A Framework for Total Productivity Measurement of Construction Projects

Construction Owners Association of Alberta

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Executive summary

Productivity measurement is a major concern for both construction practitioners and researchers. In construction research, productivity can be measured at three levels: activity, project, and industry levels. 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 impacts of all resources used in a project, a step which is necessary to effectively assess overall project performance.

This study proposes a framework for measuring construction project productivity, which takes into consideration all resources used in a project. This paper presents a reliable metric to assess the total productivity of construction projects. In addition, the process for identifying and measuring the components of the metric are discussed. The study began with a review of the current productivity measurement metrics used in construction research; findings from this literature review were them used to propose a metric to assess the utilization of resources in construction projects. Next, a detailed list of components required to quantify total productivity was outlined, and a focus group discussion was conducted with industry experts to evaluate the appropriateness and completeness of the metric and its components. In addition, the framework was verified using a questionnaire. The developed framework can be used by researchers and practitioners for data collection and analysis of total construction productivity.

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1. Introduction

1.1 Background

Productivity improvement has been a major concern in the construction industry for many years; a productivity increase in this industry will not only benefit this sector but also the country as a whole. In today's competitive environment, companies should be making the management of productivity a high priority in order to effectively and efficiently convert resources into marketable goods and services (Kao et al. 2013).

Chau and Walker (1988) describe two key considerations for productivity analysis and management: the meaning of productivity, and the methods by which it is measured. The definition of productivity varies depending 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). This variation in definitions can create confusion and may limit the transferability of productivity research to different contexts. Difficulty in productivity measurement can be attributed to the ways that it is defined, which vary depending on the stakeholder's point of view and the level of production being assessed. Given these issues, a considerable number of question may arise for researchers and practitioners, such as what are the best ways to measure productivity, and what are the challenges in measurement? Moreover, what are the challenges in quantifying the required parameters for a measurement metric? What are the challenges in generalizing metrics for different levels of aggregation in productivity measurement? (CII 2013, Crawford and Vogl 2006).

In general, productivity is defined as a ratio of outputs to inputs, and it shows the effectiveness and efficiency in utilization of resources (Equation 1) (Mani et al. 2017).

$$Productivity = \frac{Output}{Input} \tag{1}$$

The following study was conducted by the Natural Sciences and Engineering Research Council of Canada (NSERC) Industrial Research Chair in Strategic Construction Modeling and Delivery. This study illustrates the development of a framework to measure the total productivity of construction projects and the detailed input and output components of the productivity metric. The developed productivity metric will aid practitioners in analyzing and improving the productivity of construction projects.

1.2 Research objectives

The general purpose of this research is to develop a framework that can be used in evaluating total project productivity, while the specific objectives are as follows:

I. To perform a comprehensive review of existing productivity measurement studies;

II. To propose a metric that can be used to measure the total productivity of construction projects by considering the joint impact of all input resources;

III. To prepare a detailed list of components required for measuring productivity at the project level; and

IV. To investigate the applicability of the developed framework in construction.

2. Literature review: Overview of productivity measures

2.1 Productivity measurement methods

Measurement and management of productivity play an important role in the success of any project. Management of productivity can be considered as a four-phase process, commonly termed as the “productivity cycle”. The four phases are as follows: productivity measurement, productivity evaluation, productivity planning, and productivity improvement (see Figure 1) (Sumanth and Dedeoglu 1988, Najafi et al. 2014). These phases of productivity management involve quantification, comparison, establishment of targets, and application of techniques that increase productivity at any level of the production system. Productivity measurement, which is the initial step in the management process, is considered to be the important component that lays the foundation for productivity analysis. As stated by Drucker, who has contributed greatly to the development of the modern business corporation, “Without productivity objectives, a business does not have direction. Without productivity measurement, a business does not have control.” Due to the importance of productivity in achieving business objectives, it has been a major research focus area for many years (Spring 2011).

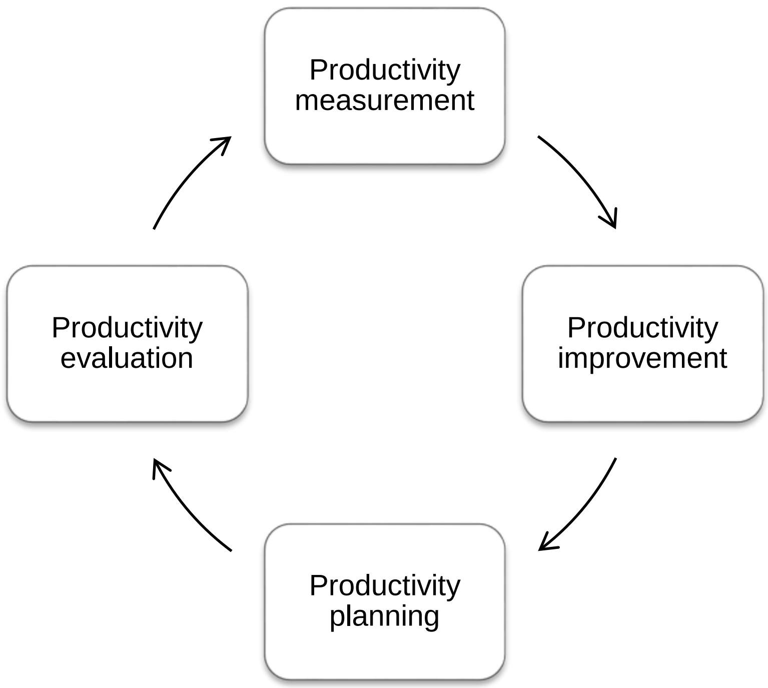

Figure 1. Productivity cycle; adapted from Sumanth and Dedeoglu (1988)

The underlying idea in the measurement of productivity is understanding 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. In contrast, better performance is shown by lower values when using input-to-output ratios (CII 2013).

The Organization for Economic Co-operation and Development (OECD) (2001) lists five main objectives for measuring productivity, which include technology, efficiency, real cost savings, benchmarking production processes, and living standards.

- Technology: Measuring the productivity growth will enable tracing of technological changes that are undertaken in the production process even though their association is not direct.

- Efficiency: Efficiency expresses real performance against theoretical standards; with productivity analysis, the observed difference in efficiency can easily be traced and quantified.
- Real cost savings: Real cost saving can be considered as the major resource input contributing to the growth of productivity; productivity measurement can thus be regarded as an attempt to quantify real cost savings in the production process.
- Benchmarking production processes: Inefficiency in a production process can be determined by comparing the productivity measures with the best performance value achieved.
- Living standards: Productivity can be considered as one of the most important factors in determining a nation’s living standards. For example, income per person, which is typically used for measuring living standards, is directly associated with labour productivity. By measuring and analyzing labour productivity, researchers and practitioners can develop a better understanding of the state of living standards.

Various studies were conducted to provide measures that can be used to quantify productivity. In general, these productivity measures can be categorized into two classes: single-factor productivity (SFP), which compares the output with one specific input factor such as labour or capital, and multifactor productivity (MFP), which evaluates output against all resources used (CII 2013, Yi and Chan 2014).

2.1.1 Single-factor productivity

Single-factor productivity (SFP) is the most commonly used productivity measurement method. SFP evaluates productivity as a ratio of one input factor to output (CII 2013, Park 2006). Various factors can be considered in SFP measurement methods. These factors can be categorized into two broad groups, labour-related factors and capital-related factors, both of which are discussed in detail in the coming sections.

Labour productivity

A great amount of research and development efforts have been carried out in the area of labour productivity, as compared to other productivity measures. The main reason that labour productivity has been a central research focus is its ability to provide information regarding operational efficiency, economic growth, and living standards. In addition, since the construction industry is labour intensive, labour productivity is seen as a major index to provide information on the productivity of construction projects (Chang and Woo 2017).

The main advantage of labour productivity measures is their ease of measurement and flexibility, as compared to MFP or capital productivity measures. Based on a 2001 report by OECD, labour productivity can be measured in terms of gross output and value added, as shown in Equation 2 and Equation 3. Gross output measures for individual firms or industry include measures for intermediate inputs (e.g., material, energy, and service) used in the production of goods and services. In contrast, value-added measures exclude consumption of intermediate inputs. When labour productivity is measured in terms of gross output, it reflects the effective use of labour to generate the output, which represents the supply of all goods and services that are being produced through the production process to get the final with the total value sales. Meanwhile, if labour productivity is defined as a form of value added, it shows the efficient use of labour to generate value added, which represents the final product that is produced without the use of the intermediate inputs (material, energy, and service). As indicated in Equations 2 and 3, the output and input quantity index represents the aggregated quantities of output and input used in the production process (OECD 2001). In this context, index represents the change in value during the time of analysis. Labour input for this metric is measured using the total number of hours worked.

$$Labour\ productivity = \frac{Quantity\ index\ of\ gross\ output}{Quantity\ index\ of\ labour\ input} \quad (2)$$

$$Labour\ productivity = \frac{Quantity\ index\ of\ value\ added}{Quantity\ index\ of\ labour\ input} \quad (3)$$

The Construction Industry Institute (CII) also developed an effective system that measures labour productivity for six disciplines, including concrete, steel, electrical, piping, instrumentation, and equipment. CII's system defines labour productivity as the ratio of installed quantity expressed in units of measurement over actual work hours (Liao et al. 2012).

Capital productivity

In productivity studies, capital generally represents physical assets, such as equipment, land, buildings, and inventories, which are used up in the production of goods and services (Spring 2011). In economic terms, Huang et al. (2009) defines capital as anything that entails a fee at present time, but generates a return in the future. Capital can be measured as a form of physical quantity or financial value (Spring 2011).

Capital productivity is commonly defined as a ratio of output over capital used; it is also considered to be a monetary value-based quantification of productivity, as it assesses the value of money on a large scale. Capital input used to produce goods has correlative characteristics with those of labour input measures. For labour productivity, labour input factors are normally quantified with labour service as total hours worked, while in the case of capital productivity, physical capital is calculated with total machine hours, which are considered to be fixed in proportion to the capital stock. Another commonality between labour input and capital input is the pricing of values. For labour inputs, prices are expressed by compensation per hour, while capital input is quantified as the cost of capital assets (Huang et al. 2009).

Capital productivity can be represented as the ratio of value added to capital input, as shown by Equation 4. Value added is commonly used as a measure of output in the capital productivity calculation; it represents the profit gathered at the end of an activity or process. This profit can be paid as a payment for employees over the course of the project, or it can be used for maintaining depreciated machinery, to pay debt, or distributed as dividends to investors (Spring 2011). According to OECD (2001), capital productivity shows the collective effect of labour, technology change, and capacity utilization. The same idea applies to the meaning of quantity indices of value added and gross output, which are shown below in Equation 4 and Equation 5 respectively. The quantity index of capital input reflects the combined effect of assets used to generate the value added or the gross output in the production of goods and services. The value added and the gross output make up the total value of the final product. The difference between these outputs is that gross output is evaluated before subtracting the value of intermediate goods used up in production.

$$Capital\ productivity = \frac{Quantity\ index\ of\ value\ added}{Quantity\ index\ of\ capital\ input} \tag{4}$$

Capital productivity can also be measured based on gross output, as illustrated in Equation 5:

$$Capital\ productivity = \frac{Quantity\ index\ of\ gross\ output}{Quantity\ index\ of\ capital\ input} \tag{5}$$

The procedure for estimating capital productivity requires quantification of the value of gross capital stock in order to provide an appropriate measure for capital input. Gross capital stock represents a capital measure that shows the overall flow of venture undertaken in the production process (Huang et al. 2009). Capital stocks can be quantified in three ways: using historic prices, using constant prices, or using current prices. In contrast, valuation of the capital stock for productivity management is performed using only constant prices and current prices. Current prices indicate the value of the asset for the current year; it should be noted that this value does not account for inflation. Constant prices show the valuation of the capital stock in a given year. The capital stock shows the cumulative flow of investments or expenses combined to obtain the required output. Crawford and Vogl (2006) suggest that capital stocks should be measured using the perpetual inventory method (PIM), which involves aggregating the inputs, and adjusting for deterioration resulting from the long-term use of the asset. Berlmann and Wesselohoft (2014) note that most of the methods used to represent capital stock entail the use of PIM. A key component of PIM is that it considers the capital stock as an inventory, which increases with the service that is provided. Over time, when the asset provides service to the production process, the amount of capital stock decreases with the amount of depreciation.

