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Complete List of Authors:	Ayele, Selam; University of Alberta, Dept. of Civil and Environmental Engineering Robinson Fayek, Aminah; University of Alberta, Dept. of Civil and Environmental Engineering
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A Framework for Total Productivity Measurement of Industrial Construction Projects

Selam Ayele[1] and Aminah Robinson Fayek, Ph.D., P.Eng.[2]

Abstract

Productivity measurement is a concern for both construction practitioners and researchers. In construction, productivity can be measured at three levels: activity, project, and industry. At the project level, previous studies focused on measuring the productivity of specific activities. In addition, existing project-level productivity metrics do not consider the effect of all resources used in a project. In order to effectively assess overall project performance, the productivity of all project activities and resources used must be taken into account. This study presents a framework that takes into consideration all resources used in a project and proposes a metric for measuring the total productivity of construction projects. A focus group session with experts, followed by questionnaire surveys, were used to assess the applicability of the framework. This paper makes a contribution by providing researchers and practitioners with a framework and tools for data collection and analysis of total construction project productivity.

Keywords: construction productivity, productivity measurement framework, total productivity metric, focus group, industrial construction.

[1] Masters Student, Hole School of Construction Engineering, Professor, Dept. of Civil and Environmental Engineering, Univ. of Alberta, 7-203 Donadeo Innovation Centre for Engineering, Edmonton, AB, T6G 1H9, Canada. E-mail: ayele@ualberta.ca

[2] Tier 1 Canada Research Chair in Fuzzy Hybrid Decision Support Systems for Construction, NSERC Industrial Research Chair in Strategic Construction Modeling and Delivery, Ledcor Professor in Construction Engineering, Professor, Dept. of Civil and Environmental Engineering, Univ. of Alberta, 7-203 Donadeo Innovation Centre for Engineering, Edmonton, AB, T6G 1H9, Canada (corresponding author). E-mail: aminah.robinson@ualberta.ca

1 Introduction

The construction industry is responsible for a significant portion of the gross domestic product in any industrialized nation (Huang et al. 2009; Vogl and Abdel-Wahab 2015). In 2016, the construction industry was responsible for approximately seven percent of Canada's total gross domestic product (GDP) (Statistics Canada 2017). Consequently, the levels of productivity and profitability observed in the construction industry have a major impact on the nation's economy (Vogl and Abdel-Wahab 2015). Due to the importance of the industry on Canada's economic health, improving and managing construction productivity has received significant attention by both practitioners and researchers during the last three decades (Huang et al. 2009; Thomas et al. 1990; Yi and Chan 2014; Yun et al. 2015).

Productivity may be conceptualized as the relationship between the output of the production process and the corresponding inputs that are required to generate that output. Typically, productivity is measured as a ratio of output to input or vice versa. For productivity measures that are expressed as a form of output-to–input ratios, higher numbers indicate better performance, however, in regard to input-to-output ratios, lower value represent better performance (CII 2013). The topic of productivity measurement extends from activity level to industry level measures and can be categorized into two classes: single-factor productivity (SFP) and multi-factor (or total-factor) productivity (MFP) (CII 2013). SFP compares the output to one specific input factor, such as labour or capital, while MFP compares the output to all relevant input factors. At the project level, productivity models utilizing measurements similar to MFP have been implemented; however, these models do not account for all available inputs, due to the difficulty and complexity of quantifying some inputs such as energy and capital (Thomas et al. 1990; Nasir et al. 2013). Previous methods in construction productivity studies have focused on

SFP, such as labour productivity, to assess the productivity level of construction projects (Yi and Chan 2014; Huang et al. 2009; Liao et al. 2012). Recent studies concerning project-level productivity have concentrated on aggregating labour productivity values of specific activities (Liao et al. 2012; Bröchner and Olofsson 2012; Yun et al. 2015).

Construction projects involve integration of different trades, stakeholders, activities, and resources in order to attain the project objective. By considering the joint impact of all resources used in a project, a meaningful measure of productivity can be achieved. Therefore, this paper proposes a framework for total productivity measurement, which considers tangible inputs used in a construction project, as well as the components required for quantification of the resource input categories. The total productivity measurement framework provides researchers and practitioners with a standard approach for data collection and analysis to measure the total productivity of industrial construction projects.

The paper is organized as follows. In section 2, a literature review is provided to examine productivity measurement and existing productivity metrics. Section 3 discusses the developed framework, which shows the metric and the list of input components. Section 4 outlines the verification of the proposed measurement approach and the developed framework. Finally, conclusions and avenues for future research are presented in Section 5.

2 Overview of productivity measurement in construction

The definition of productivity varies based on the application area, level of measurement, availability of data, and the objective of measurement (Crawford and Vogl 2006; Pekuri et al. 2011; Bröchner and Olofsson 2012). Pekuri et al. (2011) described productivity as a concept that is commonly used in theoretical and applied discussions, despite it being ambiguous and lacking a consistent definition. Table 1 shows sample productivity definitions adopted by different studies. According to Thomas et al. (1990), there are two major reasons for misconceptions about productivity measurement in the construction industry, the first of which involves the perception about what productivity is, while the second concerns the use of industrial engineering productivity measurement techniques in construction contexts.

Table 1: Definitions of productivity

Definition	Source
Productivity as the output potential of a production process, based on input resource. Measurement shows the impact of input on output.	Crawford & Vogl (2007)
Relationship between output per unit of effort employed to produce that output.	Thomas et al. (1990)
Productivity as a ratio of output produced to input used per unit of time.	Chau and Walker (1988)
Productivity as representing the efficient use of various factors of production.	Lowe (1987)
Productivity as indicating ability to use input resources to generate products and goods.	Phusavat (2013)
Productivity as a ratio of output to input for a given process.	CII (2013)
Productivity as a measure of the efficiency with which the economy turns inputs, such as labour and capital, into output.	Vogl and Abdel-Wahab (2015)
Productivity as a relationship between the output produced by a system and quantities of input resources utilized to produce that output.	Pekuri et al. (2011)
Productivity as a ratio of the output produced to the factors of production.	Vrat et al. (1998)

In general, productivity can be defined as a ratio of outputs to inputs, showing effectiveness and efficiency in utilization of resources. The most commonly used categorization of a production system in the construction industry involves three main levels: task or activity, project, and industry (Davis 2007; Huang et al. 2009; CII 2013; Thomas et al. 1990).

