Hybrid Fuzzy System Dynamics Modeling of Multi-Factor Productivity of Construction Activities

by

Nima Gerami Seresht

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Construction Engineering and Management

Department of Civil and Environmental Engineering
University of Alberta

Abstract

Productivity plays a key role in the successful delivery of construction projects, and it has long been a major research interest within the construction engineering domain. Previous research on the identification of factors influencing productivity often focused on labour-intensive activities while ignoring equipment-intensive activities, for which equipment is the driver of productivity. Therefore, there is a gap in the research on the identification of factors that affect the productivity of equipment-intensive activities.

Existing predictive models of activity-level productivity often predict construction labour productivity (CLP), which is a single-factor productivity measure for construction activities. However, CLP is not an appropriate measure of productivity for equipment-intensive activities because it does not provide any information regarding the resource input that is the driver of productivity for these activities. Determining multi-factor productivity (MFP) using labour, equipment, and material as the three model inputs results in a more comprehensive prediction of productivity than CLP. However, there is a gap in the research on developing a predictive model of productivity for equipment-intensive activities that will determine the MFP measure of these activities.

Existing construction productivity models are either static in nature or not capable of capturing the subjective uncertainty of some of the factors that influence construction productivity (e.g., crew motivation). Fuzzy system dynamics (FSD) is an appropriate technique for modeling construction productivity since it captures the dynamism of construction projects while simultaneously addressing the subjective and probabilistic uncertainty of the factors that influence construction productivity. However, there is a gap

in the research on developing computational methods for the implementation of fuzzy arithmetic operations in FSD models.

The main contributions of this research are threefold. It identifies the factors that affect the productivity of equipment-intensive activities; it enhances the FSD technique by developing computational methods for the implementation of fuzzy arithmetic in these models; and it develops a predictive model of construction productivity for determining the MFP measure of equipment-intensive activities using the FSD technique.

Preface

This thesis is an original work by Nima Gerami Seresht. The research project, based on which this thesis is written, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Research on Construction Productivity", Project ID: Pro00068631, approved on October 25, 2016. This research was funded by the Natural Sciences and Engineering Research Council of Canada Industrial Research Chair in Strategic Construction Modeling and Delivery (NSERC IRCPJ 428226–15), which is held by Dr. A. Robinson Fayek.

Parts of Chapter 5 and Chapter 6 of this thesis have been submitted for publication as Gerami Seresht, N. and Fayek, N. Robinson (2017). "Dynamic Modeling of Multi Factor Construction Productivity for Equipment-Intensive Activities." *J. Constr. Eng. Manage.,* in review, submitted November 09, 2017. I was responsible for the data collection and analysis as well as the manuscript composition. Dr. A. Robinson Fayek was the supervisory author and was involved with concept formation and manuscript composition.

Dedication

I dedicate this research to my great parents, Homayoontaj Taheri and Behrooz Gerami Seresht, and my beloved sister, Marjan Gerami Seresht.

Acknowledgement

First and foremost, I would like to express my sincere gratitude to Dr. Aminah Robinson Fayek for her continuous intellectual support, valuable guidance, and the energy and time she dedicated to guide me along the course of this research. I would have never been able to accomplish this thesis without her assistance and her dedicated involvement in every step of my research. My second acknowledgement goes to my doctoral committee, Dr. Yasser Mohammad, and Dr. Evan Davis for their great advices along the course of this research.

I would also acknowledge our partner company for the time they dedicated to this research and their invaluable inputs to this research. I also like to acknowledge my colleagues at the University of Alberta, Mr. Mohammad Raoufi, Dr. Naeimeh Sadeghi, Dr. Abraham Tsehahaye, Dr. Moataz Omar, and Mr. Nasir Siraj for their great suggestions and collaboration for conducting this research.

Finally, I would like to express my greatest gratitude to my parents, Homayoontaj and Behrooz and my sister, Marjan for their support, encouragements and inspirations during my studies.

Table of Contents

Chapter 3. Identification of Factors Influencing Productivity of Equipment-Intensive Activities

Chapter 4. Computational Method for Fuzzy Arithmetic Operations on Triangular Fuzzy Numbers by the Extension Principle

Chapter 5. Dynamic Modeling of Construction Productivity

List of Tables

List of Figures

Chapter 1. Introduction

1.1. Background

Construction is a major industrial sector in many countries worldwide, including Canada. In the five-year period between 2012 and 2016, the construction industry in Canada produced an average 7.51% of the national gross domestic product (GDP), making it Canada's second largest industry after manufacturing, which produced an average 13.03% of the GDP in the same period (Statistics Canada, 2017). Because of the importance of the construction sector, several studies have been conducted in the past few decades on different aspects of this industry. As an important factor in the successful delivery of projects, construction productivity has been one of the most researched topics in this domain. Economic data presented by the Organization for Economic Co-operation and Development (2015) indicates that Canada is ranked 25th worldwide and 8th in the G8 in terms of construction industry productivity, which is measured as GDP generated per hour of work. In general, an improvement in construction productivity is associated with a more efficient use of input resources, resulting in a decrease in total project cost.

Construction productivity is estimated at three different levels: (1) economic-level productivity, which is appropriate for industry-wide measurements of productivity; (2) project-level productivity, which is appropriate for measuring the productivity of specific projects; and (3) activity-level productivity, which is appropriate for measuring the productivity of specific activities. Moreover, there are a number of different definitions of construction productivity in the industry, which can be distinguished based on their perspective and their level of detail. From an economic perspective, construction productivity is defined at the industry level or the national level. From the perspective of construction management, productivity is often defined at the project level or the activity level. Research has been conducted in two main areas of construction productivity. The first area is the identification of the factors that influence construction productivity, and the second area is the development of predictive models for construction productivity. The identification of the factors that influence productivity is essential for the development of predictive models for productivity, which play a key role in project cost estimating, scheduling, and planning (Yi and Chen 2014).

Several modeling techniques have previously been used for developing predictive models of construction productivity, including fuzzy system dynamics (FSD), which is a suitable technique for construction productivity modeling. The FSD technique was developed by Levary (1990) by integrating system dynamics (SD) and fuzzy logic techniques. SD is a simulation technique developed by Forrester (1961) that is capable of capturing the dynamism of productivity and the interactions between the different factors influencing productivity. Fuzzy logic is an artificial intelligence technique developed by Zadeh (1965) for modeling subjective, imprecise, or linguistically expressed information, which is common among the factors influencing productivity. Thus the FSD technique is capable of capturing the dynamism of construction productivity and the interactions between the factors influencing productivity while simultaneously representing the probabilistic and subjective uncertainty of these factors.

1.2. Problem Statement

Despite the extensive research on construction productivity, there are still some gaps in the research, and they are discussed in this section. As construction is a labour-intensive industry (Jarkas 2010), previous research on the identification of the factors that influence productivity mainly focused on labour-intensive activities (e.g., Tsehayae and Fayek 2014). However, the assumption that all construction activities are labour-intensive (i.e., labour is the driver of productivity) does not hold true in recent years. According to Ok and Sinha (2006), due to advances in construction equipment technology, there are now some construction activities for which equipment, rather than labour, is the driver of productivity. These activities are called equipment-intensive activities. **The first gap** is identified in construction productivity research, where there is a lack of research on identification of the factors that affect the productivity of equipment-intensive activities.

There are several predictive models of construction productivity that have focused on the activity-level productivity of labour-intensive activities. Since the driver of productivity for these activities is labour, the accurate prediction of productivity for these activities relies on an accurate prediction of construction labour productivity (CLP). In contrast, the accurate prediction of productivity for equipment-intensive activities relies on an accurate prediction of equipment production rate (Ok and Sinha 2006). Therefore, the predictive models that were originally developed for labour-intensive activities are not appropriate for predicting the productivity of equipment-intensive activities. Moreover, the available predictive models of productivity for equipment-intensive activities fail to determine an appropriate measure of productivity for these activities. These models either measure CLP, which does not provide any information about the driver of productivity for these activities (i.e., equipment), or they measure production rate that does not provide any information about the resource inputs of these activities (i.e., labour, equipment, and material). **The second gap** is identified in construction productivity research, where there is a lack of predictive model for predicting the productivity of equipment-intensive activities using an appropriate measure.

Existing predictive models of construction productivity are commonly developed using static techniques (e.g., the fuzzy rule-based system model by Tsehayae and Fayek 2016), which means that they predict a single productivity value at a given point in time. However, due to the dynamic nature of construction projects, modeling techniques that are able to track changes in productivity over time are more suitable for modeling construction productivity. The factors that influence construction productivity are rarely independent from each other, and changes in certain factors can impact other factors (Mawdesley and Al-Jiboury, 2009). The cause and effect relationships between the factors that influence construction productivity need to be captured along with their individual impact on productivity. The SD approach has unique capabilities that are appropriate for construction productivity modeling. SD is capable of capturing the dynamism of construction projects and the interactions between the factors influencing construction productivity. However, SD models of construction productivity (e.g., Mawdesley and Al-Jibouri 2009) cannot capture the subjective uncertainty of the factors that influence productivity. **The third gap** is identified in construction productivity research, where there is a lack of predictive model that captures the dynamism of construction productivity and the interactions between the factors influencing productivity while simultaneously representing the probabilistic and subjective uncertainty of these factors.

Although FSD is an appropriate technique for construction productivity modeling since it addresses the third gap in construction productivity research, it has some limitations. There are two types of relationships in FSD models: soft relationships, where their mathematical form is unknown (e.g., the relationship between crew motivation and construction productivity), and hard relationships, where their mathematical form is known (e.g., the relationship between crew size and absenteeism). Since the mathematical form of soft relationships is unknown, these relationships need to be defined by pattern recognition if data are available. There are several pattern recognition methods available in the literature; however, existing methodologies for defining soft relationships are limited to the use of the linear regression method. **The fourth gap** is identified in the research on FSD technique, where there is a lack of research on appropriate methods for defining the soft relationships of FSD systems.

Since the mathematical forms of hard relationships are known, these relationships are always defined by mathematical equations, and fuzzy arithmetic operations are implemented to solve them. However, by implementing fuzzy arithmetic operations on these equations, the supports of the membership functions, which represent the simulation results, grow rapidly, producing a large amount of uncertainty (Tessem and Davidsen 1994). This phenomenon is called the overestimation of uncertainty (Lin et al. 2011), and it can be addressed by selecting the appropriate approach for implementing fuzzy arithmetic operations in FSD models. There are two different approaches for implementing fuzzy arithmetic operations: the α-cut approach and the extension principle approach, each of which uses different t-norms (Pedrycz and Gomide 2007). However, in previous applications of FSD models, fuzzy arithmetic has commonly been implemented by the α-cut approach due to its simplicity. **The fifth gap** is identified in the research on FSD technique, where there is a lack of research on computational methods for implementing fuzzy arithmetic operations in FSD models by the extension principle approach.

1.3. Research Objectives

The overall objective of this research is to develop a predictive model for determining the multi-factor productivity (MFP) of equipment-intensive activities using the FSD technique. To achieve this goal, this thesis set the following objectives:

1) To identify the most critical factors affecting the productivity of equipment-intensive activities, which is fulfilled in Chapter 3.
2) To develop computational methods for implementing fuzzy arithmetic operations by the α-cut approach and the extension principle approach, the latter of which uses the four common t-norms *min, product, Lukasiewicz,* and *drastic product*. These methods will improve the ability of the FSD technique to process the subjective uncertainties of the factors influencing productivity by selecting the most appropriate method for the implementation of fuzzy arithmetic operations in FSD models. This objective is fulfilled in Chapter 4 and Chapter 6.
3) To investigate appropriate pattern recognition methods for defining the soft relationships of FSD models in the case of data availability. This objective is fulfilled in Chapter 6.
4) To develop a predictive model of productivity for equipment-intensive activities that is capable of capturing the dynamism of productivity, the interactions between the factors influencing productivity, and the probabilistic and subjective uncertainty of these factors. This objective is fulfilled in Chapter 5 and Chapter 6.