2.1.2 Total factor productivity (TFP)

Total factor productivity (TFP) (also known as multifactor productivity) is a productivity measure that uses multiple input factors (energy, labour, equipment, materials and capital) to produce and output (Nasir et al. 2013; Park 2006). Since this measure evaluates output against several types of intangible inputs, such as advancement in technology, it is interpreted as the collective effect of the variation in output that cannot be accounted for by change in combined inputs (OECD 2001). TFP is commonly used to monitor the state of economy and to inform the development of economic policy.

2.2 Level of production system

In the construction industry, the production system is said to be a process whereby input resources are transformed into output. The production system is considered to have various boundaries or levels, depending on the purpose of investigation and availability of data. According to Yi and Chan (2014), research on construction labour productivity (CLP) typically focuses on three levels: industry, project, and activity levels. Activity-level productivity measures are most commonly used in the construction industry; they measure the performance of individual construction activities, such as concrete placing and steel erection. In contrast, project-level productivity measures reflect performance related to the activities required for construction of a certain facility. Industry-level productivity measures provide an assessment of the overall state of productivity in the industry sector.

2.2.1 Measuring productivity at the Industry level

At the industry level, productivity can be used as a measure of industrial efficiency; it is calculated as the amount of output produced per unit of input. The productivity measured can be expressed as a form of labour productivity or multifactor productivity (CII 2013). Macro-economic productivity measures, such as industry-level productivity, provide information regarding living standards, the status of an economy's productive capacity, a comparison of international productivity, and influence of economic policies (Huang et al. 2009).

According to CII (2013), industry-level productivity is assessed using two key metrics: total factor productivity (TFP) and labour productivity. TFP can be determined by comparing the goods and services produced with the input used in production operations. Equation 6 shows the calculations for TFP, expressed in terms of labour, material, equipment, energy, and capital (CII 2013). In this case, energy input is determined by the quantity and price of resources used for generating power, such as fuel, coal, oil products, and electricity. Capital input, which is commonly measured in dollars, represents anything used in the production process that has cost at present time, but that earns a return in the future, such as land, inventories, and human capital (CII 2013).

$$Total\ factor\ productivity = \frac{Total\ output}{Labour + Material + Equipment + Energy + Capital} \qquad (6)$$

Labour productivity at the industry level can be measured as a ratio of total output over the amount of labour hours required to deliver that output (Equation 7) (CII 2013). At the industry level, TFP is preferred over labour productivity, because labour productivity is a more limited measure and is liable to misinterpretation (Huang et al. 2009).

$$Labour\ productivity = \frac{Total\ output}{Labour\ (Direct\ workhours)} \tag{7}$$

On the other hand, the OECD (2001) has proposed a set of productivity measures that are expressed with gross output to input components and a value-added model that captures the flow of output. These measures are summarized below in Table 1. The gross output in this framework describes the goods and services that are produced by the project, firm, or industry. The output is manufactured using the available input resources, which can be labour and capital or both. Value-added is considered as the difference between the value of output and the value of intermediate input (e.g., materials, energy, and services, etc.). Put in simpler terms, value-added can be regarded as the difference between sales and cost; it represents the profit gathered through the production process (Statistics Canada 2015).

Table 1. OECD measures of productivity (2001)

Type of input measure / Type of output measure	Labour	Capital	Capital and labour	Capital, labour and intermediate inputs (energy, materials, services)
Gross output	Labour productivity (based on gross output)	Capital productivity (based on gross output)	Capital-labour productivity MFP (based on gross output)	KLEMS productivity
Value added	Labour productivity (based on value added)	Capital productivity (based on value added)	Capital-labour productivity MFP (based on value added)	-
	Single factor productivity (SFP) measures		Multifactor productivity (MFP) measures	

2.2.2 Measuring productivity at the activity level

Activity-level productivity metrics are the most commonly used productivity measures in the construction industry. Single-factor productivity metrics are widely applied to measures activity-level productivity, particularly labour productivity. In measuring productivity at the activity level, the units of measurement for quantifying tasks should be precise and easy to understand. CII (2013) describes five criteria that should be considered before selecting methods of quantity measurement for productivity analysis. These criteria are as follows: easy to understand and determine, degree of control needed, nature of the activity, construction method, and activity scope.

2.2.3 Measuring productivity at the project level

In general, a project is a collection of activities that are required for the construction of a facility. Since projects entail completion of various activities, measurement of productivity at the project level is more complicated than measurement of activity-level productivity (Huang et al. 2009).

CII (2013) lists common measures of productivity, which are expressed either as a ratio of output to input or as a ratio of input to output. Factor productivity, which is shown below in Equation 8, is similar to TFP, and it is mainly used in conceptual estimation to quantify construction productivity.

$$Factor\ productivity = \frac{Physical\ output\ (units)}{Labour(\$)+Material(\$)+Equipment\ (\$)} \tag{8}$$

Partial-factor productivity can be estimated by removing one of the input resources (e.g., labour, material, or equipment) from factor productivity, as shown in Equation 9. According to CII (2013), partial-factor productivity is mainly used for specific types of conceptual estimation for measuring productivity on construction projects.

$$Partial\ factor\ productivity = \frac{Physical\ output\ (Units)}{Labour(\$)+Equipment\ (\$)} \tag{9}$$

The other productivity measure that can be computed at the project level is labour productivity. Labour productivity can be estimated based on the cost of labour required or on direct work hours (see Equations 10 and 11).

$$Labour\ productivity = \frac{Physical\ output\ (Units)}{Labour(\$)} \tag{10}$$

$$Labour\ productivity = \frac{Physical\ output\ (Units)}{Direct\ work\ hours} \tag{11}$$

Goodrum and Haas (2002) modified Equation 8 by assigning equipment cost to fixed capital and material cost to circulating capital, as is shown in Equation 12. Goodrum and Haas (2002) studied the effect of equipment technological change on partial-factor productivity, excluding circulating capital as an input over a 22-year time period. Labour cost and fixed capital cost data for the construction activities were collected from published data that was prepared for cost estimation.

$$Factor\ productivity = \frac{Pysical\ output\ (units)}{Labour(\$)+Circulating\ capital(\$)+Fixed\ capital\ (\$)} \tag{12}$$

In measuring productivity at this level, the type of information required for inputs and outputs depends on how the metric is defined. A review of the construction engineering literature shows a number of studies dedicated to the development of meaningful project-level productivity metrics, which provide qualitative estimates on the productivity of a project using activity data (Ellis and Lee 2006; Thomas et al. 1990; Liao 2012).

In an effort to include the effect of all activities involved in construction projects, Ellis and Lee (2006) developed a project-level productivity measurement method (shown in Equation 13), which uses activity data from transportation projects to measure project-level productivity. Ellis and Lee (2006) argue that the success of a project is influenced by the productivity of all task elements in the project; therefore, evaluating only a few work elements or activities will not be adequate for the purpose of assessing overall productivity.

Ellis and Lee's (2006) project-level productivity (PLP) metric was developed on the assumption that "the total input or work effort on all activities and the total output or work produced on all activities" are incorporated during productivity measurement. The researchers outlined two major objectives to be fulfilled by the measurement approach, the first of which was to develop a single PLP value for all activities involved in a highway project. The second objective was to evaluate the PLP results over the full duration of the project. In order to achieve the outlined objectives, the procedure started with the establishment of a method specifying the mode of measurement for both inputs and outputs. Ellis and Lee (2006) expressed input in terms of the total worker hours of all crew members involved in the production of output. The output is defined in terms of total equivalent work units (EWU).

$$PLP = \frac{Total\ worker\ hours}{Total\ EWU} \tag{13}$$

EWU is a converted value of the daily installed work quantities, which may be measured in different units. To develop the unified PLP quantity value, the researchers used four steps, which are shown in Figure 2. The first step involves preparation of a database for all activities containing relevant information regarding pay items, such as estimated quantity, units of measurement, estimated man-hours, and crew composition. In the second step, average production rate, which indicates the number of hours spent in producing a single unit of some item, was calculated based on crew information data drawn from a published estimating database: “RS Means Heavy Construction Cost”. The third step involved the calculation of the equivalent unit factor, which is eight work hours divided by the unit production rate determined in the second step. Finally, the EWU was calculated for each work item as a ratio of estimated quantity and the equivalent work unit factor.

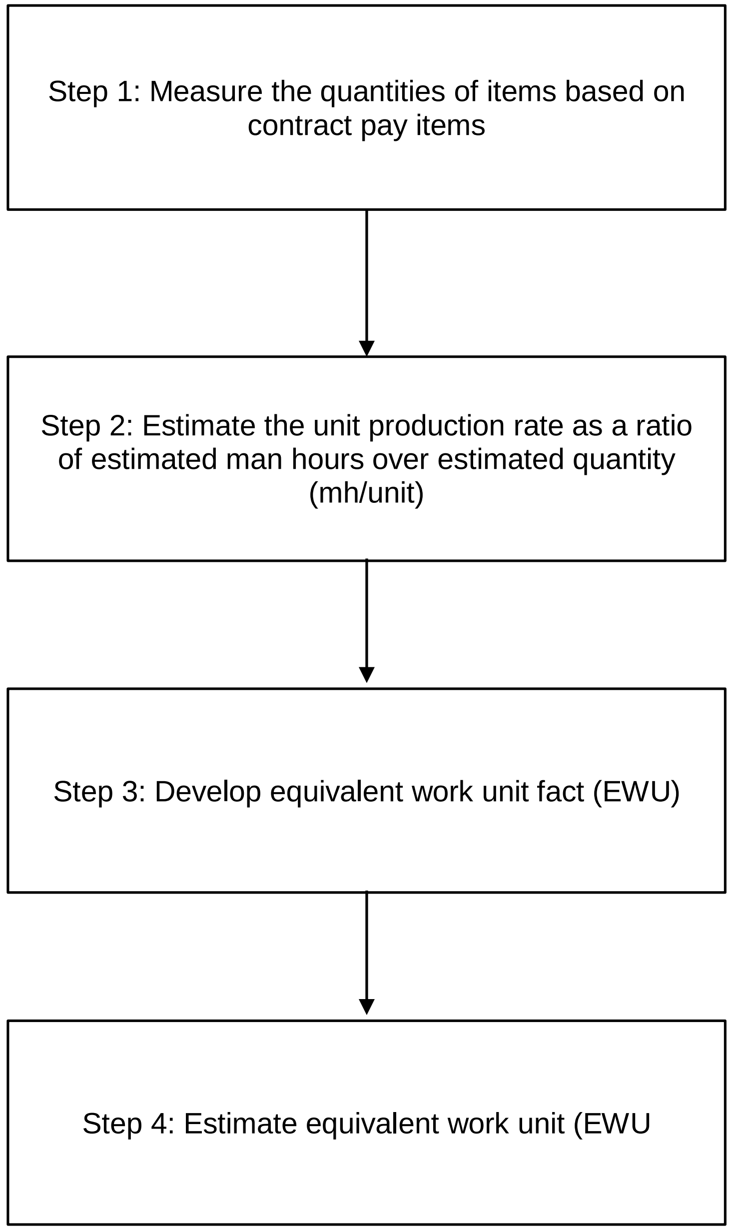

Figure 2. Procedure for calculating equivalent work unit (EWU); adapted from Ellis and Lee (2006)

After developing the unified quantity measure for the output, the PLP was calculated using Equation 13, where the total EWU is the summation of unified work quantity for each item, and total worker hours is the overall amount of work hours required for each item quantity in all activities. The developed PLP measure was used to compare the productivity for three highway projects by looking at trends and project control strategies implemented in the projects. It should be noted that this approach sums up all the construction crafts without considering the variation of installed quantities, which is a common characteristic of activities in construction projects.