Activity-level productivity measures are the most commonly used productivity measure in the construction industry; it measures performance of individual construction activities, such as concrete placing, steel erection, etc. In contrast, project-level productivity measures consider the performance related to a collection of activities required for the construction of a particular facility. Industry-level productivity measures represent an overall assessment of the state of productivity in the industry sector. Table 2 gives a summary of several productivity measurement approaches in the construction industry at different levels of analysis. To reiterate, the focus of this study is on project-level construction productivity.

Table 2. Summary of productivity metrics at different levels of assessment

Level	Measurement Method	Productivity Measurement Approach	Source
Industry	Labour productivity	Ratio of gross output or value added to labour input. Use of index approach to measure gross output (or value added) and labour input.	Crawford & Vogl (2006)
		Use of output per labour hour or output per labour cost in constant dollars.	Vereen et al. (2016)
	Capital productivity	Use of index approach to measure gross output (or value added) and capital input.	OECD (2001)
		Multi-factor productivity, which takes labour, capital, and material as its inputs.	Crawford & Vogl (2006)
		Uses a ratio of gross output to capital services (e.g., equipment).	Vereen et al. (2016)
	Total factor productivity	Uses ratio of total output to inputs (costs of labour, materials, energy, and capital).	Thomas et al. (1990); CII (2013)
	KLEMS	Uses the quantity index ratio of gross output to combined inputs, which are represented by the change in quantities of labour, capital, energy, material, and service.	OECD (2001)

Project	Labour productivity	Measures the productivity of building projects by measuring the total manpower in man-days as an input and the completed gross floor area as output.	Lim (1996)
		Produces project-level productivity data by considering all the task elements, using a ratio of total worker hours and total equivalent work unit (EWU).	Ellis and Lee (2006)
		Quantity-based approach that measures construction productivity as actual work hours per installed quantity.	Yun et. a. (2015)
		Cost-based approach that uses cost of construction activities per work hours.	
		Uses engineering productivity, which is calculated as a ratio of direct engineering work-hours to issues, for construction quantities.	Liao et. al. (2012)
		Measures construction labour productivity as a ratio of actual work hours to installed quantity.	Yi and Chan (2014)
	Partial factor productivity (Labour and equipment	Productivity is measured as a ratio of physical output (units) to a combination of labour and equipment input in monetary terms.	Thomas et. al. (1990), CII (2013)
		Uses a ratio of physical output (units) to labour, together with fixed capital in dollar form, as an input value.	Goodrum and Haas (2002)
	Multi-factor productivity	Similar to TFP, integrates labour, material, and equipment as an input.	Thomas et. al. (1990)
		Multifactor productivity with labour, circulating capital, and fixed capital as an input.	Goodrum and Haas (2002)
Activity	Labour productivity	Labour cost or work hours per physical output (units).	Thomas et al. (1990)
		Labour productivity is measured as a ratio of actual direct work hours per install quantity or quantity issued for construction (IFC) quantity.	CII (2013)
		Labour productivity as a ratio of installed quantities to working hours.	Chang and Woo (2017)

2.1 Project-level productivity

A project may be defined as a collection of activities that are required for construction of a facility with a specific resource requirement and finite amount of work. Since it involves various activities, measurement of productivity at the project level has higher degree of complexity than activity-level productivity (Huang et al. 2009). In the past, different studies were conducted to develop project-level productivity metrics, which provide an estimate of the productivity of a project based on activity data (Ellis and Lee 2006; Liao et al. 2012; Yun et al. 2015).

Based on their previous studies, the Construction Industry Institute (CII) (2013) categorized prevalent metrics at the project level as output-to-input ratio and input-to-output ratio, depending on the expression that relates input and output. The category of output-to-input ratio includes factor productivity, partial factor productivity, and labour productivity. Factor productivity is expressed as a ratio of physical output in units to input, which combine labour, material, and equipment to create a dollar value; partial factor productivity can thus be estimated by removing one of the input resources from factor productivity. According to CII (2013), partial factor productivity measures are mainly used for a specific type of conceptual estimate to measure construction productivity.

For construction project-specific models, Thomas et al. (1990) identified a productivity metric, indicated in Eq. 1, which divides the physical output in units by the total cost of labour, equipment, and material. This model can be utilized by design professionals to provide information regarding the productivity of projects (Thomas et al. 1990).

$$(1)\quad factor\ productivity = \frac{physical\ output\ (units)}{labor(\$) + material(\$) + equipment\ (\$)}$$

Goodrum and Haas (2002) later modified productivity metric (Eq.1) by specifying equipment cost as fixed capital and material cost as a circulating capital, as is shown in Eq. 2.

$$(2)\quad factor\ productivity = \frac{pysical\ output\ (units)}{labour(\$) + circulating\ capital(\$) + fixed\ capital\ (\$)}$$

In an effort to account for the impact of all activities involved in construction projects, Ellis and Lee (2006) developed a project-level productivity measurement method that uses activity data from transportation projects, as shown in Eq. 3. The following metric expresses input in terms of the total worker hours of all crew members involved in the production of output, while the output is defined in terms of total equivalent work units (EWU). EWU is a converted value of the daily installed work quantities that are measured in different units. However, this approach sums up all the construction crafts without considering the variation of installed quantities, which is the common characteristic for activities in construction projects.

(3) $$PLP = \frac{total\ worker\ hours}{total\ EWU}$$

Based on existing data from CII and the Construction Owner's Association of Alberta (COAA), Yun et al. (2015) compared Alberta capital projects with U.S. capital projects by developing high-level project productivity metrics using a quantity-based approach and a cost-based approach. For the quantity-based approach, where construction productivity is measured based on actual work hours per installed quantity, the productivity of major construction disciplines is aggregated to develop a value for project-level construction productivity. These disciplines include concrete structures, steel, piping, equipment, electrical, and instrumentation. Cost-based approaches use the equation shown below (Eq. 4) as a general metric to calculate the productivity of construction activities. The output component of the metric uses any one of the following costs for construction activities: total constructed cost, total constructed cost minus equipment cost, or construction phase cost (Yun et al. 2015). Construction phase cost includes the cost of all activities, starting from initiation of the project to mechanical completion. The total construction cost is the sum of procurement phase and construction phase costs, the latter of which comprises both direct and indirect costs. Total construction cost includes costs related to the following project components: field labour, materials, equipment, supervision, subcontractors, administration, tools, and field office expenses.