1.4. Expected Contributions

1.4.1. Academic Contributions

The expected academic contributions of this research are listed below.

1) Development of a comprehensive list of the factors influencing the productivity of equipment-intensive activities (Chapter 3).
2) Development of the first predictive model of construction productivity to determine the MFP of equipment-intensive activities (Chapter 5 and Chapter 6).

3) Development of the first FSD model of productivity for equipment-intensive activities that captures the dynamism of construction productivity and the interactions between the factors influencing productivity while simultaneously processing the probabilistic and subjective uncertainty of these factors (Chapter 5 and Chapter 6).
4) Integration of data-driven fuzzy rule-based systems and FSD for defining the soft relationships between system variables (Chapter 5).
5) Development of computational methods for the implementation of fuzzy arithmetic operations in different applications by the extension principle using product and Lukasiewicz t-norms (Chapter 4).
6) Evaluation of different approaches to fuzzy arithmetic implementation in FSD models and selection of the most appropriate approach based on the accuracy of simulation results and the amount of uncertainties included in the simulation results (Chapter 4 and Chapter 6).

1.4.2. Industrial Contributions

The expected industrial contributions of this research are listed below.

1) Assessment of the factors influencing the productivity of equipment-intensive activities in order to identify the most critical factors based on their level of influence on productivity (Chapter 3).
2) Identification of the differences between the perspectives of project management staff and tradespeople staff regarding the impact of different factors on productivity (Chapter 3).
3) Prediction of the MFP of equipment-intensive activities to provide construction planners with more information, compared to CLP predictive models, regarding the resource inputs of these activities (Chapter 5 and Chapter 6).
4) Development of an FSD simulation model of construction productivity that enables construction planners to track changes in productivity over time, evaluate potential productivity improvement strategies, analyze the effect of each factor on productivity in order to optimize these factors, and predict the productivity of different execution plans (Chapter 5 and Chapter 6).

1.5. Research Methodology

The objectives of this research (see Section 1.3) are achieved in four stages, as described below.

1.5.1. The First Stage

An extensive literature review is conducted on the relevant topics. The first topic is the identification of factors influencing the productivity of equipment-intensive activities and the development of predictive models of construction productivity. Next, previous research on the SD technique is reviewed, followed by a literature review of the FSD technique. Finally, previous computational methods for the implementation of fuzzy arithmetic operations are reviewed.

1.5.2. The Second Stage

A comprehensive list of the factors that influence the productivity of equipment-intensive activities is developed. An interview survey is designed to evaluate the level of influence of each factor on productivity, and the most critical factors are identified based on the interview survey results. A ranking framework is developed using the TOPSIS (i.e., the technique for order of preference by similarity to ideal solution) method to rank the factors influencing productivity based on the level of their influence on productivity. Finally, the perspectives of project management staff and project tradespeople staff regarding the influence of these factors on productivity are compared.

1.5.3. The Third Stage

The computational method for the implementation of fuzzy arithmetic operations is developed. There are two available mathematical approaches for implementing fuzzy arithmetic operations: the α-cut approach and the extension principle approach using different t-norms. The computational methods that are essential for implementing fuzzy arithmetic operations in different applications are only available for the α-cut approach and the extension principle approach, the latter of which uses min and drastic product t-norms. In this stage, two computational methods are developed for implementing fuzzy arithmetic operations by the extension principle approach using two common t-norms, product and Lukasiewicz t-norms. The Fuzzy Calculator class is developed in the Python programming language to automate the implementation of fuzzy arithmetic operations.

1.5.4. The Fourth Stage

The FSD model of construction productivity is developed through qualitative and quantitative FSD modeling steps. The qualitative FSD model is developed using the factors that influence productivity (identified in the second stage). Hereafter, these factors are referred as system variables. The qualitative FSD model of construction productivity has two components: the cause and effect diagram and the stock and flow diagram. The cause and effect diagram is developed to measure the cost of the three resource inputs (i.e., labour, equipment, and material cost) and the production rate of activity. The stock and flow diagram is developed to measure the MFP of the equipment-intensive activities using the cost of the three resource inputs and the outputs of the activity. The quantitative FSD model of construction productivity is developed in three steps. First, the subjective system variables are represented by fuzzy membership functions. Second, the soft relationships between the system variables are defined quantitatively. Soft relationships are characterized by the fact that their mathematical form is unknown (e.g., the relationship between crew motivation and absenteeism). Accordingly, these relationships are defined either by data-driven fuzzy rule-based systems or statistically developed mathematical equations. Third, the hard relationships between the system variables are defined quantitatively. Since the mathematical form of these relationships is known, all hard relationships are defined using mathematical equations.

1.5.5. The Fifth Stage

The FSD model of construction productivity is validated using a case study of earthmoving operations. To accomplish this, a data collection methodology and detailed data collection forms are developed. Next, the FSD model of construction productivity is validated by structural and behavioural validation tests using the field data.

1.6. Thesis Organization

Chapter 1 presents a brief background on construction productivity research and identifies the gaps in the research on construction productivity and FSD techniques. This chapter also presents the research objectives, expected academic and industrial contributions, and research methodology of the thesis.

Chapter 2 presents an extensive literature review on the relevant topics, including the identification of the factors influencing construction productivity and the development of predictive models for construction productivity, SD and its applications in construction research, FSD and its applications in construction research, and computational methods for the implementation of fuzzy arithmetic operations.

Chapter 3 presents a comprehensive list of the factors that influence the productivity of equipment-intensive activities. This chapter also presents the interview surveys and the TOPSIS ranking framework, which are developed to identify the most critical factors influencing productivity. Finally, Chapter 3 presents a comparative study on the perspectives of project management and project tradespeople staff regarding the influence of these factors on productivity.

Chapter 4 presents the computational method for the implementation of fuzzy arithmetic operations by the extension principle approach using product and Lukasiewicz t-norms, which are essential for developing the FSD model of construction productivity. This chapter also presents a comparative analysis of different approaches to the implementation of fuzzy arithmetic operations: the α-cut approach and the extension principle approach, the latter of which uses the four common t-norms (min, product, Lukasiewicz, and drastic product).

Chapter 5 presents the FSD model of construction productivity. This chapter describes the two components of the qualitative model: the cause and effect diagram and the stock and flow diagram. In this chapter, the quantitative FSD model of productivity is developed by numerically defining the soft and hard relationships of the system.

Chapter 6 presents the validation of the FSD model and describes the steps that were taken to achieve validation. It describes the field data collection methodology and the detailed data collection forms that are developed for this research as well as the validation of the FSD model of construction productivity using structural and behavioural validation tests.

Chapter 7 presents the conclusions, contributions, and limitations of this research, as well as recommendations for future research on construction productivity.

1.7. References

Forrester, J. W. (1961). "Industry dynamics." *Cambridge, MA.*

Jarkas, A. M. (2010). "Critical investigation into the applicability of the learning curve theory to rebar fixing labor productivity." *J. Constr. Eng. Manage.,* 136(12), 1279-1288.

Levary, R. R. (1990). "Systems dynamics with fuzzy logic." *Int .J. Syst. Sci.,* 21(8), 1701-1707.

Lin, K., Wen, W., Chou, C., Jen, C., and Hung, K. (2011). "Applying fuzzy GERT with approximate fuzzy arithmetic based on the weakest t-norm operations to evaluate repairable reliability." *Appl. Math. Model.,* 35(11), 5314-5325.

Mawdesley, M. J., and Al-Jibouri, S. (2009). "Modelling construction project productivity using systems dynamics approach." *International Journal of Productivity and Performance Management,* 59(1), 18-36.

Ok, S. C., and Sinha, S. K. (2006). "Construction equipment productivity estimation using artificial neural network model." *Constr. Manage. Econ.,* 24(10), 1029-1044.

Organization for Economic Co-operation and Development. (2015). “Growth in GDP per capita, productivity and ULC: Multifactor productivity”. http://stats.oecd.org/Index.aspx?DataSetCode=PDB_GR (July 3, 2017).

Pedrycz, W., and Gomide, F. (2007). *Fuzzy systems engineering: toward human-centric computing.* John Wiley & Sons, Hoboken, NJ.

Statistics Canada, (2017). “Gross domestic product at basic prices, by industry, 2012-2016.” http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/manuf10-eng.htm (September 15, 2017).

Tessem, B., and Davidsen, P. I. (1994). "Fuzzy system dynamics: an approach to vague and qualitative variables in simulation." *System Dynamics Review,* 10(1), 49-62.

Tsehayae, A. A., and Robinson Fayek, A. (2014). "Identification and comparative analysis of key parameters influencing construction labour productivity in building and industrial projects." *Can. J. Civil Eng.,* 41(10), 878-891.

Tsehayae, A. A., and Robinson Fayek, A. (2016). "System model for analyzing construction labour productivity." *Construction Innovation,* 16(2), 203-228.

Yi, W., and Chan, A. (2014). "Critical review of labor productivity research in construction journals." *J. Manage. Eng.,* 30(2), 214–225.

Zadeh, L. A. (1965). "Fuzzy sets." *Information and Control,* 8(3), 338-353.

Chapter 2. Literature Review

2.1. Construction Productivity

In general, the productivity of a construction system (e.g., construction activity, construction project) can be calculated as the ratio of the inputs of the system (e.g., person-hours) to its output (e.g., cubic meters of concrete placed). Talhouni (1990) and Rakhra (1991) introduce three different measures for construction productivity: (1) single factor productivity (SFP), which measures the productivity of construction systems using only one resource input (i.e., labour); (2) multi-factor productivity (MFP), which measures the productivity of construction systems using any combination of three resource inputs (i.e., labour, materials, and equipment); and (3) total factor productivity (TFP), which measures the productivity of construction systems using five resource inputs (i.e., labour, materials, equipment, energy, and capital). For determining MFP and TFP, the resource inputs of the construction system need to be aggregated. Thomas et al. (1990) suggested to aggregate the costs of the three inputs in dollars ($) as the only common unit of measure for the three inputs. Accordingly, MFP and TFP are calculated as the total cost of inputs ($) per unit of output. The three measures of construction productivity are presented in Equations 2.1 to 2.3 (Thomas et al. 1990).

$$\mathrm{SFP}\left(\frac{\mathrm{person-hour}}{\mathrm{unit}}\right)=\frac{\mathrm{labour\ (person-hour)}}{\mathrm{Outputs\ (unit)}} \tag{2.1}$$

$$\mathrm{MFP}\left(\frac{\$}{\mathrm{unit}}\right)=\frac{\mathrm{Labour\ (\$)+Equipment(\$)+Material(\$)}}{\mathrm{Outputs\ (unit)}} \tag{2.2}$$

$$\mathrm{TFP}\left(\frac{\$}{\mathrm{unit}}\right)=\frac{\mathrm{Labour\ (\$)+Equipment(\$)+Material(\$)+Capital(\$)+Energy(\$)}}{\mathrm{Outputs\ (unit)}} \tag{2.3}$$

There are also a number of different definitions of construction productivity in the industry, which can be distinguished based on their perspective and their level of detail. From the construction management perspective, construction productivity is mostly defined at the project level or the activity level, using two measures: construction labour productivity (CLP), which is a SFP measure that uses labour as the only input of productivity (see, for example, Moselhi and Khan 2010), or MFP, which uses any combination of the three inputs of productivity (i.e., labour, equipment, and material) (see, for example, Eastman and Sacks 2008). However, from the economic perspective, construction productivity is defined at the industry level or at the national level, which determines the TFP of construction systems using all five inputs (i.e., labour, equipment, material, energy and capital). Thomas et al. (1990) discussed that economic models of construction productivity can be highly inaccurate for measuring project- or activity-level productivity, due to the difficulties encountered in predicting the energy and capital inputs at the project or activity level.