Based on existing data from CII and the Construction Owner's Association of Alberta (COAA), Yun et al. (2015) conducted a comparison of Alberta capital projects and U.S. capital projects. To facilitate comparison, Yun et al. developed high-level project productivity metrics using quantity-based and cost-based approaches, which are listed below in Table 2.

Table 2. Quantity-based approach and cost-based approaches for project productivity

Quantity-based approach	$\textit{Project-level construction productivity}$
Cost-based approaches	$\frac{\textit{Total constructed cost}}{\textit{Total site work hours}}$
	$\frac{\textit{Total constructed cost} - \textit{Equipment cost}}{\textit{Total site work hours}}$
	$\frac{\textit{Construction phase cost}}{\textit{Total site work hours}}$
	$\frac{\textit{Construction phase cost}}{\textit{Procurement cost}}$

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. Such construction disciplines include concrete, structure steel, piping, equipment, electrical, insulation, and instrumentation. After checking the normality of productivity data for the disciplines and transforming the skewed values, the discipline productivity data was standardized using a *z*-score value, as shown in Equation 14.

$$z_i = \frac{P_{ij} - \mu_j}{\sigma_i} \tag{14}$$

Where z_i is the *z*-score of the productivity of the i^{th} construction discipline; p_{ij} is the transformed productivity metric value for the project of the i^{th} construction discipline j^{th}; μ_i is the mean value of the transformed productivity metric value of the i^{th} construction discipline; and σ_i is the standard deviation of the transformed metric value of the i^{th} construction discipline.

Finally, the discipline productivity values were aggregated in terms of work hours for each construction discipline, as shown in Equation 15.

$$Project - level\ productivity\ metric = \frac{\sum_{i=1}^{n}(WH_i \times z_i)}{\sum_{i=1}^{n} WH_i} \tag{15}$$

Equation 16 may be used as a general metric for cost-based approaches when calculating the productivity of construction activities. The output cost for the different metrics used in this research include total constructed costs, equipment costs, and construction phase costs (Yun et al. 2015). In the context of this study, construction phase costs include the cost of all activities consumed during the construction stage. The total construction cost is the sum of procurement and construction cost, the latter of which comprises both direct and indirect costs. The total construction cost includes field labour costs, material costs, equipment costs, supervision costs, subcontractor costs, administrative costs, tools, and field office expenses.

$$Project\ productivity\ metric = \frac{Cost\ for\ construction\ activities}{Work\ hours} \tag{16}$$

Lim (1996) studied the productivity of building projects by measuring construction productivity as a ratio of built-up construction per man-day; Lim proposed two separate metrics for completed and ongoing projects, as shown below in Equations 17 and 18 respectively.

$$Building\ productivity\ = \frac{Gross\ floor\ area}{Total\ manpower} \tag{17}$$

$$Monthly\ building\ productivity = \frac{Monthly\ progress\ payement\ certified}{Total\ contract\ sum} \times \frac{Gross\ floor\ area}{Monthly\ manpower} \tag{18}$$

Where 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 one-month period.

The CII Benchmarking and Metrics (BM&M) program developed the Engineering Productivity Metrics System (EPMS), which uses quantity-based measures to quantify the productivity of construction projects. These metrics are organized hierarchically across four major levels, as indicated in Figure 3. In the hierarchical EPMS structure, Level I comprises a project-level metric. Next, Level II is the discipline metric, which is grouped into six disciplines related to construction activities: concrete, steel, electrical, piping, instrumentation, and equipment. Each discipline category can then be further broken down into a sub-category (Level III) and elements (Level IV). For example, the concrete category at the discipline level has three subcategories (Level III), which include "foundation", "slab", and "concrete structures".

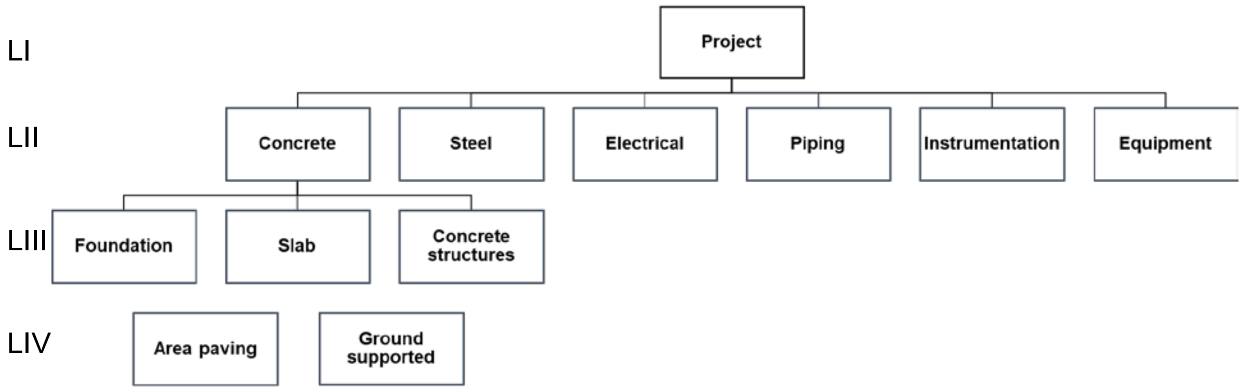

Figure 3. The EPMS metric hierarchy; adapted from Liao et al. (2012)

Since the metric shown in the EPMS is a ratio of engineering work hours per engineering quantity, Level II, Level III and Level IV values can easily be aggregated. However, it is not possible to generalize the metric up from the disciple level (Level II) to the project level (Level I), 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; this research used data collected from CII member companies 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 satisfied the requirements of the CII productivity metrics team (i.e., comprehensibility, homogeneity, and trending ability). The three approaches that were analyzed for developing a project-level productivity metric were 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 worked hours over the predicted amount of work hours for the six disciplines in order to quantify the productivity at Level I. The maximum-minimum method applies a two-step process to calculate project-level productivity. The initial step involves standardization, which is done by subtracting the minimum productivity value at discipline level; next, this value is divided by the range of the metrics, which is the maximum minus the minimum productivity value. Finally, the *z*-score method involves using a statistical method to transform the engineering productivity metric for every discipline into a dimensionless measure for aggregation. After comparing the results of the proposed methods, the *z*-score method was selected, since it satisfies the requirements of the PM team.

2.3 Measurement of input

When developing productivity metrics, the data that is used for measuring the price of capital, labour, material, and service can be collected from companies or projects, but for macroeconomic studies, productivity is calculated based on data that is collected at the national level (Crawford and Vogl 2006). These inputs are required to undertake and complete a construction process or activity.

2.3.1 Labour input

Labour input shows effort provided by the workforce in the production system. Due to the nature of work involved in construction projects, labour input constitutes 33–50% of the total project contract amount (Hanna et al. 2008). Labour is commonly measured as the total number of hours worked or as labour cost (Thomas et al. 1990). According to OECD (2001a), the price of labour input is calculated as compensation per hour, which is expressed with labour income and labour shares that incorporate wages and salaries.

For multifactor productivity calculations, inputs are combined using the corresponding costs as weights. The OECD (2008) defines labour cost for any industry-level productivity measurement in terms of three components: compensation of employees, labour income of self-employed persons, and the sum of tax-free subsidies on labour. The calculations for labour cost are shown below in Equation 19. For industry-level measurement, the price value can be collected from national statistical agencies.

$$W^{*t} = W_E^t + W_S^t + T_L^t = W^t + T_L^t \tag{19}$$

Where W^{*t} represents the total labour cost; W_E^t represents compensation of employees, (i.e., the total gross wages paid to employees in a given accounting period); W_S^t denotes labour income of self-employed persons, a value which is commonly approximated to be equivalent to employee income; T_L^t is the sum of tax-free subsidies on labour, which reflects the difference between the amount the producer is paid and the value of the transaction to the producer; and W^t represents the total labour cost excluding tax-free subsidies.

2.3.2 Capital input

Production involves the use of capital to generate output. In productivity measurement studies, capital is restricted to equipment, structure, and land (Huang et al. 2009). Huang et al. (2009) point out that in relation to provision of service flow, both capital and labour are similar, but price index data for capital input is not readily available in the same way it is for labour input.

2.3.3 Intermediate inputs

Intermediate inputs in productivity measurement include energy, material, and business service. Together with primary inputs, such as capital and labour, these inputs are used in the construction industry to estimate total factor productivity. The construction process is an energy-intensive endeavour. According to Sharrard et al. (2007), energy in a construction project may be consumed in a form of electricity, natural gas, gasoline, and diesel.

2.4 Measurement of output

At any level of productivity measurement, output can be expressed either as a physical quantity or as a financial value. Key considerations in assessing the output of production are the amount of work done or the amount of product produced in the process; these values indicate the overall result of an activity (OECD 2001). The type of measurement method selected depends on the objective of the measurement and on the availability of data. Sezer and Bröchner (2013) point out that the challenges in quantifying output are mainly due to the difficulty in determining what it includes, given the diverse nature of construction projects and the absence of data.

At the industry level, the OECD (2001) measures productivity as a ratio of the quantity index of output to input, where the output is mainly expressed as value added or as gross output. Gross output represents the service or product available for use; it includes the value of sales, depreciation, consumption of fixed capital, and net additions to inventories, among other things. In the context of value added, intermediate inputs that are used up by the production process are deducted from the gross output value (OECD 2001). A different approach can be adopted for calculating the quantity index of output using the index number. These approaches address the issue of heterogeneity in output by concentrating on the disaggregated prices and quantities of output. Commonly used index formulae include the Laspeyrse, Passche, Fisher, and Törnqvist indices (OECD 2001). According to the Office of National Statistics UK, output in the construction industry is calculated in current prices and chained volume measures from data collected through monthly surveys of the value of construction work.

In project-level productivity measurement, outputs can be expressed in terms of functional units. Thomas et al. (1990) examined a case from the United States Federal Highway Administration in which the productivity of a highway project was measured by taking using the amount of resources used in design, inspection, construction, and right of way as inputs, and then measuring the output in physical units, or in this case, lane miles. Thomas et al. (1990) also proposed a method for measuring project-level productivity by accounting for labour, equipment, and material inputs as a dollar value, and then measuring the output as physical units (i.e., square feet). In addition, Bröchner and Olofsson (2012) studied productivity measures for innovation projects by comparing the same type of beam bridge projects, all of which were constructed during a 30-year period. The output measure used for the purpose of this study was the usable area of the constructed facility; this value was subject to a correction factor related to the flexibility of structural technology. Other research that utilized area measures within a productivity metric system include work by Lim (1996), which considered built-up construction per man-day to measure the productivity of building projects. In contrast, Ellis and Lee (2006) used equivalent work units (EWU) to calculate the total output of a transportation project. In this context, EWU represents the amount of work that can be completed within an eight-hour work period. Ellis and Lee (2006) emphasize the need for using the collective value of all work items to express the global project productivity value. EWU-based approaches for determining overall output require that each activity in a project be weighted in order to develop a composite unit; however, such data can be difficult to analyze for complex projects involving many different activities. Moreover, when applying EWU to normalize and aggregate output, this method does not consider the variance of the installed quantities for each work item or activity, which results in an imprecise project-level productivity value.