(4) $$project\ productivity\ metric = \frac{cost\ for\ construction\ activities}{work\ hours}$$

Lim (1996) studied the productivity of building projects by measuring construction productivity as a ratio of built-up construction per man-day by proposing two separate metrics for completed and ongoing projects, as shown in Eq. 5 and Eq. 6 respectively.

$$\text{(5)} \qquad building\ productivity\ = \frac{gross\ floor\ area}{total\ manpower}$$

$$\text{(6)} \qquad monthly\ building\ productivity = \frac{monthly\ progress\ payement\ certified}{total\ contract\ sum} \times \frac{gross\ floor\ area}{monthly\ manpower}$$

Total manpower is equal to the total number of site workers expressed in terms of man-days (one man-day equals one man working for eight hours). Gross floor area indicates the completed floor area in m^2, and the ratio of monthly progress payment certified to total contract sum shows the percentage of building completed within a month.

The CII Benchmarking and Metrics (BM&M) program developed the Engineering Productivity Metrics System (EPMS), which uses quantity-based measures in order to quantify productivity in construction projects (Liao et al. 2012). The metric consists of four major levels. In the EPMS structure, Level I consists of a project-level metric, which is an aggregated value. The next level, Level II, entails a discipline metric, which is grouped into six disciplines that are related to construction activity: concrete, steel, electrical, piping, instrumentation, and equipment. The discipline level further comprises sub-categories (Level III) and elements (Level IV) for each category. For instance, the concrete major category in the Level II has three subcategories (Level III), "foundations", "slab", and "concrete structures", which are further divided into different element-level metrics (Level IV). Since the metric considered in EPMS is a ratio of engineering work hour per engineering quantities, the values for Level II, Level III and Level IV can easily be aggregated. However, for the discipline level (Level II), generalizing the metric to the project level (Level I) cannot be done, since it is measured using different units. In order to address this problem, Liao et al. (2012) developed a standardization approach to aggregate discipline-level metrics with different measurement units using data collected from CII member companies; this data was then used to calculate a project-level engineering productivity metric (PEPM).

The PEPM was developed by comparing three approaches for aggregating discipline-level categories, and then selecting the most effective method that satisfies the CII Productivity Metrics (PM) team requirements of "comprehensibility, homogeneity, and trending ability". The three approaches that were analyzed for include the earned-value method, the max-min method, and the z-score method (Liao et al. 2012). The earned-value method uses the ratio of total work hours over the predicted work hours for each of the six disciplines to quantify the productivity at Level I. The maximum-minimum method applies two procedures, which aggregate the disciplines to get the value for project-level productivity. The initial step is standardization, which is done by subtracting the minimum productivity value at discipline level, while the second step involves dividing the value resulting from step one by the range of the metrics, which is can be calculated by subtracting the minimum productivity value from the maximum productivity value. The third approach, the z-score method, applies a statistical method to transform the engineering productivity metric for every discipline into dimensionless measures suitable for aggregation. After comparing the results of the proposed methods, the z-score method was selected, as it satisfies the requirements listed by the productivity metrics team. Z-score has meaning only if it is calculated for observations that are part of a normal distribution.

Construction project processes involve many concurrent and interrelated activities. The metrics employed for assessing project productivity give attention to selected activities, while the success of a project depends on the performance of all activities. In general, past methods have focused on evaluating productivity using labour input, and limited attention has been given to the development of a metric that accounts for all resources used in a project. Moreover, there is no clear standard for assigning what must be included as an input. Multi-factor productivity measurement techniques are not implemented due to the difficulty in getting a proper estimate for quantifying the influence of all the activities and required inputs.

3 Total productivity measurement framework

Measuring total productivity in construction projects has challenges, which stem from the complexity in determining the components of an appropriate metric. This study proposes a framework to measure the total productivity of construction projects. The framework consists of a metric, its components, the basis for quantifying each component, and the data required for measurement, with a specific focus on industrial construction projects from an owner's perspective.

3.1 Total productivity metric

In order to propose a metric that can capture the effect of all resource inputs used in a construction project, a review of productivity studies involving different levels of the production system (industry, project, and activity) was conducted. As shown in Table 2, one difference between the measurement methods is the methodology adopted to quantify the elements of the metrics. At any level of productivity measurement, output is expressed either in physical quantity or in dollar value. For project-level productivity measurement, output is expressed in terms of functional units. Another component of productivity measurement is input, which refers to the values representing the resources required to undertake and complete a construction process or activity. The type and number of input values used in the measurement depends on whether the metric is for single-factor or multi-factor productivity. For multi-factor productivity measurements, the dollar value is used to quantify each input. Chau and Walker (1988) categorize inputs as being either tangible or intangible. Tangible inputs include resources such as labour, material, energy, and capital. Intangible inputs are factors that affect productivity, such as material quality, organizational effort, and advancement in technology.

In the development of productivity metrics for input and output data expressed in monetary terms, the values should be adjusted for inflation, which is commonly done with the use of deflators that remove the effects of price changes over time (Crawford and Vogl 2006). In examining the effect of equipment technology in partial factor productivity, Goodrum and Haas (2002) used the census construction index from the US Department of Commerce to adjust for the effect of inflation. Goodrum et al. (2009) considered the change in labour and material cost using the consumer price index (CPI) provided by the US Bureau of Labor Statistics in studying partial factor productivity measures in different periods of time.