The previous research on productivity in the construction management domain are focused either on the identification of the factors that influence activity- or project-level productivity, or the development of predictive models for activity- or project-level productivity. As construction is a labor-intensive industry (Jarkas 2010), previous research on the identification of the factors influencing activity-level productivity is often focused on labour-intensive activities, where labour is the main driver of productivity (e.g., Tsehayae and Fayek 2014, Hwang et al. 2016, Naoum, 2016). However, construction equipment are now important resources in construction projects, and they are the drivers of productivity for some activities. Goodrum and Hass (2004) refer to technological advancements in construction equipment, and determined the effects of these advancements on the construction labor productivity of 200 activities; the authors observed substantial long-term improvement in the construction labor productivity of the activities completed using equipment exhibiting significant technological advancements. Goodrum et al. (2010) developed a predictive model to measure the effect of equipment on construction productivity; this research confirms that technological advancements in construction equipment affect construction productivity. According to Ok and Sinha (2006), due to advances in construction equipment technology, there are now some construction activities for which equipment, rather than labour, is the driver of productivity. Thus, depending on which resource is the main driver of the productivity, construction activities can be grouped into two categories: labour-intensive activities, where labour is the main driver of productivity (e.g., electrical and mechanical activities) (Jarkas 2010), and equipment-intensive activities, where equipment is the main driver of productivity (e.g., earthmoving activities) (Ok and Sinha 2006). Since the resource that drives productivity is different for the two types of activities (i.e., labour-intensive and equipment-intensive), the factors influencing the productivity of these activities are different as well. However, previous research on construction productivity has failed to identify the factors influencing the productivity of equipment-intensive activities.

The previous research on the development of predictive models for activity-level construction productivity have been focused on predicting CLP, which is an appropriate measure of productivity for the labour-intensive activities (e.g., Tsehayae and Fayek 2016, Heravi and Eslamdoost 2015). However, CLP is not an appropriate measure for predicting the productivity of equipment-intensive activities because it does not provide any information regarding the resource input that is the driver of productivity for these activities (i.e., equipment). Moreover, the few predictive models developed to determine the productivity of equipment-intensive activities have failed to identify an appropriate measure of productivity for these activities. For example, Choi and Ryu (2015) developed a statistical model to determine the CLP of highway pavement operations; Ok and Sinha (2006) developed an artificial neural network model to predict the production rate of earthmoving operations; Zayed and Halpin (2005) developed a statistical model to determine the production rate of pile construction operations; and Jabri and Zayed (2017) developed an agent-based simulation model to determine the production rate of earth moving operations. Accordingly, these existing predictive models either measure the SFP of equipment-intensive activities or their production rate. While the production rate of construction systems is calculated as the ratio of the outputs of the operation to its duration, this measure does not represent any information regarding the resource inputs of the system (i.e., labour, equipment, and material). MFP is an appropriate measure for determining the productivity of equipment-intensive activities, since, it provides information regarding the three resource inputs of these activities. Moreover, MFP represents the most comprehensive measure of construction productivity at the activity level. However, unlike other industries for which predictive models are available for determining their MFP, construction industry suffers from a lack of predictive models for determining the MFP of construction systems (Carson and Abbott 2012). Thus, there is a need to develop a predictive model for determining the MFP of equipment-intensive activities.

The existing predictive models of construction productivity are commonly static in nature, such as the statistical model developed by Dai et al. (2009), the fuzzy rule-based system developed by Tsehayae (2016), the ANN models developed by Moselhi and Khan (2010) and Heravi and Eslamdoost (2015), and the neuro fuzzy systems developed by Mirahadi and Tarek (2016). However, according to Mawdesley and Al-Jiboury (2009), construction systems are dynamic (i.e., changing over time) and their components interact with each other. Accordingly, predictive models that are capable of tracking the changes of productivity over time are more appropriate for modeling construction productivity. Additionally, capturing the interactions between the factors that influence productivity can increase the accuracy of predictive models. Previous research has suggested that construction productivity be modeled using system dynamics (SD) techniques, in order to capture the dynamism of construction systems and the interactions between the factors influencing construction productivity (Mawdesley and Al-Jiboury 2009, Alzraiee et al. 2015). There are currently a few SD models of construction productivity available in the literature, such as the SD model developed by Nasirzadeh and Nojedehi (2013) for activity-level CLP, and the SD model developed by Mawdesley and Al-Jiboury (2009) for project-level MFP using labour and equipment as the two inputs of productivity. The SD model developed by Nasirzadeh and Nojedehi (2013) has been adapted from the productivity model developed by Ford (1995) for manufacturing industries. However, Riley and Brown (2001) maintain that due to significant differences between the construction and manufacturing industries, the managerial tools that were originally developed for manufacturing industries are not applicable to the construction industry. Moreover, the SD model developed by Mawdesley and Al-Jiboury (2009) for project-level construction productivity cannot be used for predicting activity-level MFP, since it overlooks the effect of the factors influencing productivity at the activity-level.

Although existing construction productivity SD models capture probabilistic uncertainties of the factors influencing construction productivity, these models cannot capture the subjective uncertainty of these factors. Nojedehi and Nasirzadeh (2017) referred to this limitation of SD models and developed a predictive model of CLP using FSD technique. However, their predictive model is not appropriate for predicting the productivity of equipment-intensive activities, since it is originally developed for labour-intensive activities and predicts CLP. Accordingly, there is a need within the existing body of construction research to develop a predictive model for the activity-level MFP of equipment-intensive activities, which captures the dynamism of construction systems and the interactions between the factors influencing productivity, while simultaneously representing the probabilistic and subjective uncertainty of these factors.

2.2. System Dynamics

SD is a simulation technique developed by Forrester (1961) for analyzing complex industrial systems. This modeling technique is able to model a dynamic system, in which the state of the system (e.g., construction productivity) changes over time and under the effect of different factors. The capacity of SD for capturing the dynamism of real-world systems, which is unique among simulation techniques (e.g., discrete event simulation), makes it an appropriate tool for strategic system modeling and analysis (Sweetser 1999). Referring to Coyle (2000), SD simulation models are developed in two steps: first, the qualitative SD model is developed by identifying and modeling the factors that influence the system, which are called system variables; and second, the quantitative SD model is developed by defining the relationships between the system variables by using mathematical equations. The qualitative SD model, which is also referred to as system thinking in the literature (Sterman 2000, Wolstenholme 1999), helps the users to identify the system behavior. In contrast, the quantitative SD model helps users to simulate system behavior and predict the state of the system (e.g., construction productivity) dynamically. Accordingly, the qualitative SD model of construction productivity helps users to identify the factors influencing construction productivity and the relationships between these factors. Moreover, the quantitative SD model of construction productivity makes dynamic predictions (i.e., tracks the changes of productivity throughout the project life cycle), while considering the interactions between the factors influencing construction productivity.

According to Coyle (2000), there are two types of relationships between the system variables: hard relationships, where the mathematical form of the relationship is known (e.g., relationship between the absenteeism and crew size), and soft relationships, where the mathematical form of the relationship is unknown (e.g., relationship between the crew motivation and labour productivity). Since the mathematical form of hard relationships is known, these relationships are always defined by mathematical equations. In contrast, since the mathematical form of soft relationships is unknown, these relationships are defined by pattern recognition methods.

Due to the abovementioned capabilities, SD is an appropriate technique for developing predictive models for construction industry; thus there are several applications of SD models in the construction domain. The applications of SD in construction includes: the construction resource management model developed by Park (2005) for optimizing the idle time of resources; the predictive model of project-level productivity developed by Mowdesley and Al-Jibouri (2009); the predictive model of activity-level CLP developed by Nasirzadeh and Nojedehi (2013); the SD model developed by Li and Taylor (2014) for determining the effects of rework on the performance of construction projects; and the SD model developed by Jiang et al. (2014) for determining the effects of project safety management on the unsafe behavior of construction workers.

2.3. Fuzzy System Dynamics

SD models are able to capture the probabilistic uncertainties of real-world systems using the Monte Carlo simulation technique (Sterman 2000). However, SD models cannot capture the non-probabilistic uncertainties (i.e., subjective, imprecise, or linguistically expressed information) of real-world systems. To address this limitation, Levary (1990) proposed the integration of SD with fuzzy logic and developed the fuzzy system dynamics (FSD) technique, which is capable of capturing deterministic values, as well as probabilistic and non-probabilistic uncertainties. There are several applications of FSD models in construction research that have been developed in recent years. The construction risk management model developed by Nasirzadeh et al. (2008) is one of the first applications of FSD models in construction, in which the risk magnitudes and probabilities are represented by fuzzy membership functions. Khanzadi et al. (2012)

developed a FSD model to determine the concession period of BOT projects by analyzing the magnitude of project risks. Nasirzadeh et al. (2013) developed a FSD model for quality management in construction projects and used fuzzy membership functions to represent the subjective factors that influence the quality management process. Finally, Nasirzadeh et al. (2014) developed a predictive model for project cost management, which determines the cost of construction projects by the quantitative risk analysis of project using FSD technique. Finally, Nojedehi and Nasirzadeh (2017) developed a predictive model of CLP using FSD technique.

Similar to SD, FSD simulation models are developed through the development of qualitative and quantitative modeling. While the development of qualitative FSD models is similar to the development of qualitative SD models, the development of quantitative FSD models is different from the development of quantitative SD models. More specifically, the subjective variables of FSD models are represented by fuzzy membership functions (Khanzadi et al. 2012), rather than deterministic or probabilistic values, which are used in SD models. These fuzzy membership functions can be developed by one of the several approaches proposed in the literature, either by using data (e.g., fuzzy *c*-means (FCM) clustering approach) or by using expert knowledge (e.g., Saaty's priority approach). In order to develop quantitative FSD models, the relationships between system variables are defined by mathematical equations or by fuzzy rule-based systems (Khanzadi et al. 2012, Nasirzadeh et al. 2014). Similar to SD models, the hard relationships of FSD models are defined by mathematical equations. Fuzzy arithmetic operations are used to implement arithmetic operations on the mathematical equations, which include subjective variables represented by fuzzy numbers. Fuzzy numbers are defined using specific types of membership functions that have the following properties: (1) bounded supports, (2) are normal (i.e., possess at least one point in the universe of discourse, which has a membership value of 1), (3) are convex, and (4) have α-cuts that are closed (i.e., continuous) intervals of real numbers (Nguyen and Walker 2005). The soft relationships of FSD models are defined either by mathematical equations developed statistically or by fuzzy rule-based systems (FRBS) developed using one of the approaches proposed in the literature. While, previous studies have suggested defining these soft relationships with statistically-developed mathematical equations if data are available, or with fuzzy rule-based systems developed by expert knowledge if data are not available (Khanzadi et al. 2012, Nasirzadeh et al. 2014, Nasirzadeh et al. 2008). However, an extensive review by Paliwal and Kumar (2009) confirms that the artificial intelligence methods of pattern recognition (e.g., artificial neural networks) outperform the statistical regression methods if data are limited (i.e., less than a thousand data points), which is common in the construction context. Thus, there is a gap in the research on FSD techniques for integrating FSD and the artificial intelligence methods of pattern recognition for defining soft relationships, which can increase the accuracy of FSD models.

