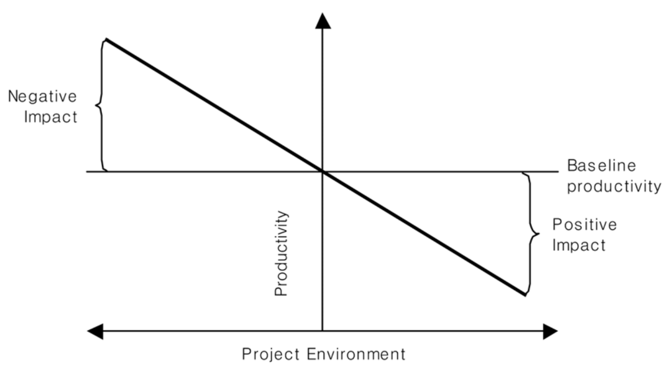

Fig. 2. Conceptual Impact of Project Environment Factors

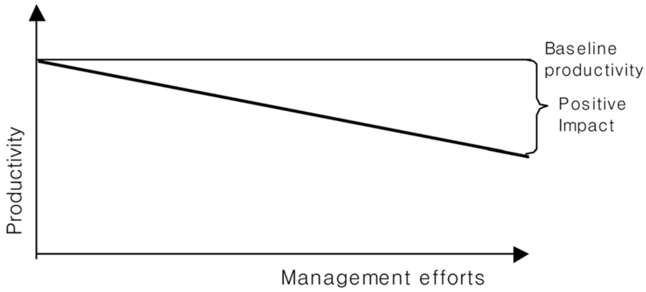

Fig. 3. Conceptual Impact of Management Efforts

The conceptual relationship between management efforts and productivity is depicted in Fig. 3. Comparing with environmental factors management efforts consider only positive impact on productivity.

The definitions of practices surveyed by the CII are listed as follow (Park, 2002):

- Change Management is the process of incorporating a balanced change culture of recognition, planning and evaluation of project changes in an organization to effectively manage project changes.
- Constructability is the effective and timely integration of construction knowledge into the conceptual planning, design, construction and field operations of a project to achieve the overall project objectives in the best possible time and to obtain accuracy at the most cost-effective levels.
- Materials Management is an integrated process for planning and controlling all necessary efforts to make certain that the quality and quantity of materials and equipment are appropriately specified in a timely manner, are obtained at a reasonable cost, and are available when needed. The materials management systems combine and integrate the takeoff, vendor evaluation, purchasing, expediting, warehousing, distribution, and disposing of materials functions.
- Zero Accident Techniques include the site-specific safety programs and implementation, auditing and incentive efforts to create a project environment and a level of training that embraces the mind set that all accidents are preventable and that zero accidents is an obtainable goal.
- Team Building is a project-focused process that builds and develops shared goals, interdependence, trust and commitment, and accountability among team members and that seeks to improve team members problem-solving skills.
- Pre-Project Planning involves the process of developing sufficient strategic information that owners can address risk and decide to commit resources to maximize the chance for a successful project. Pre-project planning includes putting together the project team, selecting technology, selecting project site, developing project scope, and developing project alternatives. Pre-project planning is often perceived as synonymous with front-end loading, front-end planning, feasibility analysis, and conceptual planning.
- Automation/Integration Technology evaluates the degree of automation and integration of automated systems for predefined tasks and work functions common to most projects.
- Quality Management incorporates all activities conducted to improve the efficiency, contract compliance and cost effectiveness of design, engineering, procurement, QA/QC, construction, and start-up elements of construction projects.

7.4 Theoretical Model for Productivity Estimation

This study established the methodology for development of the multiple regression model in terms of project environment factors and the management efforts. Further research is required to complete the model after collecting data.

The combined affects of project environment and management efforts can be assessed by development of a multiple regression model. Such a model would more fully explain variation in productivity by controlling for both environment and management efforts as illustrated below. Expected productivity can be described as a function of raw productivity, project environment factors, and management efforts as described in the following equation.

Expected Productivity
= f(raw productivity, project environment, management efforts)

The proposed multiple regression model would follow.

$$\text{Expected Productivity} = \beta_0 + \beta_1 x_1 + \beta_2 x_2$$

Where, x_1 : project environment factors
x_2 : management efforts
β_1 : standard impact of project environment factors
β_2 : standard impact of management efforts.

The coefficient "β_i" measures the effects of the project environment factors and the management efforts assuming the other index is held constant. Expected productivity can be compared with raw productivity for an indication of productivity performance using formulas listed below.

Productivity Difference (*PD*)
= Raw productivity – Expected Productivity

Productivity Performance Index (PPI) = (Raw Productivity – Expected Productivity)/Expected Productivity

If raw productivity value is smaller than expected productivity then productivity performance of the project is better than that of the similar projects in the database considering the affects of environment and management efforts for the project being analyzed. If PPI is smaller than 0 means that productivity performance is better than productivity estimate and vice versa.

8. Conclusion

Construction productivity rates differ between projects because of the varying environments, characteristics, and level of management implementation. This paper proposes a methodology for use of project environment and management efforts to assess expected productivity based upon comprehensive literature review.

The conceptual productivity estimation model was proposed: expected productivity based on both project environment factors and management efforts. Raw productivity can be measured during construction phase. Expected productivity can be calculated using a regression model developed based on a large number of similar projects in the database. Expected productivity then could be compared to raw productivity on the project and productivity performance of the project could be assessed.

Further study is needed for comprehensive statistical analyses to develop a construction productivity estimation model. This paper provided the framework on how to use project environment factor and management implementation information to develop a productivity model. The next step is to statistically establish a model with a sufficient amount of data. This model has conceptually established the relationship between project environment factors, management efforts and construction productivity. From this expected productivity can be estimated and productivity performance can be evaluated by comparing raw productivity with expected productivity.

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