Project-level productivity measurement for construction projects should include an analysis of all activities and the total output or completed work. Based on a review of the literature, this study proposes Eq. 7 as a metric to measure the total productivity in construction projects. Tangible output in the metric refers to physical units of project output (e.g., km of highway or m of pipeline). Tangible inputs include labour, material, capital, energy, and other expenses quantified as a dollar value.

$$(7) \qquad total\ productiviy\ = \frac{tangible\ \ output\ (physical\ units)}{tangible\ inputs\ (\$)}$$

After proposing a metric for quantifying the total productivity of a construction project, a list of components to be included as part of each input resource category was established. Input resources are quantified in the following categories: labour, equipment, energy, material, and other expenses. Cost elements associated with each input resource category were grouped into different phases of the construction process. According to the Project Management Institute (PMI) (2000) Project Management Body of Knowledge guide, a construction project can be broken into five phases: initiation, planning, executing, controlling, and closing. The phases consist of overlapping activities that are linked with each other by the produced outputs or deliverables. The initiation phase servers as a foundational step in starting the project, during which time the necessary information for detailed project planning is gathered. In the planning phase, the course of action most closely in line with the project objective is selected. The other project management processes involve assigning resources and monitoring project progress until the final acceptance phase or closing stage of the project (PMI 2000). CII (1997) also identifies various project delivery phases, depending on the area of practice and implementation, suggesting that the main reason for the division of the project phase is for provision of better management control mechanisms. In an effort to determine an engineering productivity measurement approach, Chang et al. (2001) adopted a project phase delivery process developed by the CII Benchmarking and Metrics (BM&M) Committee. According to Chang et al. (2001), project phases can be delineated into five categories: pre-project planning, detailed design, procurement (material management), construction, and start-up and commissioning. For this study, the project lifecycle is grouped into five common project phases, similar to other classifications for industrial construction projects such as that proposed by Choi et al. (2016): initiation, planning & design, procurement, construction, and commissioning and start-up.

Determining major participants and associated costs in each phase provides a basis for identifying each input component for the productivity metric. Table 3 shows a list of major participants and typical cost elements in each phase of construction projects.

Table 3: Major participants and cost elements at different phases of a construction project

Initiation phase	
Major participants	Owner personnel (project board), owner project manager, owner administration staff, alliance/partners, financial analyst, owner legal staff, public relations personnel, planning consultants
Typical cost elements	Owner personnel fees, consultant fees and expenses, administrative costs, project manager fees, Land purchasing costs, environmental permit costs, legal fees, office consumables (standard office supplies, paper products, etc.)
Planning and design phase	
Major participants	Owner project manager, administration staff, alliance/partners, planning consultant, design consultants (architect, structural engineer, mechanical engineer, electrical engineer, etc.), constructability expert, cost consultant, geotechnical consultant, environmental consultant, value engineering expert, constructability expert, procurement personnel
Typical cost elements	Owner project manager fees, administration staff cost, consultant fees and expenses, permit costs, project manager fees, construction manager fees, constructability expert fees, value engineering expert fees, cost consultant fees, geotechnical consultant fees, procurement personnel, environmental consultant fee, planning consultant fee, licensor costs, office consumables (standard office supplies, paper products, etc.), communications and utilities costs (telephone costs, postage, etc.), vehicle allowances and transportation costs
Procurement phase	
Major participants	Owner project management personnel, contractor project manager, procurement personnel, expediting personnel, alliance/partners
Typical cost elements	Owner project management personnel fees, project manager fees, construction manager fees, procurement personnel fees, expediting personnel fees, office material costs, transportation costs, material costs
Construction phase	
Major participants	Owner project manager, administration staff, design consultants, contractor project manager, construction manager, project engineer, safety coordinator, QA/QC manager, project controls manager, construction superintendent, foremen, craft labour, subcontractor, constructability experts, procurement staff
Typical cost elements	Owner project management expenses, administration staff fees, design consultant fees, contractor project manager fees, project engineer fees, safety coordinator fees, QA/QC manager fees, project controls manager fees, construction superintendent fees, foremen fees, craft labour fee, subcontractors fee, construction equipment, tools and supplies, material cost, inspection and quality control costs, scaffolding costs, construction permits and warranties costs, site development costs, temporary facilities and services costs, office consumables (standard office supplies, paper products, etc.), mobilization and demobilization costs
Commissioning and start-up phase	

Major participants	Owner project management personnel, design consultants, construction contractor, training consultants, equipment vendors, inspection consultant, start-up manager, supplier representative, maintenance representative, safety coordinator, alliance/partners
Typical cost elements	Owner project management personnel expenses, project manager/construction manager fees, consultant fee and expenses, operator training expenses, office material costs, vendor fees

For the purpose of this study, the input for the productivity metric is divided into five categories: labour, material, capital, energy, and other expenses over the project lifecycle. The components of each input category were developed using the cost components and major participants list (Table 3) and a set of definitions shown on Figure 1.

The tangible output, expressed in physical units, indicates the amount of work done in the construction process. Depending on the project type, the output unit can be customized to indicate the total completed quantity of work. Assessing tangible output in physical units can be done at project completion. In order to assess tangible output during project construction, the output of activities that are completed must be aggregated, which is challenging due to different units of measurement. Several approaches have been proposed in the literature for aggregating activity-level outputs to a project-level output. Ellis and Lee (2006) defined output in terms of total equivalent work units (EWU), where EWU is a converted value of daily installed quantities, measured in different units, that accounts for the work hours involved in each activity. Yun et al. (2015) adopted the z-score method implemented by the CII (Liao et al. 2012) to aggregate discipline-level productivity to project-level productivity. Other methods proposed for measuring output of construction projects include: usable area of the constructed facility (Bröchner and Olofsson 2012), built-up construction per person-day (Lim 1996), and an equivalent unit of measurement of output based on the level of effort required to complete each activity (Keane and Caletka 2008). In this study, tangible output is defined at project completion or as equivalent work units during project construction.

After proposing the metric and developing the list of components required for measuring productivity, a focus group discussion was held with industry experts to assess the completeness and viability of the measurement framework.