By implementing fuzzy arithmetic in the mathematical equations of the FSD models, the supports of the membership functions, which represent the simulation results, grow rapidly, producing a large amount of uncertainty (Tessem and Davidsen 1994). This phenomenon is called the overestimation of uncertainty, which reduces the ability of users to accurately predict the actual system output (e.g., actual productivity) based on the simulation results (Lin et al. 2011). The overestimation of uncertainty in the FSD models may be affected by various factors such as the number of parameters in the mathematical equations, number of time steps, membership functions of the inputs, and the approach of the fuzzy arithmetic implementation. Accordingly, this problem may be addressed by choosing the appropriate fuzzy arithmetic implementation approach. There are two different approaches for fuzzy arithmetic implementation: the α-cut approach, and the extension principle approach, the latter of which uses different t-norms (Pedrycz and Gomide 2007). While implementation of fuzzy arithmetic by the extension principle approach using the min t-norm provides the same results as the α-cut approach (Elbarkouky et al. 2016), implementing fuzzy arithmetic by the extension principle approach using any t-norm other than min reduces the uncertainty overestimation problem (Lin et al. 2013). However, in previous applications of FSD models, fuzzy arithmetic operations are often implemented by the α-cut approach due to its simplicity (Nasirzadeh et al. 2014, Nasirzadeh et al., 2008). Nojedehi and Nasirzadeh (2017) developed a predictive model of CLP using FSD technique; they used the α-cut approach to implement the fuzzy arithmetic operations on the mathematical equations of their model. Consequently, there is a large amount of uncertainty in the results of their case study, where the support of the fuzzy number that represents labour productivity of concrete pouring activity is $[4.08, 29.37]\ \frac{\mathrm{m}^3}{\mathrm{person-hour}}$ showing that the upper bound of the support is 620% larger than its lower bound. Moreover, based on the value of labour productivity, the project cost is calculated as a fuzzy number, with a support of $[\$206898, \$1085100]$ where the upper bound of the support is 424% larger than its lower bound; and the support of the fuzzy number that represents the project duration is $[3.59, 26.70]\ \mathrm{months}$ where the upper bound of the support is 644% larger than its lower bound. Accordingly, the large amount of uncertainty in the simulation results reduces the ability of users (e.g., construction practitioners) to accurately predict the actual productivity, project cost, and project duration based on the simulation results.

Chang et al. (2006) developed an FSD model for customer-producer-employment systems to compare the different approaches of fuzzy arithmetic implementation in FSD models. Chang et al. (2006) compared the α-cut approach and the extension principle approach using the drastic product t-norm. They concluded that using the α-cut approach leads to a higher overestimation of uncertainties, as compared to using the extension principle approach with the drastic product t-norm. However, in previous applications of FSD models, implementation of fuzzy arithmetic using the extension principle approach with the product and Lukasiewicz t-norms, which are the two common t-norms for fuzzy operations, have not been investigated. Thus, there is a gap in the research on FSD technique for developing computational methods to implement fuzzy arithmetic using the extension principle approach with the product and Lukasiewicz t-norms.

2.4. Computational Methods for Implementation of Fuzzy Arithmetic

Fuzzy sets theory, developed by Zadeh (1965), is a powerful tool for modeling subjective and imprecise information in different contexts. Introduced by Zadeh (1975), fuzzy numbers are a specific type of fuzzy sets used for representing values of real world parameters when the exact values are not measurable due to a lack of knowledge or incomplete information (Pedrycz and Gomide 2007). Fuzzy numbers have been applied in many different areas, such as engineering problems (see Ross [2009] for review). In such applications, fuzzy arithmetic is applied to mathematical equations that include fuzzy numbers by using one of the two approaches introduced in the literature: the *α*-cuts approach, and the extension principle approach using different t-norm*s*. The *α*-cuts approach is a generalization of interval analysis, presented by Moore (1966) and Moore (1979). On the other hand, the extension principle approach, proposed by Zadeh (1975), is a generalization of the operations for the real numbers context to the fuzzy sets context. Thus, implementation of fuzzy arithmetic operations using the extension principle approach is a generalization of the standard operations performed on real numbers. Hereafter, this chapter will refer to the *α*-cuts and interval calculations approach as “standard fuzzy arithmetic” and to the extension principle approach as “extended fuzzy arithmetic”.

Although the literature contains an extensive discussion on the mathematical aspects of the two fuzzy arithmetic implementation approaches (Dubois and Prade 1978), mathematical implementation of the two approaches is not always possible due to the following challenges. The mathematical solution of standard fuzzy arithmetic requires the calculation of inverse function for the input fuzzy numbers, which is computationally complex. Moreover, the mathematical solution of extended fuzzy arithmetic is equivalent to solving a non-linear programming problem, which implies that there is not a universal solution for the extended fuzzy arithmetic problem, regardless of the t-norm used. Therefore, there are computational methods developed in the literature for implementing fuzzy arithmetic using one of the two approaches. For implementing standard fuzzy arithmetic, Dubois and Prade (1980) developed a computational method, which vertically discretizes the input fuzzy numbers (i.e., the supports of the fuzzy numbers) and approximates the membership values for the discrete points of the resulting fuzzy number supports. Dong and Wong (1987) criticized the method proposed by Dubois and Prade (1980) for its low accuracy of approximation when implementing consecutive fuzzy division operations; to remedy this limitation, they proposed a computational method for implementing standard fuzzy arithmetic operations, which horizontally discretizes the input fuzzy numbers into intervals and calculates the intervals of the resulting fuzzy number. The computational method proposed by Dong and Wong (1987) is a discrete yet exact method, which calculates the exact values of the intervals (i.e., exact method) for a finite number of intervals of the resulting fuzzy numbers (i.e., discrete method).

Due to the uncertainty overestimation issue that is caused by standard fuzzy arithmetic, computational methods for implementing extended fuzzy arithmetic have been proposed in the literature. Heshmaty and Kandel (1985) prove that the triangular fuzzy numbers are closed under all extended fuzzy arithmetic operations using drastic product t-norm. In other words, the result of implementing any extended fuzzy arithmetic operation using the drastic product t-norm on two triangular numbers is a triangular number. Accordingly, an exact computational method has been developed by Kolesarova (1995), Mesiar (1997), and Hong and Do (1997) for implementing extended fuzzy arithmetic using the drastic product t-norm on triangular fuzzy numbers. Despite the availability of the computational method, the drastic product t-norm is not appropriate for implementing extended fuzzy arithmetic in engineering applications, since the drastic product t-norm is not continuous and the resulting fuzzy numbers will be highly sensitive to changes to the input fuzzy numbers (Pedrycz and Gomide 2007).

The product and Lukasiewicz t-norms are two common t-norms that are appropriate for implementing extended fuzzy arithmetic since, they are continuous t-norms, and reduce the overestimation of uncertainty in the resulting fuzzy numbers in comparison to the standard fuzzy arithmetic. However, extended fuzzy arithmetic operations using these two t-norms do not result in triangular fuzzy numbers. Therefore, due to their complexity, there are no available computational methods for implementing extended fuzzy arithmetic using product and Lukasiewicz t-norms. To remedy this gap in the literature, this research proposes a computational method for implementing extended fuzzy arithmetic on triangular fuzzy numbers using product and Lukasiewicz t-norms.

2.5. Summary

This chapter provides a literature review on the construction productivity research, system dynamics, fuzzy system dynamics, and computational methods for implementing fuzzy arithmetic, as well as, identifying the research gaps in these topics. The research gaps that are identified in construction productivity research are: lack of research on the identification of the factors that influence the productivity of equipment-intensive activities, and the lack of predictive models of the activity-level productivity of equipment-intensive activities. Due to the capabilities of FSD technique, it is an appropriate technique for developing predictive models of productivity; however, the following gaps are identified in research on FSD technique: investigation on the appropriate methods for defining the soft relationships of FSD models, and developing a computational method for implementing fuzzy arithmetic operations by the extension principle approach in FSD models. In the next chapter a comprehensive list of the factors that influence productivity of equipment-intensive activities is developed.

2.6. References

Alzraiee, H., Zayed, T., and Moselhi, O. (2015). "Dynamic planning of construction activities using hybrid simulation." *Automat. Constr.,* 49 176-192.

Carson, C., and Abbott, M. (2012). "A review of productivity analysis of the New Zealand construction industry." *Construction Economics and Building,* 12(3), 1-15.

Chang, P., Pai, P., Lin, K., and Wu, M. (2006). "Applying fuzzy arithmetic to the system dynamics for the customer–producer–employment model." *Int. J. Syst. Sci.,* 37(10), 673-698.

Choi, J., and Ryu, H. (2015). "Statistical analysis of construction productivity for highway pavement operations." *KSCE J. Civ. Eng.,* 19(5), 1193-1202.

Coyle, G. (2000). "Qualitative and quantitative modelling in system dynamics: some research questions." *Sys. Dynam. Rev.,*16 (3), 225.

Dai, J., Goodrum, P. M., and Maloney, W. F. (2009). "Construction craft workers' perceptions of the factors affecting their productivity." *J. Constr. Eng. Manage.,* 135(3), 217-226.

Dong, W., & Wong, F. (1987). "Fuzzy weighted averages and implementation of the extension principle." *Fuzzy Sets and Systems*, 21(2), 183-199.

Dubois, D., & Prade, H. (1978). "Operations on fuzzy numbers." *International Journal of Systems Science*, 9(6), 613-626.

Dubois, D., & Prade, H. (1980). "Fuzzy sets and systems: Theory and applications." *Academic press*, Massachusetts.

Eastman, C. M., and Sacks, R. (2008). "Relative productivity in the AEC industries in the United States for on-site and off-site activities." *J. Constr. Eng. Manage.,* 134(7), 517-526.

Elbarkouky, M. M., Fayek, A. Robinson, Siraj, N. B., & Sadeghi, N. (2016). “Fuzzy arithmetic risk analysis approach to determine construction project contingency.” *J. Constr. Eng. Manage.,* 142(12), 04016070.

Ford, D. N. (1995). “The Dynamics of Project Management: An Investigation of the Impacts of Project Process and Coordination on Performance” (Doctoral dissertation Massachusetts Institute of Technology). Retrieved from http://hdl.handle.net/1721.1/11105.

Forrester, J. W. (1961). "Industry dynamics." *Cambridge, MA, USA*.

Goodrum, P. M., and Haas, C. T. (2004). "Long-term impact of equipment technology on labor productivity in the US construction industry at the activity level." *J. Constr. Eng. Manage.,* 130(1), 124-133.

Goodrum, P. M., Haas, C. T., Caldas, C., Zhai, D., Yeiser, J., and Homm, D. (2010). "Model to predict the impact of a technology on construction productivity." *J. Constr. Eng. Manage.,* 137(9), 678-688.

Heravi, G., and Eslamdoost, E. (2015). "Applying Artificial Neural Networks for Measuring and Predicting Construction-Labor Productivity." *J. Constr. Eng. Manage.,* 141(10), 04015032.

Heshmaty, B., & Kandel, A. (1985). “Fuzzy linear regression and its applications to forecasting in uncertain environment.” *Fuzzy Sets and Systems*, 15(2), 159-191.

Hong, D. H., & Do, H. Y. (1997). “Fuzzy system reliability analysis by the use of Tω (the weakest t-norm) on fuzzy number arithmetic operations.” *Fuzzy Sets and Systems*, 90(3), 307-316.

Hwang, B. G., Zhu, L., and Ming, J. T. T. (2016). “Factors affecting productivity in green building construction projects: The case of Singapore.” *J. Manage. Eng.,* 33(5), 04016052.

Jabri, A., and Zayed, T. (2017). "Agent-based modeling and simulation of earthmoving operations." *Automat. Constr.,* 81 210-223.

Jarkas, A. M. (2010). "Critical investigation into the applicability of the learning curve theory to rebar fixing labor productivity." *J. Constr. Eng. Manage.,* 136(12), 1279-1288.

Jiang, Z., Fang, D., and Zhang, M. (2014). "Understanding the causation of construction workers' unsafe behaviors based on system dynamics modeling." *J.Manage.Eng.,* 31(6), 04014099.

Khanzadi, M., Nasirzadeh, F., and Alipour, M. (2012). "Integrating system dynamics and fuzzy logic modeling to determine concession period in BOT projects." *Automat. Constr.,* 22 368-376.