For activity-level productivity measurement in construction projects, the commonly adopted output measure is based on quantity (Thomas et al. 1990, CII 2013, Park 2006). According to CII (2013), when measuring the productivity of a construction activity, the output quantity unit must be measured with precision, and the unit itself should also be convenient for measurement and computation. CII (2013) notes five major quantity measurement methods along with their advantages and disadvantages. Keane and Caletka (2008) and Humphreys (2004) describe these quantity measures as methods for measuring work progress. The methods include unit measures, incremental milestones, start /finish, level of effort or cost ratio, and observational assessment. Unit measures can be used for tracking tasks that are done repeatedly. This method of measurement provides a detailed and accurate value for project control; however, the major drawback of this approach is that it requires extensive data collection (CII 2013). Incremental milestones are another quantity measurement method, which require documentation of each step as a mini-milestone that represents a percentage of the total installation process. This method is used for cost accounting involving tasks that need to be completed in a linear fashion. For activities without intermediate milestones, start/finish measurement can be implemented by focusing on the starting and finishing points of a task. When using the start/finish technique, the percentage of progress is assigned when the task starts, based on agreement between contractor and owner of the project. One hundred percent of progress is achieved when the task is considered complete. For non-critical tasks, simple and quick observational assessment can be done on the progress of the task at hand. Observational assessment of percent complete is a subjective method that relies on the experience and opinion of a project manager to determine project status. Finally, the cost-ratio method of measurement is applicable to tasks that are continuous throughout the lifecycle of a project.

The equivalent unit measurement of output is another method that can be implemented to express the final product of sub-tasks within an activity, which have different units of measurement (Keane and Caletka 2008). This method is used for complicated activities with overlapping subtasks. In this approach, each sub-task is given a weighted value in equivalent units, which are then used for calculating a composite unit of measurement. The allocated weights in this technique are determined by estimating the level of effort required to complete a task (Keane and Caletka 2008).

2.5 Summary

In summary, the progress of construction projects involves many concurrent and interrelated activities. The metrics employed for assessing project productivity often focus on selected activities, despite the fact that 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 also a lack of standards for determining which components should be included as inputs in productivity measurement.

3. Methodology

This study adopted a three-phase process (outlined in Figure 4) in order to develop a framework to assess the utilization of all resources used in a construction project. During the first phase, a comprehensive literature review was conducted on productivity quantification techniques to identify a suitable metric for measuring total productivity at the project level. In the second phase, the framework was developing by identifying a list of input components and the output required to quantify total productivity. Finally, in the last phase, the framework was verified based on feedback from industry experts solicited through a questionnaire.

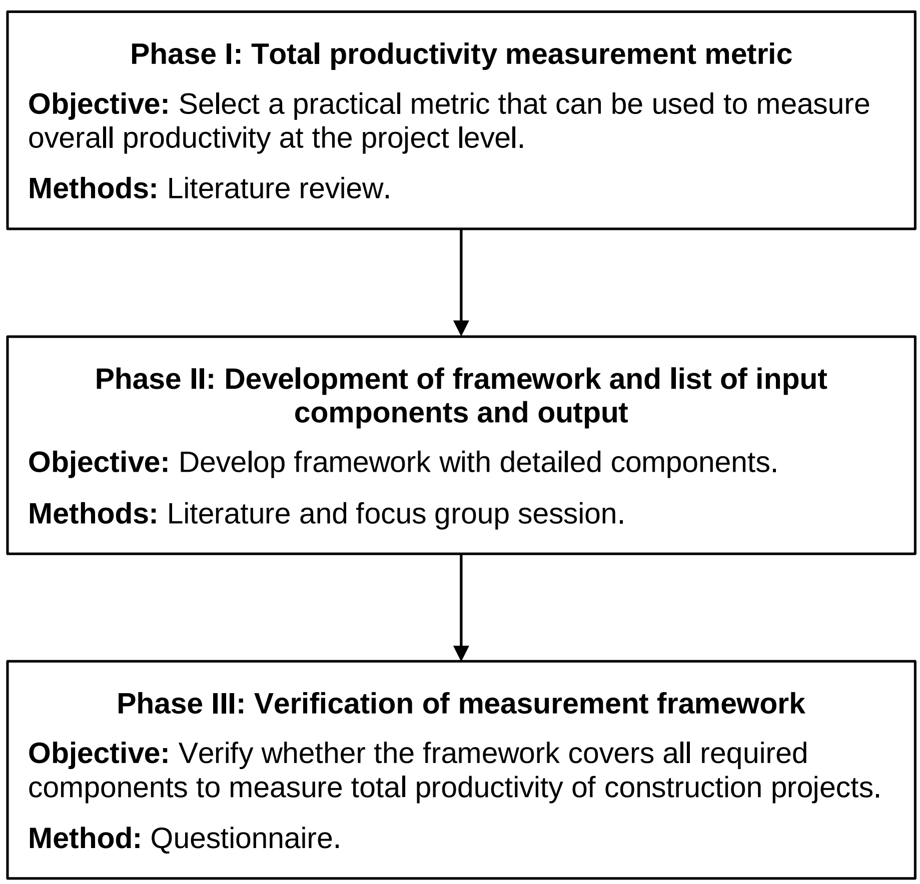

Figure 4. Research methodology.

4. Total productivity measurement framework

Measuring the total productivity of a construction project can be a challenging process. These challenges stem from the complexity in determining the components of an appropriate metric. This report 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.

4.1 Phase I: Total productivity measurement metric

To propose a metric that can assess the impact of all resource inputs used in a construction project, a review of productivity studies was conducted at different levels of the production system (i.e., industry, project, and activity levels). One of the main differences between these different methods for measuring total productivity lies in the methodology adopted to quantify the elements of the metrics. This study proposes the equation shown below (Equation 20) as a metric to measure the total productivity in construction projects. In this case, tangible output represents physical units of project output (e.g., *km* for a highway project or *m* for a pipeline project). Tangible inputs include labour, material, capital, energy, and other expenses quantified as a dollar value.

$$Total\ productiviy\ = \frac{Tangible\ output\ (Physical\ unit)}{Tangible\ inputs\ (\$)} \tag{20}$$

4.2 Phase II: Development of list of input components

After proposing a total productivity metric, a list of components was established to be included as part of each input resource category. Each input resource is quantified in terms of amount of labour, equipment, energy, material, and other expenses. Cost elements associated with each of these input categories are grouped in terms of phase in the construction process. Chang et al. (2001) propose five project phases: pre-project planning, detailed design, procurement (material management), construction, and start-up and commissioning. For the purpose of the research discussed in this report, the project lifecycle is grouped into five phases, which are based on CII performance assessment project classifications: initiation, planning and design, procurement, construction, and commissioning and start-up (Choi et al. 2016). The phases consist of overlapping activities linked with each other by the produced outputs or deliverables.

Using the typical cost components and major participants list developed during the first phase (see Appendix A), along with the definitions shown in Figure 5, the components of each input category were outlined. After proposing a metric and developing a 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.

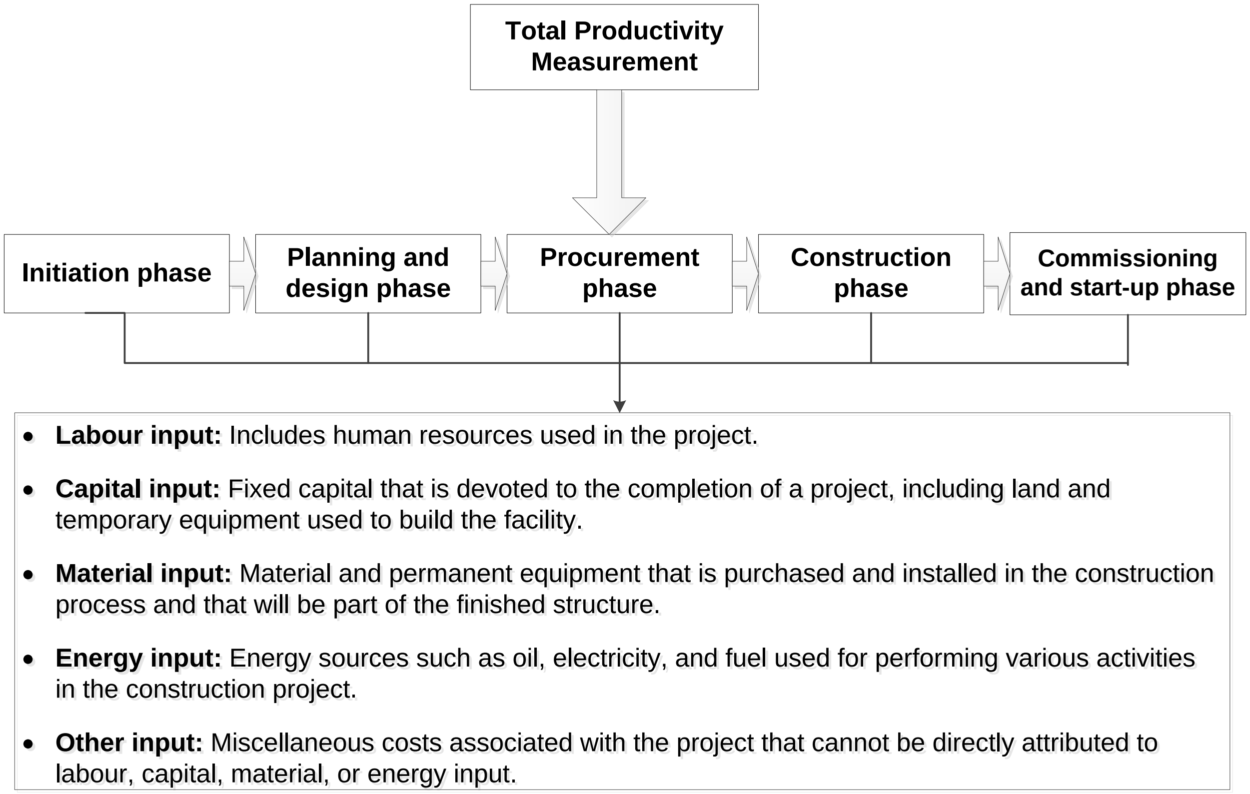

Figure 5. Total productivity measurement framework components

Focus group discussions are designed to explore individual perspectives and experiences regarding a particular topic. In this study, the purpose of the focus group discussion was 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 10 or more years of experience working in heavy industrial construction were approached to participate in the study session. Four managing directors and senior managers representing owner companies agreed to participate. The participants had experience ranging between 11 to 20 years in sectors including heavy industrial construction, engineering construction, institutional commercial construction, and home building and renovation. The participants held the following positions within their respective companies: vice-president, general manager, manger, and director.