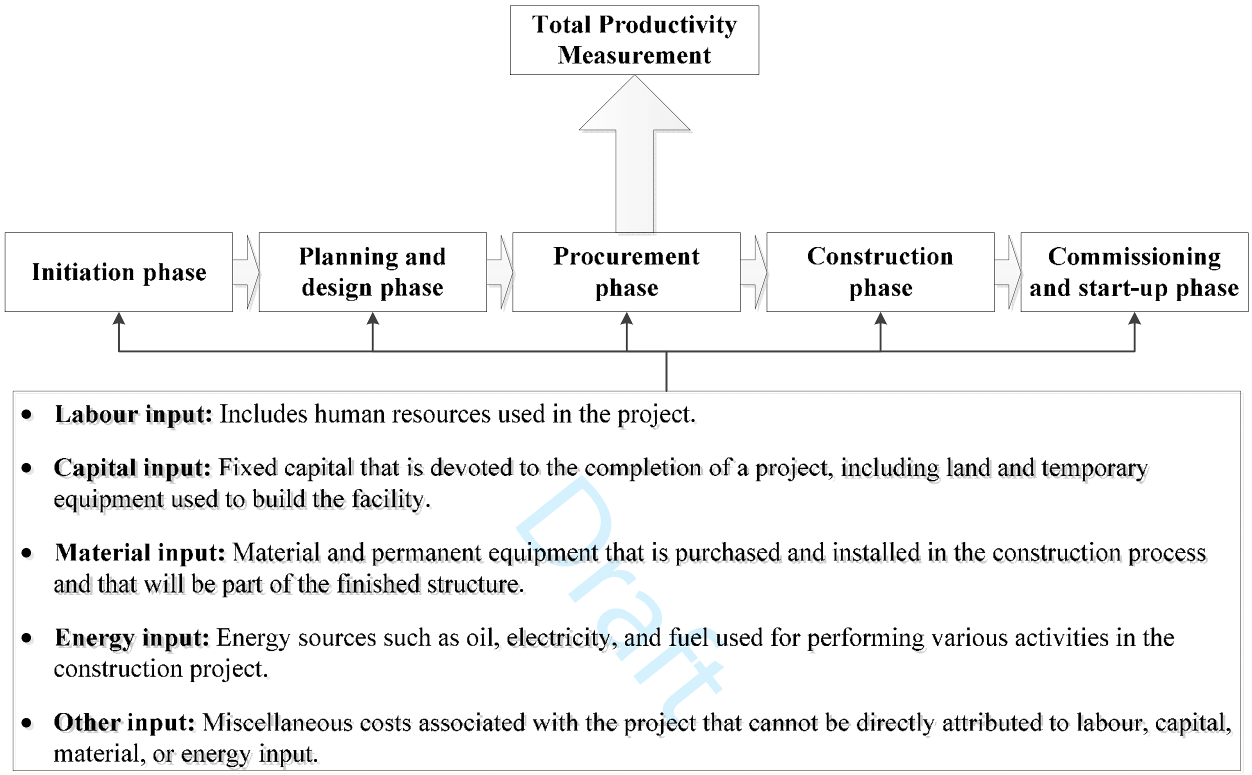

Figure 1. Total productivity measurement framework components

3.2 Measurement framework development and evaluation

Focus group discussions are a qualitative research technique designed to explore individual perspectives regarding a particular topic and collect multiple perspectives simultaneous (Albanesi 2014). For the purpose of this study, focus group discussions were used to assess the feasibility of the measurement framework and to determine all the input categories and their components required for measuring total productivity. After identifying the list of components for each input category, an in-depth semi-structured focus group discussion was held with industry experts. Individuals with expert-level experience working in heavy industrial construction were approached to participate in the study session. Four experts comprising managing directors and senior managers representing company owners participated in the study, and they held the following positions: vice-president, general manager, manager, and director. Participants had over 20 years of experience, mostly in the heavy industrial construction sector.

The discussion was first initiated by giving an overview of the research and the aim of the focus group discussion. Each participant was asked a series of questions related to their perspective on the utilized approach, input categories, and challenges associated with the approach. In addition, a semi-structured questionnaire was provided in the discussion session. The questionnaire had three sections. The first section covered general demographic information, including total years of experience, and current occupation. In the second section, participants were provided with open-ended questions to assess their agreement on the following items: the metric, method of quantifying output and inputs, categorization of inputs, and difficulties that may be encountered using the proposed measurement approach. The third section asked participants to evaluate whether the listed components belonged in the input category and in the identified project phase. A sample is shown in Table 4 for indirect labour input category.

Table 4. Sample semi-structured questionnaire for indirect labour input category

☑ Place a check mark in the box only if the component belongs to both the project phase and the input category under which it is classified.

	Initiation Phase	**Planning & Design Phase**	**Procurement Phase**	**Construction Phase**	**Commissioning and Start-Up Phase**
Indirect Labour	☐ Public relations ☐ Financial analysts ☐ Owner legal staff **Additional suggestions** ______ ______	☐ Owner's project manager ☐ Administrative staff ☐ Procurement personnel ☐ Alliance/partners' representative **Additional suggestions** ______	☐ Procurement manager ☐ Design consultants ☐ Legal staff ☐ Alliance/partners' representative **Additional suggestions** ______ ______	☐ Owner project staff ☐ Project manager ☐ Construction manager ☐ Constructability consultant ☐ Accounting staff **Additional suggestions**	☐ Subcontractor staff ☐ Safety engineer ☐ Quality assurance/Quality control ☐ Equipment vendors **Additional suggestions** ______ ______

To analyze the data collected through the focus group session, "framework analysis", a five-step qualitative data analysis process proposed by Srivastava and Thomson (2009) was implemented. This approach involves the systematic process of arranging key information gathered from focus group discussions into themes. The steps involved are familiarization, identifying a thematic framework, indexing, charting, and interpretation. Familiarization refers to the stage where the researcher gets accustomed to the data collected (focus group data or notes). During the second stage, emerging themes are identified from the recorded notes and issues that are raised in the discussion. After identifying the themes, the data are labelled to correspond to a particular theme.

In the charting step, the collected data labelled in the previous stage are arranged in the themes. The final stage involves analysis of the key points identified in each theme. The framework analysis method was chosen because it has been well-established in social science research projects for the analysis of semi-structured interviews and textual data including documents, such as meeting minutes, diaries, and field notes from observations (Albanesi 2014; Leavy and Phillips 2014). The method provides clear steps to follow and offers structured output for qualitative data. Based on the analysis, the following themes emerged from the responses of the participants on the semi-structured questionnaire and through the discussion session: proposed total productivity metric; method of quantifying input and output; project phase classification; and categorization of tangible inputs.