Kolesárová, A. (1995). "Additive preserving the linearity of fuzzy intervals." *Tatra Mountains Mathematical Publications*, 6, 75-81.

Levary, R. R. (1990). "Systems dynamics with fuzzy logic." *Int.J.Syst.Sci.,* 21(8), 1701-1707.

Li, Y., and Taylor, T. R. (2014). "Modeling the impact of design rework on transportation infrastructure construction project performance." *J.Constr.Eng.Manage.,* 140(9), 04014044.

Lin, K., Wen, W., Chou, C., Jen, C., and Hung, K. (2011). "Applying fuzzy GERT with approximate fuzzy arithmetic based on the weakest t-norm operations to evaluate repairable reliability." *Appl. Math. Model.,* 35(11), 5314-5325.

Mawdesley, M. J., and Al-Jibouri, S. (2009). "Modelling construction project productivity using systems dynamics approach." *International Journal of Productivity and Performance Management,* 59(1), 18-36.

Mesiar, R. (1997). "Shape preserving additions of fuzzy intervals." *Fuzzy Sets and Systems*, 86(1), 73-78.

Mirahadi, F., and Zayed, T. (2016). "Simulation-based construction productivity forecast using neural-network-driven fuzzy reasoning." *Automat. Constr.,* 65 102-115.

Moore R. (1966). "Interval Analysis." *Prentice-Hall, Englewood Cliffs*, New Jersey.

Moore, R. E. (1979). "Methods and applications of interval analysis." *SIAM*, Philadelphia.

Moselhi, O., and Khan, Z. (2010). "Analysis of labour productivity of formwork operations in building construction." *Construction Innovation,* 10(3), 286-303.

Naoum, S. G., and Heap, J. (2016). "Factors influencing labor productivity on construction sites. A state-of-the-art literature review and a survey." *International Journal of Productivity and Performance Management,* 65(3).

Nasirzadeh, F., Afshar, A., Khanzadi, M., and Howick, S. (2008). "Integrating system dynamics and fuzzy logic modelling for construction risk management." *Constr. Manage. Econ.,* 26(11), 1197-1212.

Nasirzadeh, F., and Nojedehi, P. (2013). "Dynamic modeling of labor productivity in construction projects." *Int. J. Project Manage.,* 31(6), 903-911.

Nasirzadeh, F., Khanzadi, M., Afshar, A., and Howick, S. (2013). "Modeling quality management in construction projects." *International Journal of Civil Engineering*, 11(1), 14-22.

Nasirzadeh, F., Khanzadi, M., and Rezaie, M. (2014). "Dynamic modeling of the quantitative risk allocation in construction projects." *Int. J. Project Manage.,* 32(3), 442-451.

Nguyen, H. T., and Walker, E. A. (2005). *A first course in fuzzy logic.* CRC press.

Nojedehi, P., & Nasirzadeh, F. (2017). “A hybrid simulation approach to model and improve construction labor productivity.” *KSCE Journal of Civil Engineering*, 21(5), 1516-1524.

Ok, S. C., and Sinha, S. K. (2006). "Construction equipment productivity estimation using artificial neural network model." *Constr. Manage. Econ.,* 24(10), 1029-1044.

Paliwal, M., and Kumar, U. A. (2009). "Neural networks and statistical techniques: A review of applications." *Expert Syst.Appl.,* 36(1), 2-17.

Park, M. (2005). "Model-based dynamic resource management for construction projects." *Autom.Constr.,* 14(5), 585-598.

Pedrycz, W., and Gomide, F. (2007). *Fuzzy systems engineering: toward human-centric computing.* John Wiley & Sons.

Rakhra, A. (1991). "Construction productivity: concept, measurement and trends, organisation and management in construction." *Proc., of the 4th Yugoslavian Symposium on Construction Management, Dubrovnik,* 487-497.

Riley, M., and Clare-Brown, D. (2001). "Comparison of cultures in construction and manufacturing industries." *J. Manage. Eng.,* 17(3), 149-158.

Ross, T. J. (2009). “Fuzzy logic with engineering applications.” *John Wiley & Sons*, West Sussex.

Sterman, J. D. (2000). *Business dynamics: systems thinking and modeling for a complex world.* Irwin/McGraw-Hill Boston, USA.

Sweetser, A. (1999). "A comparison of system dynamics (SD) and discrete event simulation (DES)." *17th International Conference of the System Dynamics Society*, Wellington, New Zealand, 20-23.

Talhouni, B. T. (1990). Measurement and Analysis of Construction Labour Productivity (Doctoral dissertation university of Dundee).

Tessem, B., and Davidsen, P. I. (1994). "Fuzzy system dynamics: an approach to vague and qualitative variables in simulation." *System Dynamics Review,* 10(1), 49-62.

Thomas, H. R., Maloney, W. F., Horner, R. M. W., Smith, G. R., Handa, V. K., and Sanders, S. R. (1990). "Modeling construction labor productivity." *J. Constr. Eng. Manage.,* 116(4), 705-726.

Tsehayae, A. A., and Fayek, A. Robinson (2014). "Identification and comparative analysis of key parameters influencing construction labour productivity in building and industrial projects." *Can. J. Civil Eng.,* 41(10), 878-891.

Tsehayae, A. A., and Fayek, A. Robinson (2016b). "Developing and Optimizing Context-Specific Fuzzy Inference System-Based Construction Labor Productivity Models." *J. Constr. Eng. Manage.,* 142(7), 04016017.

Wolstenholme, E. F. (1999). "Qualitative vs quantitative modelling: the evolving balance." *J. Oper. Res. Soc.,* 422-428.

Zadeh, L. A. (1965). “Fuzzy Sets.” *Information and Control*, 8(3), 338-353.

Zadeh, L. A. (1975). “The concept of a linguistic variable and its application to approximate reasoning.” *Information Sciences*, 8(3), 199-249.

Zayed, T. M., and Halpin, D. W. (2005). "Productivity and cost regression models for pile construction." *J. Constr. Eng. Manage.,* 131(7), 779-789.

Chapter 3. Identification of Factors Influencing Productivity of Equipment-Intensive Activities

3.1. Introduction

There are several studies in the literature on the identification of the factors that influence construction productivity at different levels (i.e., activity-level and project-level construction productivity). As construction is a labour-intensive industry (Jarkas 2010), previous research on the identification of factors influencing activity-level productivity mainly focused on labour-intensive activities (e.g., Tsehayae and Fayek 2014). However, since the drivers of productivity for the labour- and equipment-intensive activities are different, the factors influencing their productivity are different as well. Although there are several studies on the identification of factors influencing the productivity of labour-intensive activities, there is a lack of research on equipment-intensive activities. To address this research gap, a comprehensive list of factors influencing the productivity of equipment-intensive activities, identified through and extensive literature review, is presented in this chapter.

Moreover, in order to assess the key factors influencing the productivity of equipment-intensive activities, an interview survey was designed to acquire expert knowledge from two perspectives, that of project management and that of tradespeople. The interview survey is designed to identify the key factors influencing construction productivity based on two measures: agreement (i.e., the extent to which a respondent agrees that a given factor exists in the current project) and impact (i.e., the extent to which a given factor affects the productivity of the current project), as proposed by Tsehayae and Fayek (2014), and Dai et al. (2009). Accordingly, identifying the key factors influencing productivity is a multi-criteria decision making (MCDM) problem where the objective is to identify the most critical factors. The decision-making criteria are the agreement and impact measures. Previous research used a weighted product model (WPM) to identify the key factors influencing productivity (Tsehayae and Fayek 2014; Dai et al. 2009). Although the WPM is a common MCDM method because of its simplicity, this method over-values extreme conditions (Mateo 2012). “Extreme conditions” refers to situations in which the agreement (or impact) score of a factor is far from the mean value of the agreement (or impact) score for all factors. Thus, the WPM may rank extreme conditions (i.e., the most critical factors) inaccurately.

There are several MCDM methods available in the literature that can be used to identify the most critical factors influencing construction productivity. The technique for order of preference by similarity to ideal solution (TOPSIS) is a commonly used method in construction applications (e.g., Gkountis and Zayed 2015). The TOPSIS method was developed by Hwang and Yoon (1981). It evaluates decision alternatives based on their distance from the positive ideal solution (PIS; i.e., the decision alternative with the maximum agreement and impact scores) and the negative ideal solution (NIS; i.e., the decision alternative with the minimum agreement and impact scores). Opricovic and Tzeng (2004) asserted that the evaluation process of the TOPSIS method is similar to the human decision-making process. El Amine et al. (2014) implemented the different MCDM methods (i.e., Weighted Sum Model, WPM, Kim and Lin, compromise programming, TOPSIS, and Elimination and Choice Expressing Reality [ELECTRE I]) on a decision-making problem and validated the results of the MCDM methods using expert knowledge. El Amine et al. (2014) concluded that the results of the TOPSIS method were the most consistent with the results of expert judgment.

3.2. Research Methodology

In order to develop a comprehensive list of the factors that influence the productivity of equipment-intensive activities, the relevant studies on construction productivity were reviewed using a literature review methodology that was applied in previous critical reviews (i.e., Tsai and Wen 2005; Ke et al. 2009; Hong et al. 2011; Yi and Chan 2013; Naoum 2016). The common scientific search engine Scopus was used to search for any articles that included “construction” and “productivity” in their title. Further refinement of the search results was accomplished by limiting the results to articles published in the 10 top-ranked construction journals, as introduced by Wing (1997): *Construction Engineering and Management; Construction Management and Economics; Engineering, Construction and Architectural Management; Journal of Management in Engineering; International Journal of Project Management; Automation in Construction; Proceedings* *of the Institution of Civil Engineers; International Journal of Construction Information Technology; Transactions of the American Association of Cost Engineers;* and *Journal of Construction Procurement*. Additionally, based on the search results, the three other journals that had the highest number of publications on this topic, *Canadian Journal of Civil Engineering, Korean Society of Civil Engineers,* and *International Journal of Productivity and Performance Management*, were added to the list. Finally, 117 articles were reviewed and the factors influencing the productivity of equipment-intensive activities were identified. These factors are presented in Section 3.3.

Based on the approach used by Tsehayae and Fayek (2014) and Dai et al. (2009) to assess the most critical factors influencing the productivity of equipment-intensive activities, an interview survey was developed. The interview survey identifies the most critical factors influencing productivity based on two measures: agreement (i.e., the extent to which a respondent agrees that a given factor exists in the current project) and impact (i.e., the extent to which a given factor affects the productivity of the current project). The agreement and impact scores of each factor are measured using a seven-point Likert scale, which is a symmetrical measurement scale for survey questions (Burns and Bush 2007). The design of interview survey is discussed in Section 3.4. Once the agreement and impact scores have been evaluated for all of the factors using the interview surveys, those factors are ranked using the TOPSIS method, which is discussed in Section 3.5. Finally, the project management and tradespeople perspectives regarding the influence of factors on productivity are compared. To do this, project management and tradespeople interview survey results are compared using the analysis of variance (ANOVA) F-test to determine any significant differences between the two perspectives. The F-test is a statistical method for testing if the mean values (i.e., the mean value of the impact score for each factor) of two sample populations (i.e., project management and tradespeople survey respondents) are significantly different.

3.3. Identification of the Factors Influencing the Productivity of Equipment-Intensive Activities

Construction productivity tends to be a micro-level issue, where a group of organized workers are required to transform a set of inputs into tangible project outputs (Bernold and AbouRizk 2010). However, in addition to micro-level factors (i.e., crew-level, activity-level, and project-level factors), macro-level factors (i.e., organizational-level, provincial-level, national-level, and global-level factors) may directly or indirectly influence construction productivity (Construction Industry Institute [CII] 2006; Knight and Fayek 2000). Accordingly, in this paper, the list of factors influencing the productivity of equipment-intensive activities includes both micro-level factors and macro-level factors. The identification of the factors influencing productivity was accomplished by reviewing the aforementioned 117 articles, which were selected as discussed in the third section. Although there is no comprehensive research on the identification of factors influencing the productivity of equipment-intensive activities among the reviewed articles, there are some articles that focus on specific construction activities or operations, as discussed below.