The discussion was initiated by providing 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 pertaining to the approach. In addition, a questionnaire was provided during the discussion session, which is available in Appendix B. The form comprises three sections, the first of which covers general demographic information, such as total years of experience and current occupation. In the second section, open-ended questions are provided to assess experts' opinions regarding the feasibility of the metric, the method of quantifying output and inputs, categorization of inputs, and any potential challenges they could foresee occurring. Finally, the third section asks participants to evaluate whether the listed components belong in the input category and identified project phase; a sample for the indirect labour input category is shown below in Table 3.

Table 3. Sample semi-structured form 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 project manager ☐ Admin. staff ☐ Procurement personnel ☐ Alliance/partner rep. **Additional suggestions**	☐ Procurement manager ☐ Design consultants ☐ Legal staff ☐ Alliance/ partner rep. **Additional suggestions**	☐ Owner project staff ☐ Project manager ☐ Construction manager ☐ Constructability consultant ☐ Accounting staff **Additional suggestions**	☐ Subcontractor staff ☐ Safety engineer ☐ QA/QC ☐ Equipment vendors **Additional suggestions**

In order to analyze the data collected through the focus group session, a five-step qualitative data analysis process proposed by Srivastava and Thomson (2009) was implemented. This approach, which is referred to as "framework analysis", 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 a process whereby the researcher reviews the data collected (e.g., focus group data or notes). In the second stage, emerging themes are identified from the notes from the discussions. After identifying the themes, the data are labelled to correspond to a particular theme. In the charting step, the labelled data are arranged in the themes. The final stage involves analysis of 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. Following the analysis, five main themes were identified from participant responses: proposed total productivity metric, method of quantification of input and output, project phase classification, categorization of tangible inputs, and limitation of the proposed technique and difficulty associated with the approach.

4.2.1 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 developed metric and felt that it properly captures the total productivity of construction projects by measuring effectiveness in resource utilization. Studies link efficiency to “doing things right”, which may be interpreted as consumption of available resources to 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 to specified characteristics (Pekuri et al. 2011, Sundqvist et al. 2014). Productivity can thus be considered 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 to break the project elements into different activities, and assessing the cost required to complete an activity.

4.2.2 Method of quantification of input and output

All participants agreed with the quantification method proposed for both input and output. The participants indicated that measuring input 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.

4.2.3 Project phase classification

Understanding the phases involved in the project lifecycle is essential for successfully guiding a project from initiation to completion. The participants expressed that in the construction industry, there are different ways to describe construction processes. The participants agreed with the appropriateness of 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 sectors involved in heavy industrial construction, measurement of project performance should be done after the investment decision, and it should not include any of the cost elements associated with the initiation phase of the project.

4.2.4 Categorization of tangible inputs

The participants agreed that the categorization of tangible inputs into labour, capital, material, and energy in the metric is consistent with respect to common practices in the construction industry. Participants suggested a modification related to the other expense input cost category. According to the participants, the commonly adopted cost categories in the heavy industrial construction sector include owner cost, engineering cost, procurement cost, and construction cost. While input categories suggested in this research, such as labour, material, capital, and energy, can be derived from commonly adopted cost classifications, other expense input components were not consistently interpreted by users of the framework. In order to address this problem, participants suggested the creation of a separate input category, which considers an indirect cost input component and owner cost. As a result, the other expense input category components were re-distributed to construction project indirect input and owner cost input.

Furthermore, it was indicated that having a common approach for collecting input data would aid in the development of a standardized data collection approach that is suitable 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 a similar approach had previously been adopted within their company to compare projects. Under this approach, all associated costs are listed, and the cost elements not common to all the projects can be removed in order to facilitate cost comparison. Therefore, based on feedback from the participants, the initial framework shown in Figure 5 was later modified, as is shown in Figure 6. In the modified framework, input quantification for total productivity measurement is initiated during the planning and design stage. In addition, the other expense input is further grouped into construction project indirect and owner costs. The description and list of components for each input category is discussed below.

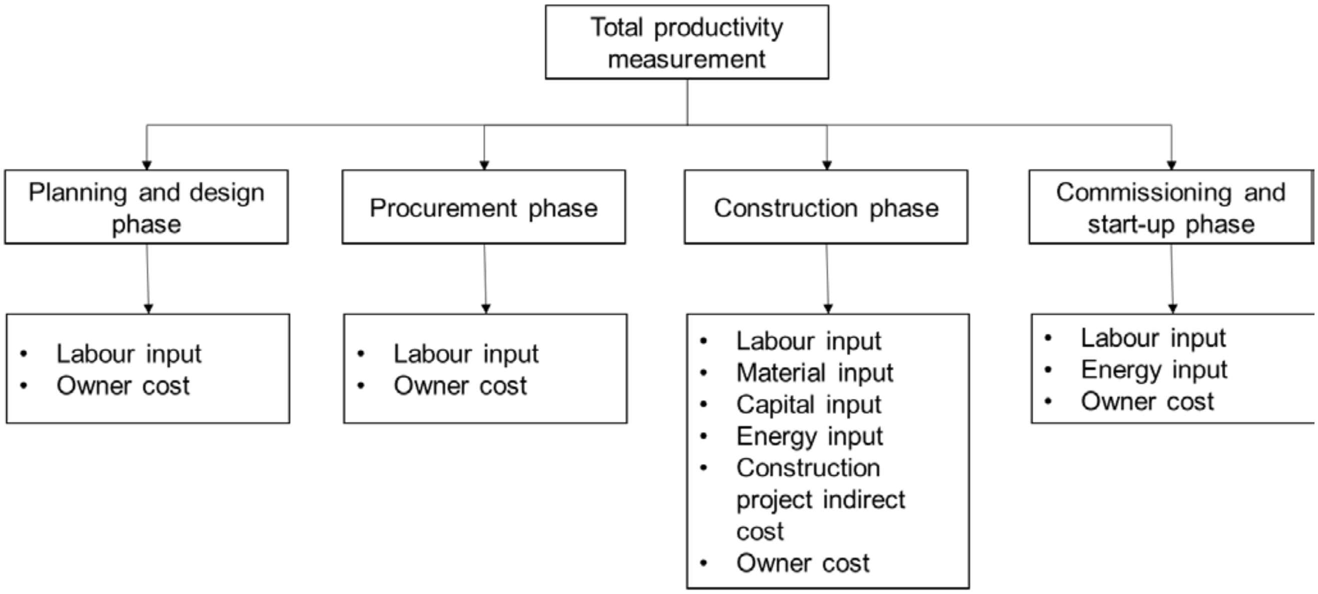

Figure 6. Modified total productivity measurement framework

Labour input

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 stage of the project. For the purpose of this research, labour input represents the cost of human resource input utilized in the project. Based on feedback from the focus group discussion, a set of major direct and indirect labour input components for calculating project total productivity were finalized (see Table 4).

Table 4. 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 operator	
Commissioning and start-up	• Owner project staff • Design consultants • Facility operators • Commissioning consultants	
Project phase	**Indirect labour input**	
Planning and design	• Owner project manager • Admin. staff • Legal staff	• Accounting staff • Procurement personnel • Alliance/partner rep.
Procurement	• Owner project manager • Project manager • Accounting staff • Admin. staff	• Procurement manager • Design consultants • Legal staff • Alliance/partner rep.
Construction	• Owner project manager • Owner project staff • Project manager • Construction manager • Discipline engineer • Site engineer • Design consultants • Project engineer • Project controls • Constructability consultant • Accounting staff • Admin. staff • Procurement staff	• Material controls • Workface planner • General foreman • Superintendent • Safety personnel • QA/QC • 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 • Admin. staff • Subcontractor specialists	• Safety engineer • QA/QC • Equipment vendors • Start-up manager

Material input

Material input includes any physical material constructed to be part of the finished structure. All focus group participants unanimously agreed on the classification of material input as materials that are purchased and installed during the construction process, as shown in Table 5.

Table 5. Material input category

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

Energy input

Energy input is considered to be a critical component of multifactor productivity measures at the industry level (OECD 2001). However, measuring the effect of energy input on project-level productivity has not been addressed in previous research. This study proposes a definition of energy input in construction projects as the cost of oil, fuel, and electricity required during the construction and commissioning and start-up phases.

Participants agreed with the proposed energy input category. However, many participants noted that energy is not tracked as a separate input component in their companies; instead, energy is considered as an overhead cost. It was indicated that extraction of energy consumption data might be useful for companies, depending on the nature of the project; this data can be used to track carbon efficiency in a project. Participants also 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 for other phases will be insignificant.

Capital input

The meaning of capital varies across 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. Intangible assets such as organizational effort, software development, and advertisement costs are excluded during capital input calculation (Huang et al. 2009). Goodrum and Haas (2002) separate capital input into fixed and circulating capital. Fixed capital includes buildings and equipment used in the production process. Circulating capital refers to the available funds required for purchasing raw materials. In this study, capital input denotes fixed capital that is devoted to the completion of a project, and it represents temporary equipment used to build the facility. Temporary equipment costs include direct (e.g., rental or ownership, tires, and filters) and indirect costs (e.g., maintenance, depreciation, and insurance).

Construction project indirect input

The cost of a construction project is categorized into direct and indirect costs. Becker et al. (2012), in collaboration with CII, developed an indirect construction cost characterization framework that can be implemented by owners and contractors to improve cost component accounting. 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 this definition from Becker et al. (2012), this research utilizes the following list of construction project cost components shown below in Table 6.

Table 6. Construction project indirect inputs

Phase	**Cost components**	
Construction	• Temp. roads and parking • Temp. office and services • Temp. field facilities • Temp. housing and camps • Temp. structures • Temp. 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

Owner cost input

In cost estimation for capital projects in the heavy industrial construction sector, there are distinct cost components related to project owners, excluding the financing cost (EIA 2016). According to the Energy Information Administration (EIA) (2016), capital project cost can be grouped into civil and structural costs, mechanical equipment supply and installation, electrical and 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 commercially operable status. Table 7 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.

Table 7. Owner input cost components

Project phase	Owner cost input components	
Planning and design	• Office equipment and consumables • Environmental costs • Site analysis and surveying • Legal expenses • Permitting costs	• Advertising costs • Bidding costs • Training of personnel • Travel expenses
Procurement	• Office equipment and consumables • Advertising costs • 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

4.3 Phase III: Verification of the measurement framework

The framework was verified based on responses from industry experts. A questionnaire was distributed to owner companies that attended the focus group session to verify the modified measurement framework within their respective organizations. The main objective of the questionnaire was to gather further insight about the proposed metric and list of input components. The first part of the questionnaire was used to evaluate the feasibility of the metric, while the second part of the questionnaire provided a list of input components in each category and was used to evaluate whether respondents agreed that each listed input component belongs in the specified phase and input category.

Four completed questionnaires were received back from the participating companies. The respondents had between 11 and 20 years of experience in sections including heavy industrial construction, home building and renovation, engineering construction, institutional and commercial construction. Respondents held the following positions within their respective organizations: senior engineer, technical lead, engineer technologist, and field engineer technologist.

The survey results were similar to the focus group discussion, and all respondents agreed with the proposed metric. Furthermore, it was noted that even though the list of input components might be used as a basis for data collection, the metric may face challenges related to accuracy in cost tracking and allocation of the measurement components. Based on a literature review, as well as responses from focus group discussion and survey questionnaires, a final list of the categories and components of the productivity metric was established (Table 8). The presented list of input components can be used to calculate the total productivity of construction projects.