3.2.1 Proposed total productivity metric

The total productivity metric is expressed as a ratio of total tangible output to total tangible input. The participants involved in the research study agreed on the appropriateness of the developed metric, and that it properly captures the total productivity of construction projects by measuring the effectiveness in utilization of resource. Studies link efficiency to the notion of “doing things right”, which indicates consumption of available resource at a satisfactory level (Yi and Chan 2014; Sundqvist et al. 2014). Effectiveness, on the other hand, is expressed as “doing the right things”, where the focus is on producing an output in accordance with specified requirements (Pekuri et al. 2011; Sundqvist et al. 2014). Productivity can thus be seen as a combined measure of effectiveness and efficiency (Pekuri et al. 2011; Roghanian et al. 2012). One participant pointed out that the commonly adopted procedure for capturing capital effectiveness and efficiency in their company is by breaking the project elements into different activities and assessing the cost required to complete an activity.

3.2.2 Quantifying input and output

All participants agreed with the method proposed for quantifying both the input and output values. The participants indicated that measuring the input of resources in terms of dollar value and output as a physical unit is a good approach for future benchmarking purposes and for comparing the productivity of a wide variety of projects.

3.2.3 Project phase classification

Understanding the phases involved in the project lifecycle is valuable for successfully guiding a project from its initiation stage to completion. The participants expressed that in the construction industry, there are different ways to describe the different construction phases. The participants agreed with the project phase classification adopted in this study, which involves the following five steps: initiation, planning and design, procurement, construction, and commissioning and start-up. The participants mentioned that for companies involved in heavy industrial construction sector, measurement of project performance should be done after the investment decision and should not include any of the cost elements associated with the initiation phase of the project.

3.2.4 Categorization of tangible inputs

Participants agreed that the categorization of tangible inputs into labour, capital, material, and energy in the metric is consistent with standard construction industry practices for classifying project inputs. However, the participants suggested a modification related to the other expense input category. According to the participants, the commonly adopted cost categories in heavy industrial construction include owner's costs, engineering costs, procurement costs, and construction costs. Input categories suggested in this research, including labour, material, capital, and energy, can be derived from the commonly adopted cost classifications. However, other expense input components cannot be consistently interpreted by framework users. In order to address this problem, participants suggested the creation of a separate input category, which considers indirect cost input components and owner costs. As a result of this modification, the other expense input category components were re-allocated to construction project indirect input and owner cost input, as described in sections V and VI below.

Furthermore, it was indicated that having a common approach for collecting input data would aid in the development of a standardized data collection approach for use by companies. Companies can also customize the framework to fit the project, depending on their sector of involvement in the construction industry. One participant mentioned that their company had previously implemented a similar approach to compare projects. In order to compare projects, all associated costs are listed, and the cost elements that are not common to all the projects can be removed to facilitate comparison of cost data among projects. Therefore, based on the participant’s suggestion, the initial framework shown on Figure 1 was later modified as shown in Figure 2. In the modified framework, consideration of input quantification for total productivity measurement starts at the planning and design stage. In addition, the other expense input is further grouped into construction project indirect and owner costs. A description and list of components for each input category are provided below in Sections I to VI.

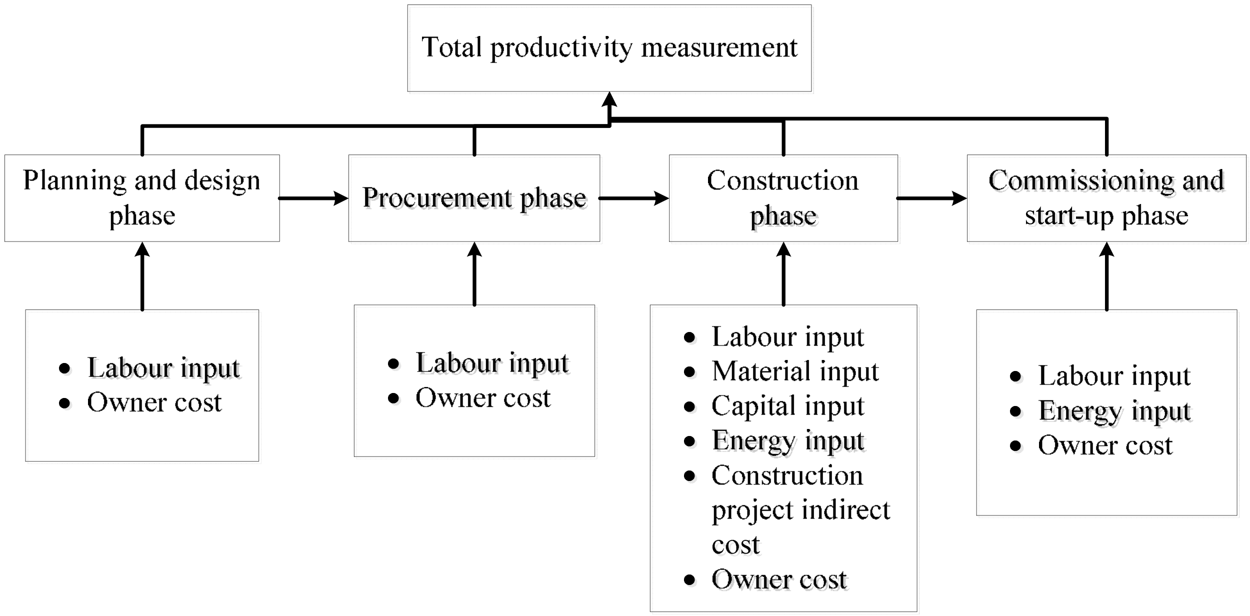

Figure 2. Modified total productivity measurement framework

I. Labour Input

Labour input shows effort provided by the workforce in the production system. Due to the nature of work involved in the construction industry, labour input constitutes 33–50% of the total project contract amount (Hanna et al. 2008). According to the focus group participants, determining the category of direct and indirect labour depends on various factors, such as type of organization, company strategy and project stage. For the purpose of this research, labour input represents the cost of human resource input utilized in the project. Based on the discussion in the focus group, Table 5 shows the major direct and indirect labour input components that are considered in calculating project total productivity.