Choi and Ryu (2015) identified nine activity-level factors influencing the productivity of highway pavement operations and developed a predictive model of productivity using a statistical method. Ok and Sinha (2006) identified 14 activity-level factors that affect the production rate of earthmoving operations and developed an artificial neural network to predict the production rate of this operation. Zayed and Halpin (2005) identified 23 activity-level factors that affect pile construction productivity and costs and developed a statistical model to predict productivity. Goodrum and Haas (2004) studied the long-term impact of equipment technology on construction productivity and identified five activity-level factors that influence construction productivity and that are related to equipment technology. In a more recent study, Goodrum et al. (2010) identified 11 activity-level and organizational-level factors that influence construction productivity. Ghoddousi et al. (2015) identified 32 activity-level and project-level factors that affect the productivity of road construction projects. Kannan (2011) identified 25 organizational-level factors influencing the productivity of earthmoving operations, which factors are related to organizational management, equipment repair policies, equipment ownership policies, and job-site optimization. Tsehayae and Fayek (2014) developed a comprehensive multi-level list of 169 factors influencing construction labor productivity, including micro-level and macro-level factors. In addition to the abovementioned articles, other research works were reviewed to identify the factors influencing the productivity of equipment-intensive activities; the complete list of factors and sources is presented in Appendix A. Finally, 221 micro- and macro-level factors influencing the productivity of equipment-intensive activities were identified, as presented in Table 3.1.

Table 3.1. Micro- and Macro-Level Factors Influencing Productivity of Equipment-Intensive Activities

Category	Factors
	Micro-level factors
Crew-level	
Labor and crew	**Crew size, adequacy of crew size, crew composition, crew experience, crew makeup changes, crew turnover rate, number of languages spoken in the crew, crew motivation (intensity of effort, persistence of effort, direction of effort), level of interruptions and disruptions, number of consecutive working days, total daily overtime work, crew skill level, unscheduled breaks, late arrival/early quit, level of absenteeism**
Material and consumables	**Material availability, waiting time for material, material quality, material storage practice, pre-installation requirements**
Equipment and tools	**Number and type of active equipment on the task, equipment breakdown frequency, equipment breakdown downtime, equipment maintenance frequency, equipment maintenance downtime, work equipment availability, equipment delivery to working area, waiting time for equipment, appropriateness of equipment, equipment ownership, equipment production capacity, equipment age, equipment operator experience, equipment operator education, equipment operator skill level, amplification of human energy, level of control, functional range, equipment ergonomic design, information feedback provision , moving technology, equipment warranty, equipment specifications**
Foreman	**Foreman (supervisor) experience, change of foreman (supervisor), work planning skills, leadership and supervisory skills, coordination between labor and equipment operators**
Activity-level	
Task characteristics	**Task complexity, total volume of work, task repetitiveness, out-of-sequence work, problems with predecessors, construction method, task waste disposal, level of rework (contractor initiated), frequency of rework (contractor initiated), rework cost (contractor initiated), balance between labor and equipment**
Location properties	**Spaciousness of working area, site restrictions, soil conditions (dependency), soil type, soil moisture, groundwater level, underground facilities, hauling/delivery elevation difference, hauling/delivery distance**
Engineering/ instructions	**Availability of drawings, quality of drawings, number of revisions on drawings, design changes, quality of specifications, time to respond to RFIs, frequency of rework (design initiated), level of rework (design initiated), rework cost (design initiated), time to do inspections**
Project-level	
Project delivery and contract	Level of sub-contracting (subcontracted amount, number of subcontractors), delivery system, contract type, level of fast tracking, contract conditions for changes, lack of information, change in specifications, change in design drawings, lack of information
Project best practices	Use of automation and information technology, constructability review (constructability review participants, constructability review implementation), start-up planning, productivity measurement practices, use of workface planning

Category	Factors
	Micro-level factors
Project's owner nature	Owner's supervision, owner's intervention, owner's primary driver, clarity of owner's objectives, delivery of site to contractor, owner's staff on site, owner-initiated suspension of work (frequency of suspensions, length of suspensions)
Project conditions	Camp conditions, total project site area, site facilities' conditions (project site lunchroom for workers, project site washroom for workers), project working time, project working cycle, site layout (temporary facilities, equipment storage location, access roads and on-site paths, workspace and site objects), restrictions for project site access, construction method, distance between project site and city, project size, project type (industry sector), government and regulatory inspections (frequency of inspections, total time for inspections), suspension of project (frequency of suspensions, length of suspensions), project complexity (use of unproven technology, facility size and process capacity, past experience with configurations and geometry, familiarity with construction methods), year of construction, level of modularization, site congestion
Project scope management	Project scope definition, project scope verification, project scope change control
Project time management	Project activity definition, project activity sequencing, **project activity duration (project activity duration estimation, activity duration prediction accuracy)**, project schedule development, project duration accuracy, project schedule criticality index, project schedule control, schedule compression, project activity weights definition, project progress curves development and progress monitoring
Project cost management	Project resource planning, project cost estimate (development of material and equipment requirement list, project cost estimator experience, time allowed for cost estimate, bidding process conditions, labor force conditions), project cost budgeting, project cost control, use of earned value methods
Project quality management	Project quality planning, demand for over-quality work, project quality assurance, quality audits, project quality control (inspection delay, interference, out-of-sequence inspections or survey work)
Project procurement management	Procurement planning, procurement solicitation planning, procurement solicitation execution, procurement administration
Project safety management	Project safety planning, use of site safety officer, **project safety plan execution (daily job hazard assessment forms, personnel protective equipment, site safety communication, project safety equipment, drug testing, safety training, safety inspections, safety audits), safety incidents (near miss, first aid, medical aid, modified work incidents, number of modified work days, lost time incidents, fatality incidents, equipment/property damage)**, safety incident investigation (personnel involved in investigation, process time), uniformity of safety procedures, project safety administration and reporting
Project risk management	Risk identification and planning, use of risk assessment tool, risk monitoring and control, crisis management
Project communication management	Project communication plan and implementation, **communication between trades**, communication devices

Category	Factors
	Micro-level factors
Project human resource management	Project interface development, **project staff hiring practices**, project team development (team-building activities, reward and recognition system, work culture), **project team closeout (use of personal exit interviews, layoff practices, personnel record development)**
Project environmental management	Environmental rating of project, project environmental planning, project environmental assurance, environmental audits, project environmental control (rework/remedial action, environmental inspections)
Project claim management	Project claim identification, project claim team characteristics (experience of claim reviewer, claim review process time), project claim resolution (resolution method, resolution process)
Miscellaneous factors	Job security, weather conditions (temperature, humidity, precipitation, wind speed, solar radiation), contractor financial status, research and development, coordination between trades, project completion percentage, superintendent management style, superintendent trainings, superintendent education, uniformity of work rules by superintendent, project management team experience, project manager trainings, project manager education, level of paperwork, **permits**, availability of labor, contractor experience, project level rework, parking facilities, **project financial management (project team salary, project team payments)**, labor disputes
	Macro-level factors
Organizational properties	Organization's principal project type, organization experience, organization annual turnover, annual employee turnover, number of active projects, organizational structure, organization level of subcontracting, organization construction equipment fleet, organization equipment maintenance policy, equipment fleet inspections and analysis, equipment operator trainings, organization policy for equipment ownership, organization equipment warranty policy, ownership period and economic analysis
Provincial	Provincial economy, number of provincial construction projects, provincial codes and regulations, unemployment rate of construction workers, labor strikes, available supervisor pool in province, tax (income tax, GST), construction material price fluctuation, availability of labor in province, expenditure level towards projects (residential, non-residential, energy), cost of project (index)
National	Political system, competing projects across nation, availability of labor in nation, foreign construction worker recruitment, Canada population (size of population, growth of population, aging of population), interest rates, inflation rate, construction price index
Global	Global economic outlook, global energy supply and demand (global energy demand, global energy supply), oil price and price fluctuation (oil price, price fluctuation), natural gas price and price fluctuation (natural gas price, natural gas fluctuation)

Note: Factors that are common to both surveys (project management survey and tradespeople survey) are shown in bold.

3.4. Interview Survey Design

Once a comprehensive list of the factors influencing productivity had been developed, an interview survey was designed to identify the most critical factors based on their level of influence on productivity. A systematic approach was used to design the interview surveys for the two groups of project staff (i.e., project management staff and project tradespeople staff) and to identify the most critical factors influencing construction productivity. Two different surveys were designed: a project management survey, which includes all micro- and macro-level factors included in Table 3.1, and a tradespeople survey, which includes all crew- and activity-level factors as well as some project-level factors (shown in bold in Table 3.1). Only some of the project-level factors were included in the tradespeople survey because information regarding all project- and macro-level factors might not be known by tradespeople survey respondents. Crew-level, activity-level, and some project-level factors are common to the two surveys, and the perspectives of the two surveys' respondents regarding those factors' impacts on productivity can be compared.

The first section of each survey is designed to collect background information on the respondents, such as demographic information, highest level of education obtained, union status, trade, and current position of employment. The second section is designed to measure the influence of each factor on productivity based on two scores: the agreement score (i.e., the extent to which a respondent agrees that a given factor exists in the current project) and the impact score (i.e., the extent to which a given factor affects the productivity of the current project). Table 3.2 presents two examples of survey questions measuring agreement and impact.

Table 3.2. Examples of Interview Survey Questions

Factors	Agreement							Impact						
	Strongly disagree	Disagree	Slightly disagree	Neither disagree or agree	Slightly agree	Agree	Strongly agree	Strongly negative	Negative	Slightly negative	No impact	Slightly positive	Positive	Strongly positive
The crew size is adequate for the task at hand	1	2	3	4	5	6	7	1	2	3	4	5	6	7

Factors	Agreement							Impact						
	Strongly disagree	Disagree	Slightly disagree	Neither disagree or agree	Slightly agree	Agree	Strongly agree	Strongly negative	Negative	Slightly negative	No impact	Slightly positive	Positive	Strongly positive
There are frequent unscheduled breaks during work hours	1	2	3	4	5	6	7	1	2	3	4	5	6	7

The surveys are designed to question respondents using statements that describe either positive or negative factors affecting productivity. Table 3.2 presents two examples of survey questions, the first of which describes a positive factor affecting productivity, and the second of which describes a negative factor affecting productivity. A seven-point Likert scale to measure agreement and impact was adopted, as proposed by CII (2006) and Dai (2006). For measuring the agreement score, this scale has three levels of disagreement (i.e., “Strongly Disagree,” “Disagree,” and “Slightly Disagree”), one neutral point (i.e., “Neither Disagree or Agree”), and three levels of agreement (i.e., “Slightly Agree,” “Agree,” and “Strongly Agree”). For measuring the impact score, this scale has three levels of negative impact (i.e., “Strongly Negative,” “Negative,” and “Slightly Negative”), one neutral point (i.e., “Neither Negative or Positive”), and three levels of positive impact (i.e., “Slightly Positive,” “Positive,” and “Strongly Positive”).

3.5. TOPSIS Framework for the Analysis of Interview Survey Results

In order to identify the most critical factors influencing the productivity of equipment-intensive activities, the factors identified through the literature (see Table 3.1) need to be ranked based on their level of influence on productivity, which is measured by the agreement and impact scores. Therefore, identifying the most critical factors influencing productivity is an MCDM problem wherein the objective is to identify the most critical factors and the decision-making criteria are the agreement and impact scores. In this paper, the TOPSIS method is used for solving this MCDM problem, which is accomplished through the following steps.