Table 8. List of input components for measuring the total productivity of construction projects

	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 operator	• Owner project staff • Design consultants • Facility operators • Commissioning consultants
Indirect labour	• Owner project manager • Admin. staff • Legal staff • Accounting staff • Procurement personnel • Alliance/partner rep.	• Owner project manager • Project manager • Accounting staff • Administrative staff • Procurement manager • Design consultants • Legal staff • Alliance/partner rep.	• Owner project manager • Owner project staff • Project manager • Construction manager • Discipline engineer • Site engineer • Design consultants • Project engineer • Project controls • Constructability consultant • Accounting staff • Admin. staff • Procurement staff • Material control • Workface planner • General foreman • Superintendent • Safety personnel • QA/QC • Field survey/layout crew(s) • Subcontract specialists	• Owner project manager • Project manager • Document controller • Admin. staff • Subcontractor specialists • Safety engineer • QA/QC • Equipment vendors • Start-up manager

	Planning and design phase	Procurement phase	Construction phase	Commissioning and start-up
Indirect labour cont'd			• Field clerical staff • Legal staff • Security • Janitorial staff	
Material input			• Civil structural components • Interior and exterior parts, excluding structural parts • Piping • Mechanical components • Electrical components • Fittings and fixtures • Fire protection • HVAC • Miscellaneous	
Capital input			• Direct and indirect equipment cost	
Energy input			• Oil, fuel, and electricity	• Oil, fuel, and electricity
Construction project indirect input			• Temp. roads and parking • Temp. office and services • Temp. field facilities • Temp. housing and camps • Temp. structures • Temp. utilities for trades • Temp. water supply services • Subcontractor facilities	

	Planning and design phase	Procurement phase	Construction phase	Commissioning and start-up
Construction project indirect input cont'd			• Mobilization/demobilization costs • Communications 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 • Permitting cost • Advertising costs • Bidding costs • Training costs • Travel expenses	• Office equipment and consumables • Advertising costs • Travel expenses	• 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 expense	• Office equipment and consumables • Handover costs • Operation costs • Staff training • Document preparation costs • Clean-up costs • Travel expenses

5. Conclusions and recommendations

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 exclusively 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 methods for assessing 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, 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. Furthermore, this framework will assist in determining the basic components of productivity measurement for future data collection and analysis.

Future research will explore further refinement of the developed framework and verification in different construction sectors. The framework will be validated by collecting and analyzing data from additional projects to derive a total productivity value. 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. Common inflation indices for construction output will be considered, such as the construction price indices used by Statistics Canada (e.g., new housing, nonresidential buildings, and construction union wage rate index). These indices will be used to develop an approach to convert a current year output measure into a real output, which will allow year-to-year changes in output, adjusting for the change in the quality of the built facility.

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7. Appendices

APPENDIX A. Description of project phase activities, major participants, and typical cost elements

Table A.1 Project phase activities, major participants, and typical cost elements

Project phase	Major participants	Typical activities	Deliverables	Typical cost elements
Initiation phase	• Owner personnel (project board) • Owner project manager • Owner admin. staff • Alliance/partners • Financial analyst • Owner legal staff • Public relations • Planning consultants	• Define project broadly and identify milestones • Determine project scope • Address business requirements • Analyze project requirements • Identify constraints and outcomes • Develop high-level plan (establish timescale and resource requirements) • Identify stakeholders • Select team • Prepare a conceptual estimate • Define issues, problems, and opportunities • Discuss risks and potential issues • Identify, document, and validate assumptions for planning stage	• Project initiation document (PID) • Project charter • Project stage plan form • Project definition package • Stakeholder analysis and communication plan • Risk register	• Owner personnel fee • Consultant fees and expenses • Admin. costs • Project manager fees • Land purchasing costs • Environmental permitting costs • Legal fees • Office consumables (standard office supplies, paper products, etc.)
	• Owner project manager • Admin. staff • Alliance/partners	• Set project objectives • Identify and address project barriers • Asses the site • Asses technological requirements	• Scope management plan • Site layout • Project execution plan • Contracting strategy	• Owner project manager fees • Admin. staff costs

Project phase	Major participants	Typical activities	Deliverables	Typical cost elements
Planning and design phase **Planning and design phase**	• 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	• Analyze alternative course of action • Define quality of deliverables • Identify relationship between project participants • Combine objectives of designers, contractors, and owners to form integrated project strategy • Determine activities and required resources for project • Identify interaction between different work tasks • Study sequence of operations • Develop human resource plan • Prepare drawings and specifications • Prepare bill of material • Develop a pre-tender estimate • Perform escalation and contingency analysis • Prepare contract document • Define constructability objectives and measures • Performing constructability reviews • Identify and address project barriers • Develop risk mgmt. strategy • Identify relevant quality standards and prepare project quality program/plan • Determine procurement responsibility	• Organizational chart and role details • Communication mgmt. plan • Activity list • Project network diagrams • Activity duration • Work breakdown structure • Resource requirements • Cost management plan • Drawing and specifications • Value engineering • Construction proposal • Change mgmt. plan • Quality mgmt. plan and checklist • Procurement plan • Material mgmt. plan • Site logistics plan • Risk mgmt. plan • Risk ranking and risk analysis results • Safety plan • Emergency response plan • Contractual agreements • Constructability procedures • Start-up execution plan	• Consultant fees and expenses • Permitting costs • Project manager fees • Construction manager fees • Constructability expert fees • Value engineering expert fees • Cost consultant fees • Geotechnical consultant fees • Procurement personnel • Environmental consultant fees • Planning consultant fees • Licensor costs • Office consumables (standard office supplies, paper products, etc.) • Communications and utilities (telephone cost, postage, etc.) • Vehicle allowances and transportation costs

Project phase	Major participants	Typical activities	Deliverables	Typical cost elements
Planning and design phase		• Identify requirements for purchase of materials and equipment • Training of personnel • Value engineering • Identify warehousing needs • Determine testing and inspection requirements • Bid analysis and award construction contract • Define the impact of start-up plan • Estimate start-up costs • Identify start-up risks		
Procurement phase	• Owner project mgmt. personnel • Contractor project manager • Procurement personnel • Expediting personnel • Alliance/partners	• Coordinate procurement plan with project schedule • Analyze alternatives • Review construction documents • Compare material delivery schedule and construction schedule • Vendor inquiries • Vendor qualification • Bid analysis for selecting a provider • Review vendor documents • Award contract • Purchase material and equipment items • Transportation • Vendor QA/QC • Expediting	• Evaluation criteria • Procurement documents • Solicitation proposals • Procurement contract	• Owner project mgmt. personnel fees • Project manager fees • Construction manager fees • Procurement personnel fees • Expediting personnel fees • Office material costs • Transportation costs • Material costs

Project phase	Major participants	Typical activities	Deliverables	Typical cost elements
Construction phase	• Owner project manager • Admin. staff • Design consultants • Contractor project manager • Construction manager • Project engineer • Safety coordinator • QA/QC manager • Project controls manager • Construction superintendent • Foremen • Craft labour • Subcontractors • Constructability experts • Procurement staff	• Mobilize equipment • Site preparation • Construction plan for methods • Procurement of materials • Warehousing • Issue subcontractors • Build the facility • Testing and quality control • Apply constructability concepts and procedures • Monitor and evaluate project program effectiveness • Administer procurement contract and confirm compliance with requirements • Schedule and cost control • Demobilize construction equipment	• Work results • Inputs to performance appraisals • Quality improvements • Performance improvements • Project reports • Project records • Risk database • Built facility • Lessons learned	• Owner project mgmt. expenses • Admin. staff fee • 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 fees • Subcontractor fees • Construction equipment, tools, and supplies • Material costs • Inspection and quality control costs • Scaffolding costs • Construction permits and warranties costs • Site development costs • Temp. facilities and services

Project phase	Major participants	Typical activities	Deliverables	Typical cost elements
Construction phase				• Office consumables in construction phase (standard office supplies, paper products, etc.) • Mobilization and demobilization costs

APPENDIX B: Focus group data collection forms

UNIVERSITY OF ALBERTA
TOTAL PRODUCTIVITY MEASUREMENT IN CONSTRUCTION PROJECTS

Dear Participant,

The NSERC Industrial Research Chair in Strategic Construction Modeling and Delivery would like to thank you for agreeing to participate in this focus group discussion. The main objective of this study is to propose a metric that can be used to measure the overall productivity of construction projects by considering the joint impact of all input resources, such as labour, material, capital, and energy. Furthermore, a detailed framework has been developed that includes a list of the information required for quantification of the total inputs or resources used in construction projects. This focus group discussion will aid in the assessment of the applicability and viability of the proposed metric and its components.

It is estimated that 90 minutes will be required to complete the session. All information provided by respondents will remain confidential, and only the aggregated results will be made available for publication.

This session involves three activities. During the first part of the session, the proposed metric and a list of items that have been identified as input resources will be validated using prepared questions. During the second part of the session, an open discussion will be held about the proposed metric and challenges associated with its method of application. As a last activity, based on the information you provided on the prepared form, an open discussion will be held on the additional metric elements.

PART I: GENERAL INFORMATION

1. Please indicate your organization’s sector of involvement in the construction industry: (select ALL options that apply)

☐ *Home building and renovation*: New home building, renovation, and specialized trade construction (e.g., plumbing, heating, ventilation, air conditioning).

☐ *Heavy industrial construction*: Construction of industrial facilities such as power plants, refineries, nuclear plants, mines, and oil sand installations.

☐ *Engineering construction*: Construction of highways and streets, bridges, sewers, and railroads, as well as irrigation, flood control, and marine infrastructure.

☐ *Institutional and commercial construction*: Building of structures such as high-rise condos and office towers, stadiums, schools, hospitals, malls, libraries, art galleries, and museums.

☐ *Other(s)* (please specify): ______________________________

2. Please indicate your organization type:

☐ Owner

☐ Consultant

☐ Contractor

☐ Other (please specify): ______________________________

3. Please indicate your total years of construction experience:

☐ 0−2 years ☐ 3−5 years ☐ 6−10 years ☐ 11−20 years

☐ Over 20 years

4. Please indicate your current employer:

____

5. Please select your current occupation:

☐ Director
☐ Project Manager
☐ Senior Engineer
☐ Senior Management
☐ Vice-President
☐ Other (please specify): ____________________
☐ Project Director
☐ Manager

6. Please indicate years in your current position:

☐ 0−2 years
☐ 3−5 years
☐ 6−10 years
☐ 11−20 years
☐ Over 20 years

7. Please indicate all sector types in which you have experience:

☐ Home building and renovation
☐ Heavy industrial construction
☐ Engineering construction
☐ Institutional and commercial construction
☐ Other(s) (please specify): ____

8. Please indicate your age:

☐ 20−30
☐ 31−40
☐ 41−50
☐ 51−60
☐ Over 60

9. Please indicate your highest level of education:

☐ Some high school
☐ High school diploma
☐ Some college credit, no degree
☐ Vocational, technical, or trade school
☐ College diploma
☐ Some university credit
☐ Bachelor's degree
☐ Master's degree
☐ Doctorate degree
☐ Professional designation
☐ Other (please specify): ______________________________

PART II: MEASURMENT METRICS AND COMPONENTS

1. Do you agree with the total productivity measurement metric proposed in this research? Do you have any suggestions for modification?

$$\text{Total Productivity} = \frac{\text{Total Tangible Output (Physical Units)}}{\text{Total Tangible Inputs (\$)}}$$

2. Do you agree with the method of quantifying inputs ($) and output (physical units)? Do you have any additional suggestions for modification?

3. Do you agree with the classification and definition of total tangible input resources (labour, capital, material, energy, and other)? Do you have any additional suggestions for categories to add?