Table 5. Labour input components

Project phase	**Direct labour input**
Planning and design	Owner project staff, planning consultants, constructability consultants, design consultants, cost consultants, value engineering experts, environmental consultants
Procurement	Owner project staff, procurement personnel, expediting personnel
Construction	Direct craft labour, foreman, heavy equipment operators
Commissioning and start-up	Owner project staff, design consultants, facility operators, commissioning consultants
Project phase	**Indirect labour input**
Planning and design	Owner project manager, administrative staff, legal staff, accounting staff procurement personnel, alliance/partner representative
Procurement	Owner project manager, project manager, accounting staff, administrative staff, procurement manager, design consultants, legal staff, alliance/partner representative
Construction	Owner project manager, owner project staff, project manager, construction manager, discipline engineer, site engineer, design consultants, project engineer, project control personnel, constructability consultant, accounting staff, administrative staff, procurement staff, material control personnel, workface planner, general foreman, superintendent, safety personnel QA/QC personnel, field survey/layout crew(s), subcontract specialists, field clerical staff, legal staff, security, janitorial staff
Commissioning and start-up	Owner project manager, project manager, document controller, administrative staff, subcontractor specialists, safety engineer, QA/QC personnel, equipment vendors, start-up manager

II. Material Input

Material input category includes any physical material constructed to be part of the finished structure. All focus group participants unanimously agreed on a classification of material input that includes material that are purchased and installed in the construction process, as shown in Table 6.

Table 6. Material input categories

Project phase	Material category	Examples
Construction	Civil structural components	Materials included in substructure and superstructure work such as excavation, concreting.
	Interior and exterior parts (excluding structural parts)	Includes interior partitions, finishes, and furnishings
	Piping	Underground and aboveground systems, pipe, fittings, valves, and pipe supports.
	Mechanical components	Permanent equipment and mechanical parts of the built facility
	Electrical components	Conduits, cables, fixtures, and transformers
	Fittings and fixtures	
	Fire protection	
	Heating, ventilation, and air conditioning (HVAC)	
	Miscellaneous	External site works

III. Energy Input

Construction processes are energy-intensive endeavours. According to Sharrard et al. (2007), in construction projects, energy can be consumed as electricity, natural gas, gasoline, and diesel. Energy input is considered as a significant part of multifactor productivity measures at industry level (OECD 2001). However, measuring the effect of energy input on project-level productivity has not been addressed by previous research. This study proposes the definition of energy input in construction projects as the cost of oil, fuel, and electricity required during construction and commissioning and start-up phases.

Focus group participants agreed with the appropriateness of the proposed energy input category, however, they noted that energy is not tracked as a separate input component in their company. Instead, energy is considered as an overhead cost. It was indicated that the extraction of energy consumption data might be useful for companies, depending on the nature of the project, and it can be used to track carbon efficiency and use in the project. Participants suggested that energy consumption analysis for total productivity measurement should be performed only at the construction and commissioning and start-up phases of the project since energy consumption values for other phases of the project will be insignificant.

IV. Capital Input

The meaning of capital varies across different disciplines. In the context of economics, capital input includes any tool that is used to produce goods and services (Goodrum and Haas 2002). In productivity measurement studies, capital is restricted to equipment and land that has been used in the production system; here, intangible assets such as organizational effort, software development, and advertisement costs are excluded from the capital input calculation (Huang et. al. 2009). Goodrum and Haas (2002) categorized capital input into fixed and circulating capital. Fixed capital includes buildings and equipment used in the production process, while circulating capital refers to the available funds required for purchasing raw materials. In this study, capital input denotes fixed capital allocated to the completion of a project, and it refers to the temporary equipment used to build the facility. Temporary equipment costs include direct (rental or ownership, tires, and filters) and indirect costs (maintenance, depreciation, and insurance).

V. Construction Project Indirect Input

The cost of construction projects can be divided into direct and indirect costs. Becker et. al. (2012), in collaboration with CII, developed an indirect construction cost characterization framework, which can be implemented by owners and contractors to improve cost component accounting for construction projects. Becker et al. (2012) defines indirect construction cost (IDCC) as "project expenses incurred by the primary construction company in providing supportive functions and shared general resources, which are (1) typical for proper execution of field construction operations, (2) are not accurately or feasibly identifiable with a single direct cost object, and (3) do not become incorporated into a component of the final physical improvements delivered to the owner". Based on Becker et al. (2012) this research adopts the following list of construction project indirect input cost components shown on Table 7.

Table 7. Construction project indirect input cost components

Phase	Cost components
Construction	Temporary roads and parking, temporary office and services, temporary field facilities, temporary housing and camps, temporary structures, temporary utilities for trades, temporary water supply services, subcontractor facilities, mobilization and demobilization costs, communications and computers, safety and first aid, material testing costs, construction consumables

VI. Owner Cost Input

In estimating cost for capital projects involved in heavy industrial construction, there are distinct cost component related to project owners, excluding financing costs (EIA 2016). According to Energy Information Administration (EIA) (2016), capital project cost estimate can be grouped as follows: civil and structural costs; mechanical equipment supply and installation; electrical, instrumentation, and control; project indirect costs; and owners costs. The owner cost input category includes expenses incurred by the owner to bring the project to a commercially operable status. Table 8 shows the components associated with owner cost that cannot be directly attributed to labour input, material input, capital input, energy input, and construction project indirect input costs.