Step 1. In this step, the agreement and impact scores for each factor are evaluated. The agreement score for each factor is calculated using Equation 3.1.

$$R_A = A \times 1 + B \times 2 + C \times 3 + 4 \times D + 5 \times E + 6 \times F + 7 \times G, \quad (3.1)$$

where R_A represents the agreement score, and A, B, C, D, E, F, and G are the number of respondents rating the agreement of the factor as 1 (Strongly Disagree) to 7 (Strongly Agree), respectively.

Once the agreement score has been calculated for each factor, the positive and negative impact scores are calculated for each factor. As shown in Table 3.2, the surveys were designed to question the respondents using statements that describe either positive or negative factors affecting productivity. Based on the direction of the statement used for questioning the effect of a given factor on productivity, the factor may have a positive impact on productivity, which is calculated using Equation 3.2, or a negative impact on productivity, which is calculated using Equation 3.3.

$$I_P = X \times 1 + Y \times 2 + Z \times 3, \quad (3.2)$$

where I_p represents the positive impact score, and X, Y, and Z are the number of respondents rating the impact of the factor on productivity as 1 (Slightly Positive) to 3 (Strongly Positive), respectively.

$$I_N = U \times 1 + V \times 2 + W \times 3, \quad (3.3)$$

where I_N represents the negative impact score, and U, V, and W are the number of respondents rating the impact of the factor on productivity as 1 (Slightly Negative) to 3 (Strongly Negative), respectively.

In order to determine the impact of the factor on productivity, regardless of the statement used in the survey, the overall impact (R_I) is calculated using Equation 3.4. The overall impact score is hereafter referred to as the impact score.

$$R_I = \max(I_P, I_N) \quad (3.4)$$

Step 2. In this step, the decision matrix is developed as presented in Equation 3.5.

$$\begin{bmatrix} R_{A,1} & R_{I,1} \\ R_{A,2} & R_{I,2} \\ \vdots & \vdots \\ R_{A,i} & R_{I,i} \end{bmatrix}, \tag{3.5}$$

where $R_{A,i}$ and $R_{I,i}$ represent the agreement and impact scores for factor i, respectively.

Step 3. In this step, the weighted normalized decision matrix is developed using Equation 3.6 and Equation 3.7.

$$v_{A,i} = w_1 \times \frac{R_{A,i}}{\sqrt{\left(\sum_{j=1}^{m} \mathrm{R}_{A,j}\right)^2}}, \qquad \forall m \in M, \forall n \in N \tag{3.6}$$

$$v_{I,i} = w_2 \times \frac{\mathrm{R}_{I,i}}{\sqrt{\left(\sum_{j=1}^{m} R_{I,j}\right)^2}}, \qquad \forall m \in M, \forall n \in N, \tag{3.7}$$

where $v_{A,i}$ and $v_{I,i}$ are the weighted normalized agreement and impact scores of factor i, and w_1 and w_2 are the weights of the agreement and impact scores for decision making, respectively. In this paper, the agreement and impact scores are equally weighted.

Step 4. In this step, the PIS and the NIS are identified for the decision-making problem. Since the objective of the decision making problem is to identify the most critical factors influencing construction productivity, the PIS has the maximum agreement and impact scores, and the NIS has the minimum agreement and impact scores.

Step 5. In this step, the geometric distances between each factor and the PIS and NIS are calculated using Equation 3.8 and Equation 3.9, respectively.

$$d_i^+ = \sqrt{(v_{A,i} - v_A^+)^2 + (v_{I,i} - v_I^+)^2} \tag{3.8}$$

$$d_i^- = \sqrt{(v_{A,i} - v_A^-)^2 + (v_{I,i} - v_I^-)^2}, \tag{3.9}$$

where d_i^+ is the Euclidian distance between factor i and the PIS, and d_i^- is the Euclidian distance between factor i and the NIS. In addition, $v_{A,i}$ and $v_{I,i}$ are the weighted normalized agreement and impact scores of factor i, respectively. Finally, v_A^+ and v_I^+ are the agreement and impact scores of the PIS, respectively, and v_A^- and v_I^- are the agreement and impact scores of the NIS, respectively.

Step 6. In this step, the evaluation score for each individual factor is calculated based on its closeness to the positive and negative ideal solutions using Equation 3.10. A higher evaluation score is obtained by simultaneously maximizing closeness to the PIS and minimizing closeness to the NIS.

$$ES_i = \frac{d_i^-}{(d_i^+ + d_i^-)}, \tag{3.10}$$

where ES_i represents the evaluation score of factor i.

Step 7. In this step, the factors are ranked based on their evaluation scores in descending order. The top factor in the ranking (i.e., the factor with the highest evaluation score) is the most critical factor influencing productivity.

3.6. Case Study for Validating the Factors and the TOPSIS Framework

In order to validate the list of factors influencing productivity, the survey design, and the TOPSIS framework, the interview surveys were administered to a construction company that is active in the industrial construction sector in Alberta, Canada. First the population size (i.e., the total number of potential respondents to the surveys) was determined for each type of interview survey (i.e., the project management and the tradespeople survey). The population size of the project management survey respondents was 16 respondents, including all staff with the following positions: vice president, general manager, main office project manager, project controller, project coordinator, scheduler, safety officer, project manager, construction manager, superintendent, and site project manager. The population size of the tradespeople survey respondents was 64 respondents, including all staff with the following positions: foreman, equipment operator, welder, and laborer.

Once the population size for the two groups of survey respondents was determined, a random sampling within each population was conducted. An adequate sample size ensures proper representation of the population as a whole (Fellows and Liu 2015). The aim of this study was to achieve a 10% margin of error and a 90% confidence interval. There were 15 project management surveys collected from the population of 16 respondents, which provided a 99% confidence interval and a 10% margin of error for the project management survey results. Out of the population of 64 respondents for the tradespeople survey, there were 20 responses collected, which provided a 93% confidence interval and a 10% margin of error for the tradespeople survey results.

3.6.1. Interview Survey Respondents' Demographics

As presented in Figure 3.1 the respondents of project management survey held the following positions: "General Management" (i.e., vice president, general manager, main office project manager, project controller, project coordinator, scheduler, and safety officer) (40% of respondents), "Safety" (20%), "Project Management" (i.e., on-site project manager, construction manager, and superintendent) (20%), "Project Controls" (13%), and "Field Engineers" (7%).

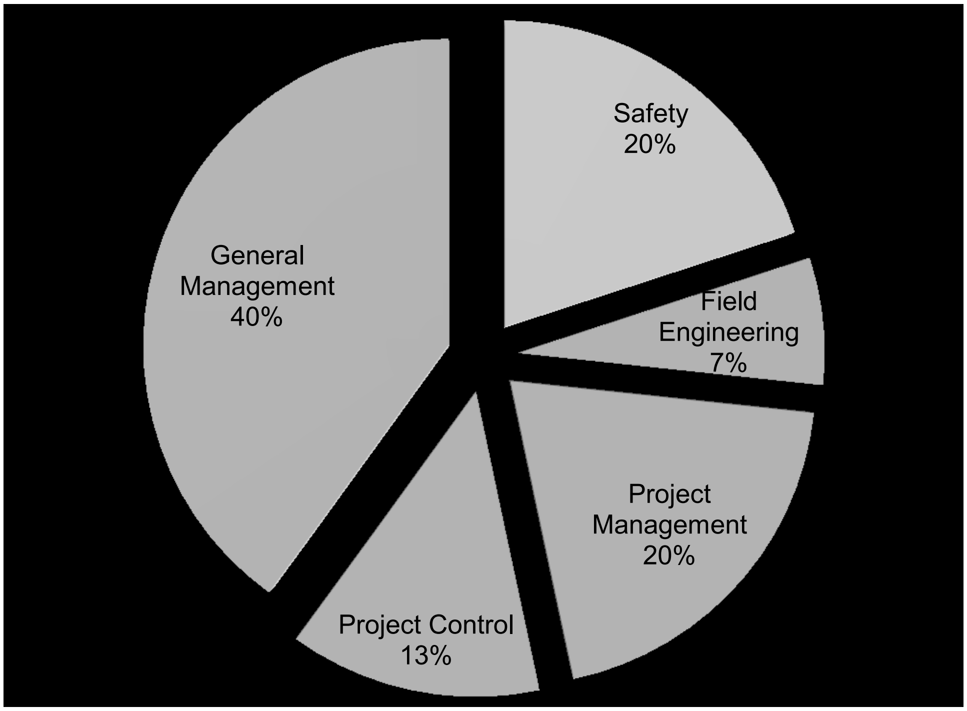

Figure 3.1. Project Management Survey: Current position of survey respondents

In regards to years of experience working in construction, as shown in Figure 3.2, 13% of respondents to the project management survey had "≤5 years of experience", 40% had "5–10 years of experience", 13% had "10–15 years of experience", 13% had "15–20 years of experience", and 20% had "≥20 years of experience". It should be mentioned that three of the categories in Figure 3.2 ("Less than 5 years," "5–10 years," and "15–20 years") each include 13.3% of the respondents; thus the summation of the five categories in this figure is equal to 100%.

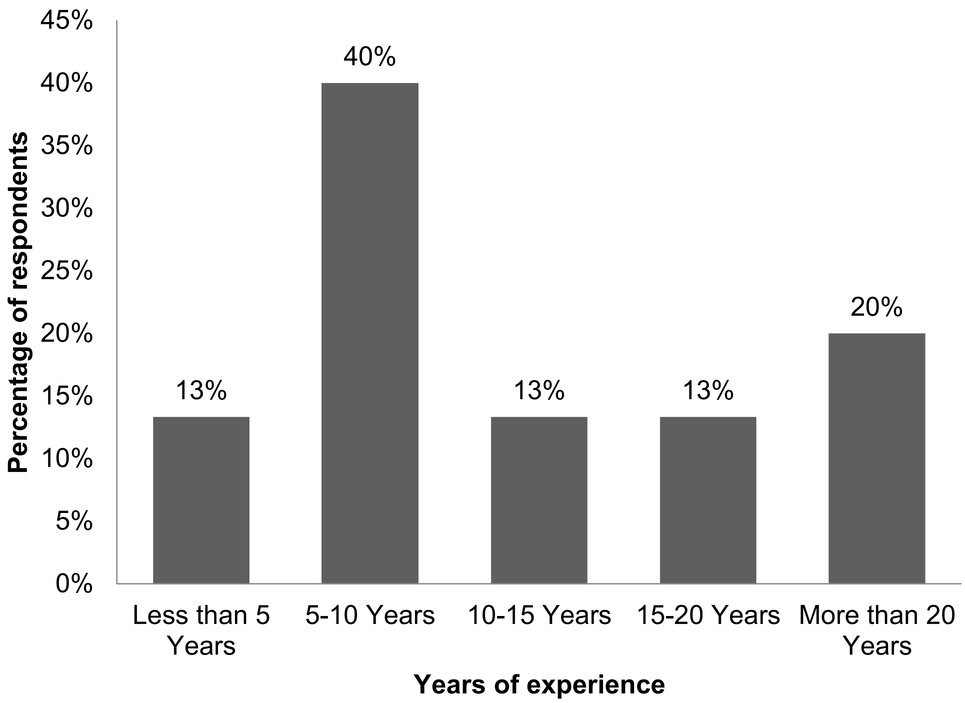

Figure 3.2. Project Management Survey: Respondents' years of experience

Figure 3.3 shows the highest level of education obtained by respondents to the project management survey, where 21% held a "High School Diploma", 29% held a "Vocational, Technical, or Trade School Diploma", 14% held a "College Diploma", 29% held a "Bachelor's Degree", and 7% held a "Master's Degree".