4. Based on your experience, what are the limitations or difficulties that may be encountered while using the proposed metric?

PART III TOTAL PRODUCTIVITY MEASUREMENT INPUT COMPONENTS IN A CONSTRUCTION PROJECT

Below is a list of components proposed for each input category (labour, capital, material, energy, and other) during the different phases of a construction project that are required for measuring total project productivity. Please evaluate whether the listed cost component belongs to both the identified project phase (e.g., the construction phase) **and** the input category (e.g., capital input) under which it is found by marking ✓ in the checkbox ☐. If you believe the cost element does not belong to the group, leave the box blank. If there are additional components that you believe should be included in the specified input category under the stated phase, please write the suggested components on the provided blank rows.

LABOUR INPUT

	Initiation phase	Planning & design phase	Procurement phase	Construction phase	Commissioning and start-up phase
Direct labour	☐ Owner project staff **Additional suggestions** __________ __________ __________ __________ __________ __________ __________ __________	☐ Owner project staff ☐ Planning consultants ☐ Constructability consultants ☐ Design consultants (architect, engineer, etc.) ☐ Cost consultants ☐ Value engineering experts ☐ Environmental consultants **Additional suggestions**	☐ Owner project staff ☐ Procurement personnel ☐ Expediting personnel **Additional suggestions** __________ __________ __________ __________ __________ __________ __________	☐ Direct craft labour ☐ Foreman ☐ Heavy equipment operators **Additional suggestions** __________ __________ __________ __________ __________ __________	☐ Owner project staff ☐ Design consultant ☐ Facility operators ☐ Commissioning consultants **Additional suggestions** __________ __________ __________ __________ __________

	Initiation phase	Planning & design phase	Procurement phase	Construction phase	Commissioning and start-up phase
Indirect labour	☐ Owner personnel (project board) ☐ Owner project manager ☐ Owner admin. staff ☐ Public relations ☐ Financial analysts ☐ Owner legal staff ☐ Environmental specialists ☐ Alliance/partner rep. **Additional suggestions** __________ __________ __________ __________ __________ __________ __________	☐ Owner project manager ☐ Admin. staff ☐ Legal staff ☐ Accounting staff ☐ Procurement personnel ☐ Alliance/partner rep. **Additional suggestions** __________ __________ __________ __________ __________ __________ __________ __________ __________ __________ __________ __________	☐ Owner project manager ☐ Project manager ☐ Accounting staff ☐ Administrative staff ☐ Procurement manager ☐ Design consultants (architect, engineer, etc.) ☐ Legal staff ☐ Alliance/partner rep. **Additional suggestions** __________ __________ __________ __________ __________ __________ __________ __________	☐ Owner 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 engineer ☐ QA/QC	☐ Owner project manager ☐ Project manager ☐ Document control ☐ Admin. staff ☐ Subcontractor staff ☐ Safety engineer ☐ QA/QC ☐ Equipment vendors ☐ Start-up manager **Additional suggestions** __________ __________ __________ __________ __________ __________

	Initiation phase	Planning & design phase	Procurement phase	Construction phase	Commissioning and start-up phase
Indirect labour cont'd				☐ Field survey/ layout crew(s) ☐ Subcontractor specialists ☐ Field clerical staff/ record mgmt. clerks ☐ Legal staff ☐ Security ☐ Janitorial staff **Additional suggestions** ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________	

CAPITAL INPUT

Phase	Initiation phase	Planning & design phase	Procurement phase	Construction phase	Commissioning and start-up phase
Capital input	☐ ***Land-related costs*** ***(***land purchase costs, land transfer taxes, land registry charges, and land-related legal expenses) **Additional suggestions**	**Suggestions**	**Suggestions**	☐ Direct equipment costs (Includes rental/ownership costs, tires, filters) ☐ Indirect equipment costs (Includes repairs and maintenance, depreciation, and insurance) **Additional suggestions**	**Suggestions**

MATERIAL INPUT

	Initiation phase	Planning & design phase	Procurement phase	Construction phase	Commissioning and start-up phase
Material input	**Suggestions** ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________	**Suggestions** ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________	**Suggestions** ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________	☐**Material input:** ☐ ***Civil structural components***: Materials included in substructure and superstructure work such as excavation, concreting, etc. ☐ ***Interior and exterior parts, excluding structural parts***: Interior partitions, finishes, furnishings, etc. ☐ ***Piping*****:** Underground and aboveground systems, pipes, fittings, valves, pipe supports, etc. ☐ ***Mechanical components*****:** Equipment and mechanical parts of the built facility ☐ ***Electrical components*****:** Conduits, cables, fixtures, transformers, etc. ☐ ***Fittings and fixtures*** ☐ ***Fire protection***	**Suggestions** ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________ ____________

	Initiation phase	Planning & design phase	Procurement phase	Construction phase	Commissioning and start-up phase
				☐ ***Heating, ventilation, and air conditioning (HVAC)*** ☐ ***Miscellaneous*** (e.g., site external) **Additional suggestions** __________________ __________________ __________________ __________________ __________________ __________________ __________________ __________________	

ENERGY INPUT

	Initiation phase	Planning & design phase	Procurement phase	Construction phase	Commissioning and start-up phase
Energy input	☐ Electricity **Additional suggestions** ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________	☐ Electricity **Additional suggestions** ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________	☐ Electricity **Additional suggestions** ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________	☐ Oil ☐ Fuel ☐ Electricity **Additional suggestions** ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________	☐ Oil ☐ Fuel ☐ Electricity **Additional suggestions** ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________ ____________________

OTHER INPUT

	Initiation phase	Planning & design phase	Procurement phase	Construction phase	Commissioning and start-up phase
Other input	☐ General office equipment (copiers, printers, computers, fax machines, etc.) ☐ Office consumables (standard office supplies, paper products, etc.) ☐ Travel and transportation costs ☐ Environmental costs ☐ Site analysis and surveying ☐ Legal expenses	☐ General office equipment (copiers, printers, computers, fax machines, etc.) ☐ Office consumables (standard office supplies, paper products, etc.) ☐ Travel and transportation costs ☐ Advertising costs ☐ Bidding costs ☐ Training of personnel ☐ Environmental costs ☐ Legal expenses	☐ General office equipment (copiers, printers, computers, fax machines, etc.) ☐ Office consumables (standard office supplies, paper products, etc.) ☐ Travel and transportation costs ☐ Advertising **Additional suggestions** ________________ ________________ ________________	☐ Temp. roads and parking ☐ Temp. office and services ☐ Temp. field facilities ☐ Temp. housing and camps ☐ Temp. structures ☐ Temp. utilities for trades ☐ Temp. water supply services ☐ Subcontractor facilities ☐ Mobilization and demobilization costs	☐ Handover costs ☐ Operating costs ☐ Staff training and preparation of necessary documents for operation ☐ Clean-up costs ☐ Travel and transportation costs **Additional suggestions** ________________ ________________ ________________

	Initiation phase	Planning & design phase	Procurement phase	Construction phase	Commissioning and start-up phase
Other input cont'd	**Additional suggestions** ________________ ________________ ________________	☐ Permitting costs **Additional suggestions** ________________ ________________ ________________		☐ Communications and computers ☐ Safety and first aid ☐ Permits (construction-related) ☐ Material testing costs ☐ Construction consumables ☐ Insurance ☐ Personnel training costs ☐ Escalation ☐ Profit ☐ Contingency ☐ Legal services ☐ Environmental and mitigation costs **Additional suggestions** ________________ ________________ ________________	

DESCRIPTION OF METRIC COMPONENTS

Initiation phase: As the first phase of a project, the initiation phase involves the process of determining project scope and requirements. This phase includes identifying stakeholders, defining opportunities and problems associated with the project, and documenting necessary assumptions in preparation for the planning stage.

Planning phase: Planning involves defining and refining project objectives and selecting the best of the alternative courses of action to attain those objectives.

Design phase: Typical design phase activities include the preparation of drawings, specifications, and bills of materials, as well as the development of a definitive cost estimate, technical reviews, and engineering procurement plans.

Procurement phase: This is a phase in the construction project life cycle that involves obtaining and organizing the external resources needed to complete a project.

Construction phase: This phase consists of a series of activities to build the facility.

Commissioning and start-up: This is a transitional phase between the construction and operations of the facility; it involves activities such as checking the system, performance testing, and acceptance of work.

Labour input: The human resources used in the project.

Direct labour input: Labour input that is directly involved in the handling and installation of materials; it can easily be traced to an activity.

Indirect labour input: Labour associated with the support of the direct construction process required for completion of the project.

Capital input: Fixed capital that is devoted to the completion of a project; it includes land and temporary equipment used to build the facility.

Material input: Material and permanent equipment that is purchased and installed in the construction process; it will be part of the finished structure.

Energy input: Energy sources such as oil, electricity, and fuel that are used for performing various activities in the construction project.

Other input: Miscellaneous costs associated with the project that cannot be directly attributed to labour, capital, material, or energy input.

DIRECT LABOUR INPUT
INITIATION PHASE
Owner project staff: Owner representative assigned to work only on the specified project.
PLANNING & DESIGN PHASE
Owner project staff: Owner representative assigned to work only on the specified project. ***Planning consultants:*** Provide pre-development feasibility studies, municipal approval processing, and expert advice on planning matters. ***Constructability consultants:*** Perform constructability reviews to assess the viability of construction plans and specifications. ***Design consultants (architect, engineer, etc.):*** Responsible for developing the design and providing construction specifications, plans, and drawings. ***Cost consultants:*** Provide quantity surveying and construction cost management plan preparations for the project. ***Value engineering experts:*** Provide consultation with the aim of achieving the best value for the money by identifying and eliminating unnecessary costs. ***Environmental consultants:*** Responsible for devising methods and plans for avoiding, minimizing, or mitigating effects on the environment and surrounding area.
PROCUREMENT PHASE
Owner project staff: Owner representative assigned to work only on the specified project. ***Procurement personnel:*** Analyze market dynamics and process purchasing transactions for equipment, materials, supplies, capital goods, and services. ***Expediting personnel:*** Coordinate delivery schedules of materials and recommend corrective actions to ensure materials arrive on site in accordance with contractual and project schedule.
CONSTRUCTION PHASE
Direct craft labour: Individuals with a particular trade skill, such as boilermakers, ironworkers, electricians, and pipefitters. ***Foreman:*** Supervisor who oversees tasks and provides proper documentation to the crew so that tasks can be performed. ***Heavy equipment operator**:* Operates equipment used at the construction site and performs tasks, both pre- and post-usage, to ensure everything works properly.
COMMISSIONING AND START-UP PHASE
Owner project staff: Owner representative assigned to work only on the specified project. ***Design consultants:*** Provide assistance for the deficiency assessment, field review, review of warranties, and total performance inspection and certification. ***Facility operators:*** Individuals involved in the operation of the facility or plant. ***Commissioning consultants:*** Facilitate the commissioning process.