Table 8. Owner cost input components

Project phase	Owner cost input components
Planning and design	Office equipment and consumables, environmental costs, site analysis and site surveying, legal expenses, permit costs, advertising costs, bidding costs, personnel training costs, travel expenses
Procurement	Office equipment and consumables, advertising, travel expenses
Construction	Office equipment and consumables, insurance, taxes and duties, site development outside of project boundaries, safety program, contingency, legal services, escalation, personnel training costs, environmental and mitigation costs, permits (construction-related), travel expenses, transportation expenses
Commissioning and start-up	Office equipment and consumables, handover costs, operating costs, staff training and preparation of necessary documents for operation, clean-up costs, travel expenses

4 Verification of total productivity measurement framework

After the focus group discussion about the feasibility and components of the measurement framework, a questionnaire was distributed to owner companies that attended the focus group discussion session to verify the modified measurement framework within their respective organizations. The main objective of the questionnaire was to gather further insight about the metric and list of input components. The first part of the questionnaire was used to evaluate the feasibility of the proposed metric. The second part of the questionnaire gives a list of input components in each category and evaluates whether the respondent agrees that the listed input component belongs on the specified phase and input category.

The questionnaire was distributed within owner organizations through the participants who were involved in the focus group. Four completed questionnaires were received back from the companies. The respondents had between 11 and 20 years of experience, mostly in the heavy industrial construction sector. The respondents held the following positions: senior engineer, technical lead, engineer technologist, and field engineer technologist.

The focus group participants had 20 years or more of construction industry experience, while the experts who completed the questionnaire had between 11 and 20 years of construction industry experience. Despite the different levels of experience and positions within their respective organizations, the survey results were similar to the results of focus group discussion, and all the respondents agreed with the proposed metric. Furthermore, it was pointed out that even though the list of input components might be used as a basis for data collection, the metric may face challenges related to accurate cost tracking and allocation of the measurement components. Based on the literature review, responses from the focus group discussion, and responses from the survey questionnaire a final list of categories and productivity metric components were compiled, as is shown in Table 9. The presented list of input components can be used to calculate the total productivity of construction projects. Since the number of participants in the focus group and the number of respondents to the questionnaire is small, the use of actual project data to refine the list of input components and to verify the framework in practice is an area for future research.

Table 9. List of input components for measuring total productivity in construction project

	Planning and design phase	Procurement phase	Construction phase	Commissioning and start-up
Direct labour	Owner project staff, planning consultants, constructability consultants, design consultants, cost consultants, value engineering experts, environmental consultants	Owner project staff, procurement personnel, expediting personnel	Direct craft labour, foreman, heavy equipment operators	Owner project staff, design consultants, facility operators, commissioning consultants
Indirect	Owners project manager, administrative staff, legal staff, accounting staff procurement personnel, alliance/partner representative	Owners project manager, project manager, accounting staff, administrative staff, procurement manager, design consultants, legal staff, alliance/partners representative	Owners project manager, owner project staff, project manager, construction manager discipline engineer, site engineer, design consultants, project engineer, project control constructability consultant, accounting staff, administrative staff, procurement staff, material control, workface planner, general foreman, superintendent, safety personnel, QA/QC personnel, field survey/layout crew(s), subcontract specialists, field clerical staff, legal staff, security, janitorial staff	Owners project manager, project manager, document controller, administrative staff, subcontractor specialists, safety engineer, QA/QC personnel, equipment vendors, start-up manager
Material input			Civil structural components, interior and exterior parts (excluding structural parts), piping, mechanical components, electrical components, fittings and fixtures, fire protection, heating, ventilation, air conditioning (HVAC), miscellaneous	
Capital input			Direct and indirect equipment costs	

Energy input			Oil, fuel, and electricity	Oil, fuel, and electricity
Construction project indirect input			Temporary roads and parking, temporary office and services, temporary field facilities, temporary housing and camps, temporary structures, temporary utilities for trades, temporary water supply services, subcontractor facilities, mobilization and demobilization costs, communications resources and computers, safety and first aid, material testing costs, construction consumables	
Owner cost input	Office equipment and consumables, environmental costs, site analysis and site surveying, legal expenses, permit costs, advertising costs, bidding costs, personnel training costs, travel expenses	Office equipment and consumables, advertising, travel expenses	Office equipment and consumables, insurance, taxes and duties, site development outside of project boundaries, safety programs, contingency, legal services, escalation, personnel training costs, environmental and mitigation costs, permit costs (construction-related), travel expenses, transportation expenses	Office equipment and consumables, handover costs, operating costs, staff training and document preparation for operation, clean-up costs, travel expenses

5 Conclusions and future research

Productivity measurement is a major concern for both construction practitioners and researchers. Previous studies undertaken in assessing construction productivity have developed metrics for measuring the productivity of specific activities, and many have focused on labour productivity. Few studies exist that propose a method to account for the overall impact of all tangible input resources used in construction projects on total productivity. In addition, there is lack of standard measurement mechanisms to assess the total productivity of construction projects. This paper explores productivity measurement at different levels and develops a framework for measuring total productivity of construction projects. The framework consists of a total productivity metric, a categorization and itemization of input components, and an approach for measuring each element in the total productivity metric, thus contributing to the standardization of total productivity measurement. This framework provides practitioners with a means to assess the total productivity of construction projects. Furthermore, the framework helps researchers in determining the basic components of productivity measurement for future data collection and analysis.

The study was undertaken with a small number of experts both at the formulation and verification stages of the research. Future research will further refine the developed framework and extend its verification in different construction sectors with additional experts from the construction industry. The framework will also be validated in practice by collecting data from projects and analysing such data to derive the total productivity of construction projects. Because the framework is new, it can be used to collect actual data in real time on future projects, which will more accurately reflect its applicability, rather than historical data, which may not match the newly developed metric. Future research can also compare the results obtained using the framework with results obtained from existing methods for measuring total productivity. With the application of the framework on various project types and industry sectors, a standard data collection tool for measuring total productivity will be developed and used for future benchmarking purposes. Additionally, in order to effectively benchmark projects over time, the framework will be expanded to consider inflation and changes in the quality of the output. The use of inflation indices in productivity measurement is to account for the change in value of price from the reference period to the analysis period, which is essential in analyzing productivity by removing the effect of price change over time. Common inflation indices for construction output will be considered, such as the construction price indices used by Statistics Canada (e.g., new housing, non-residential buildings, construction union wage rate index). These indices will be used to develop an approach to convert a current year output measure to a real output, which will allow year-to-year changes in output, adjusting for the change in the quality of the built facility. Finally, different methods of measuring tangible output during project construction will be tested so that the framework can be used for benchmarking throughout the construction process.

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