INDIRECT LABOUR INPUT
INITIATION PHASE
Owner personnel (Project board): Representatives of key project stakeholders. ***Owner's project manager:*** Acts as the client representative and consultant throughout the project, from initiation through completion. ***Owner administrative staff:*** Perform administrative support related to the project (e.g., secretarial services). ***Public relations:*** Marketing and strategic communication group that creates a relationship between the organization and the public. ***Financial analysts:*** Evaluate construction project-specific financing information. ***Owner legal staff:*** Provide legal advice related to project construction contracts and services. ***Planning consultants:*** Provide pre-development feasibility studies, assist with the municipal approval processing, and provide expert advice on planning matters. ***Environmental specialist:*** Assesses the environmental needs and environmental scope of the work. ***Alliance/partners' representative:*** Individual appointed by partner companies that share a common interest in the outcome of the project.
PLANNING & DESIGN PHASE
Owner project manager: Acts as the client representative and consultant throughout the project, from initiation through completion. ***Administrative staff:*** Give administrative support, including human resources, secretarial services, and IT support, to the planning and design team. ***Legal staff:*** Provide legal advice in relation to project construction contracts and services. ***Accounting staff:*** Perform financial analysis and reporting. ***Procurement personnel:*** Analyze market dynamics and assist in the development of specifications for equipment, materials, and services to be purchased. ***Alliance/partner representative:*** Individual appointed by partner companies that share a common interest in the outcome of the project.
PROCUREMENT PHASE
Owner's project manager: Acts as the client representative and consultant throughout the project, from initiation through completion. ***Project manager:*** Responsible for overseeing all elements and activities of the project, including budgeting. ***Accounting staff:*** Perform financial analysis and reporting. ***Administrative staff:*** Give administrative support (including human resources, secretarial services, and IT support). ***Procurement manager:*** Supervises procurement personnel and acquisition of the required goods and services. ***Design consultants (architect, engineer, etc.):*** Responsible for developing the design and providing construction specifications, plans, and drawings. ***Legal staff:*** Provide legal advice related to project construction contracts and services. ***Alliance/partner representative:*** Individual appointed by partner companies that share a common interest in the outcome of the project.

INDIRECT LABOUR INPUT
CONSTRUCTION PHASE
Owner's project manager: Acts as the client representative and consultant throughout the project, from initiation through completion. ***Owner project staff:*** Owner representative assigned to work only on the specified project. ***Project manager:*** Responsible for overseeing all elements of the project. ***Construction manager:*** Undertakes the responsibility of managing day-to-day personnel and site supervision activities. ***Discipline engineer:*** Provides technical support during the construction phase. ***Site engineer:*** Part of the site management team, which offers advice in the planning and supervision of the technical aspects of a construction project. ***Design consultants:*** Responsible for developing the design and providing construction specifications, plans, and drawings. ***Project engineer:*** Interacts with other engineers to coordinate staffing and prioritization and manage approval processes with municipalities and other agencies. ***Project control:*** Provides the schedule as well as cost control tasks. ***Constructability consultant:*** Performs constructability reviews to determine and improve construction plans and specifications in order to mitigate on-site problems. ***Accounting staff:*** Perform financial analysis, reporting, and project cost forecasting. ***Administrative staff:*** Give administrative support to participants in the construction phase. ***Procurement staff:*** Responsible for purchasing and material control tasks. ***Material control:*** Manages and supervises inventory transaction processes to ensure inventory accuracy and timeliness. ***Workface planner:*** Responsible for the development, monitoring, and control of construction work packages. ***General foreman:*** In charge of organizing all site teams, inspecting work, and controlling the overall job. ***Superintendent:*** Responsible for running day-to-day operations on the construction site and controlling the short-term schedule. ***Safety engineer:*** Investigates the working environment and recommends changes that keep workers from being exposed to injuries and accidents. ***Quality assurance/Quality control:*** Inspects work and products for defects and deviations from specifications. ***Field survey/Layout crew(s):*** Prepare all data, charts, plots, maps, records, and documents related to elevations and site boundary measurements. ***Subcontract specialists:*** Administer subcontracted work. ***Field clerical staff/Record management clerks***: Process daily reports and provide administrative support by performing data entry duties. ***Legal staff:*** Provide legal advice related to the project. ***Security:*** Protects valuable assets against theft, vandalism, and illegal entry. ***Janitorial staff:*** Give general site support related to site cleaning.

INDIRECT LABOUR INPUT
COMMISSIONING AND START UP PHASE
Owner's project manager: Acts as the client representative and consultant throughout the project, from initiation through completion. ***Project manager:*** Liaises with the commissioning team to assess the quality, budget, schedule, and risks related to the commissioning process. ***Document controller:*** Organizes files and retrieves records related to the construction and operation of the project. ***Administrative staff:*** Give administrative support during the commissioning phase of the project. ***Subcontractor specialists:*** Administer and oversee subcontracted work. ***Safety engineer:*** Investigates the working environment and recommends changes to keep workers from being exposed to injuries and accidents. ***Quality assurance/Quality control:*** Inspects work and products for defects and deviations from specifications. ***Equipment vendors:*** Suppliers of materials and services that are used as part of the final built facility. ***Start-up manager:*** Oversees/manages start-up/commissioning personnel in order to meet project goals and schedules.

CAPITAL INPUT
INITIATION PHASE
Land: Property obtained for project use. Land costs include land purchase costs, land transfer taxes, land registry charges, and land-related legal costs.
CONSTRUCTION PHASE
Equipment Input: Includes direct (rental or ownership, tires, and filters) and indirect costs (maintenance, depreciation, and insurance).

MATERIAL INPUT
CONSTRUCTION PHASE
Construction material input: • ***Civil structural components:*** Materials included in substructure and superstructure work such as excavation, concreting, etc. • ***Interior and exterior parts, excluding structural parts***: Includes interior partitions, finishes, furnishings, etc. • ***Piping:*** Underground and aboveground systems, pipe, fittings, valves, pipe supports, etc. • ***Mechanical components:*** Equipment and mechanical parts of the built facility. • ***Electrical components:*** Conduits, cables, fixtures, transformers, etc. • ***Fittings and fixtures*** • ***Fire protection*** • ***Heating, ventilation, and air conditioning*** (HVAC) • ***Miscellaneou***s (e.g., external site works)

ENERGY INPUT
INITIATION PHASE
Electricity input: Electric power utility consumption required for preliminary tests and operating office equipment
PLANNING & DESIGN PHASE
Electricity input: Electric power utility consumption required for preliminary tests and operating office equipment
PROCUREMENT PHASE
Electricity input: Electric power utility consumption required for operating office equipment
CONSTRUCTION PHASE
Oil: Expenditures associated with the use of lubricating oil consumed by equipment and machines ***Fuel:*** Costs associated with the consumption of fuel (gasoline or diesel) for the operation of equipment ***Electricity:*** Electricity consumption bill that is charged as a result of power use for equipment operation and temporary site facilities
COMMISSIONING & START-UP PHASE
Oil: Required for the testing and inspection of necessary machines and parts of the built facility ***Fuel:*** Required for the operating components of the built facility and equipment ***Electricity:*** Electricity utility costs for consumption of electrical energy use after the built facility is connected to a permanent utility provider

OTHER INPUT
INITIATION PHASE
General office equipment: Supplies such as copiers, printers, office computers, and fax machines ***Office consumables:*** Typically includes standard office supplies such as paper products, etc. ***Travel and transportation:*** Expenses for moving required items and project participants for inspection trips. Includes airfare, lodging, rental cars, vehicle gasoline and fuel, maintenance and tires (owned vehicles), and subsistence and field per diems ***Site analysis and site surveying:*** Supplies necessary for site inspection and preliminary assessments ***Environmental costs:*** Potential environmental permitting costs required at the initiation phase of the project ***Legal expenses:*** Expenses associated with legal issues, excluding fees paid for professional services
PLANNING & DESIGN PHASE
General office equipment: Supplies such as copiers, printers, office computers, and fax machines ***Office consumables:*** Standard office supplies, paper products, etc. ***Travel and transportation:*** Travel expenses for staff, consultants, and required items during the planning and design phase of the project, including subsistence and field per diems and relocation, airfare, lodging, rental cars, vehicle gasoline and fuel, and maintenance and tires (owned vehicles) ***Advertising costs:*** Advertisements in local or provincial publications in order to select a competent designer and contractor ***Bidding costs:*** Indirect costs related to preparing and reviewing bids ***Training of personnel:*** Expenditures associated with the training of personnel for developing special project-related skills ***Environmental costs:*** Costs associated with the analysis of environmental impacts, development of mitigation strategies, and documentation of technical reports ***Legal expenses:*** Expenses associated with legal issues, excluding fees paid for professional services ***Permitting expenses:*** Costs required to be paid to government agencies in order to build the facility
PROCUREMENT PHASE
General office equipment: Supplies such as copiers, printers, office computers, and fax machines ***Office consumables:*** Standard office supplies, paper products, etc. ***Travel and transportation:*** Travel expenses for staff, consultants, and required items during the procurement phase of the project, including subsistence and field per diems, airfare, lodging, rental cars, vehicle gasoline and fuel, and maintenance and tires (owned vehicles) ***Advertising:*** Advertisements in local or provincial publications in order to select a competent vendor for materials

OTHER INPUT
CONSTRUCTION PHASE
Temporary roads and parking: Costs related to the construction or maintenance of roads, parking, and lay-down areas around the construction site. ***Temporary office and service:*** Expenses related to setting up an office trailer, lease expenses, office supplies, and consumables. ***Temporary field facilities:*** Expenses related to warehousing, storage facilities, portable toilets, trash services, drinking water, and off-site storage. ***Temporary housing and camps:*** Housing allowances and relocation expenses. ***Temporary structures:*** Expenses associated with structures erected to assist in the construction of a permanent project, such as scaffolding, shoring, falsework, concrete formwork, and other site protection structures. ***Temporary utilities to trades:*** Costs associated with setting up temporary electrical systems and temporary water distribution services in the field. ***Temporary water supply service:*** Expenses associated with the water supply for construction purposes. ***Subcontractor facilities:*** Potential site facilities required for use by subcontractors. ***Mobilization and demobilization:*** Costs associated with moving construction equipment, site clean-up, dumpsters, and dust control. ***Communications and computers:*** Costs related to software, phone chargers, site computers, and internet. ***Safety and first aid:*** Personal protection and safety gear, fire protection sensors and alarms, fire extinguishers, safety barricades, and railings. ***Travel and transportation:*** Cost of transportation for materials, equipment, and personnel during the construction stage, including relocation of the construction staff to the new project location, subsistence, and field per diems. ***Permit (construction-related):*** Fees paid to various government entities to secure authorization to undertake construction work. ***Material testing*:** Costs associated with material testing and quality control services (may be done by an independent laboratory service). ***Construction consumables (defined by the project team):*** (e.g., welding rods, small hand tools, cable, rope, fasteners, bolts, nails, etc.) ***Insurance:*** Includes builder risk insurance, liability insurance, property insurance, vehicle insurance, etc. ***Personnel training:*** Expenses paid for training workers. ***Escalation:*** An adjustment of price based on market conditions in the event of price fluctuations. ***Profit:*** The return on the contractor's investment in the project. ***Contingency:*** An allowance to cover unforeseen circumstances or unanticipated conditions related to construction. ***Legal services:*** Costs associated with legal services, excluding fees associated with project legal staff. ***Environmental mitigation:*** Costs incurred by developers and imposed by the law to offset or minimize a project's environmental or/and cultural impact.

OTHER INPUT
COMMISSIONING AND START UP PHASE
Handover costs: The necessary indirect costs for activities during the commissioning process. ***Operating costs:*** Costs related to operating equipment and machines in order to ensure that all systems and components of the building, industrial plant, etc., are designed, installed, tested, operated, and maintained according to operational requirements. ***Staff training and document preparation*****:** Training of staff members on the necessary skills for operating the systems and components of the newly constructed project. ***Clean-up costs:*** Necessary costs related to cleaning of the construction site. ***Travel and transportation:*** Travel expenses for staff, consultants, and items required during the commissioning and start-up phase of the project, including subsistence and field per diems and relocation.