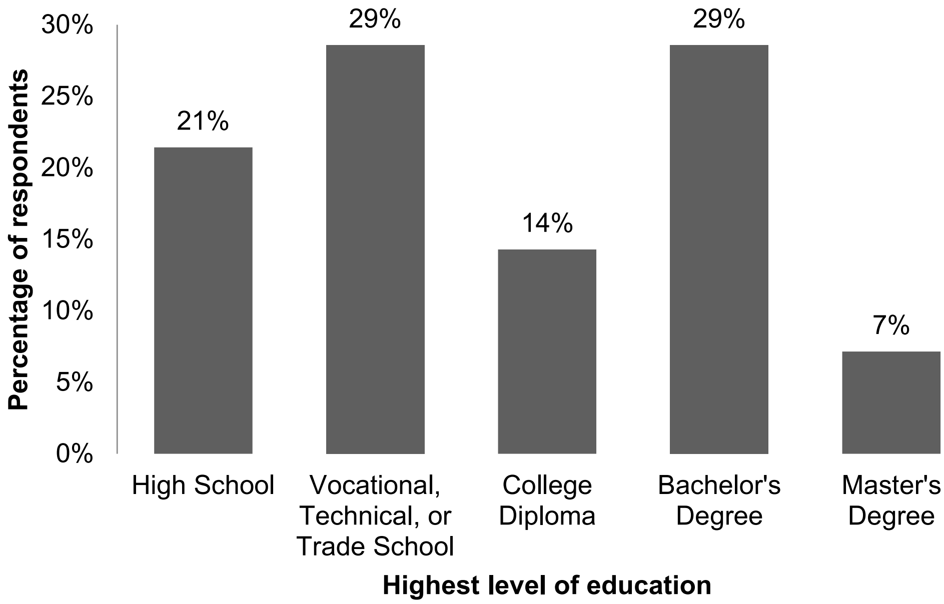

Figure 3.3. Project Management Survey: Highest level of education

As presented in Figure 3.4 the respondents of tradespeople survey held the following positions: “Foreman” (45%), “Labourer” (40%), “Equipment Operator” (10%), and “Welder” (5%).

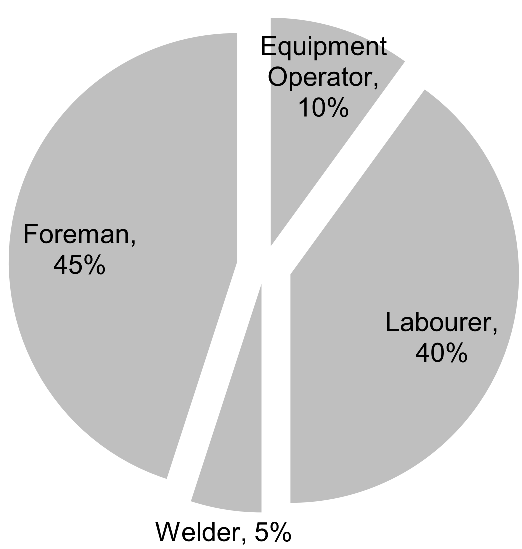

Figure 3.4. Tradespeople Survey: Current position of respondents

In regards to years of experience working in construction, as presented in Figure 3.5, 35% of respondents to the tradespeople survey had “≤5 years of experience”, 20% had “5–10 years of experience”, 15% had “10–15 years of experience”, 20% had “15–20 years of experience”, and 10% had “≥20 years of experience”.

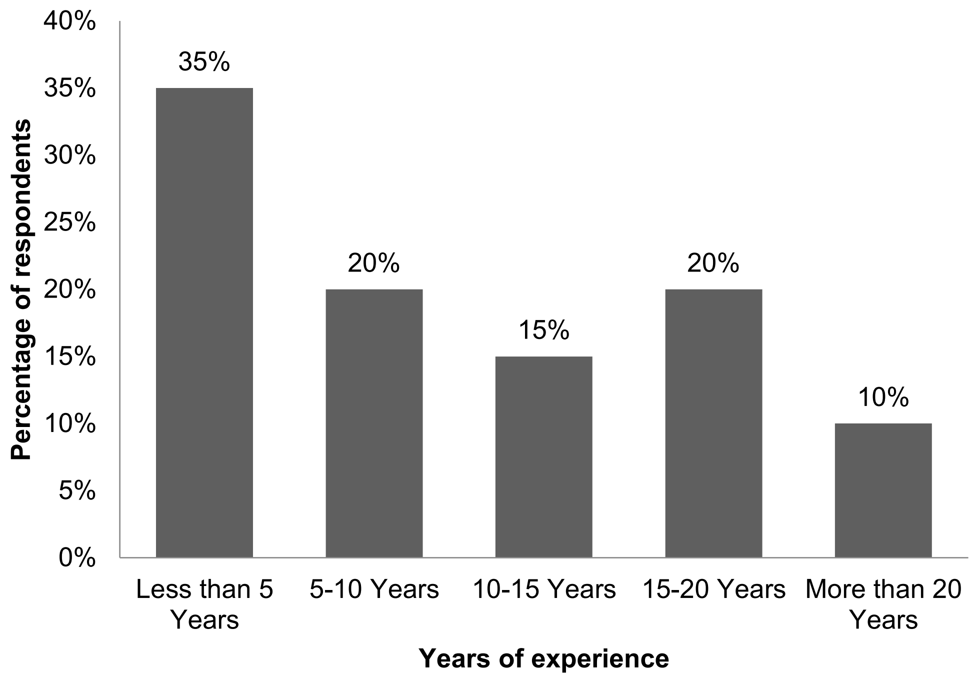

Figure 3.5. Tradespeople Survey: Years of experience

Figure 3.6 shows the highest level of education obtained by respondents to the tradespeople survey, where 5% of respondents held a “High School Diploma”, 60% held a “Vocational, Technical, or Trade School Diploma”, 10% held a “College Diploma”, 20% held a “Bachelor’s Degree”, and 5% held a “Master’s Degree”.

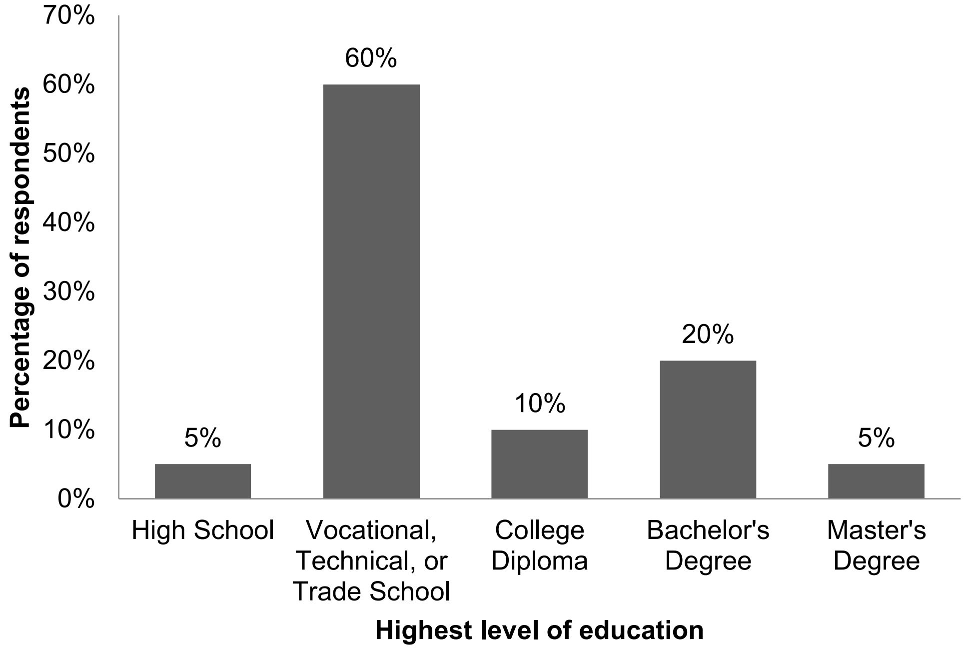

Figure 3.6. Tradespeople Survey: Highest level of education

3.6.2. Critical Factors Influencing the Productivity of Equipment-Intensive Activities

The project management survey includes all micro- and macro-level factors, which are ranked using the TOPSIS method. Table 3.3 presents the top 20 critical factors influencing productivity based on project management survey responses.

Table 3.3. Project Management Survey: Top 20 critical factors

Factors	Distance to PIS	Distance to NIS	Evaluation score	Rank
Equipment operator experience	0.005	0.077	0.942	1
Crew skill level	0.005	0.077	0.935	2
Personal protective equipment	0.006	0.076	0.924	3
Crew motivation	0.007	0.079	0.922	4
Past experience of crew with project configurations	0.007	0.076	0.921	5
Adequacy of crew size	0.008	0.074	0.906	6
Foreman supervisory skills	0.010	0.072	0.884	7
Foreman experience	0.011	0.071	0.863	8
Safety training	0.012	0.070	0.855	9
Communication between trades	0.013	0.069	0.845	10

Factors	Distance to PIS	Distance to NIS	Evaluation score	Rank
Coordination between labor and equipment operators	0.013	0.069	0.837	11
Project safety plan execution	0.014	0.068	0.829	12
Equipment operator skill level	0.014	0.068	0.826	13
Activity duration prediction accuracy	0.015	0.068	0.825	14
Daily job hazard assessment forms	0.015	0.068	0.823	15
Crew skill level	0.015	0.067	0.815	16
Foreman work planning skills	0.016	0.066	0.800	17
Foreman leadership style	0.017	0.065	0.794	18
Appropriateness of equipment	0.017	0.065	0.791	19
Equipment level of control	0.018	0.064	0.784	20

The top three critical factors influencing the productivity of equipment-intensive activities are: (1) equipment operator experience, (2) crew skill level, and (3) personal protective equipment. It should be noted that all of the top 20 critical factors that were identified by the project management respondents are micro-level factors. The 16 categories of factors in the project management survey are also ranked based on their influence on productivity, as presented in Table 3.4. The evaluation score for each category is calculated as the mean value of the evaluation scores of all factors in that category.

Table 3.4. Project Management Survey: Factor categories' rankings

Factor category	Level of detail	Mean evaluation score	Rank
Foreman-related factors	Micro-level	0.773	1
Crew-related factors	Micro-level	0.698	2
Safety	Micro-level	0.648	3
Equipment and tools	Micro-level	0.613	4
Materials and consumables	Micro-level	0.592	5
Project management practices	Micro-level	0.547	6
Nature of the project owner	Micro-level	0.458	7
Task-related factors	Micro-level	0.431	8
Engineering and instructions	Micro-level	0.416	9
Project conditions	Micro-level	0.414	10
Provincial factors	Macro-level	0.387	11
Location-related factors	Micro-level	0.371	12
Organization-related factors	Macro-level	0.347	13

Factor category	Level of detail	Mean evaluation score	Rank
Project best practices	Micro-level	0.324	14
National factors	Macro-level	0.309	15
Global factors	Macro-level	0.264	16

The top three critical categories of factors influencing the productivity of equipment-intensive activities are: (1) foreman-related factors, (2) crew-related factors, and (3) safety. The top 10 critical categories of factors are micro-level factors. Once the project management survey analysis is completed, the same analysis is implemented on the tradespeople survey. The tradespeople survey includes all the crew- and activity-level factors as well as some project-level factors (refer to Table 3.1), which are ranked using the TOPSIS method. Table 3.5 presents the top 20 critical factors influencing construction productivity based on the tradespeople survey responses.

Table 3.5. Tradespeople Survey: Top 20 critical factors

Factors	Distance to PIS	Distance to NIS	Evaluation score	Rank
Number of languages spoken in the crew	0.000	0.104	1.000	1
Equipment operator experience	0.003	0.101	0.972	2
Crew motivation	0.004	0.102	0.962	3
Protective equipment	0.004	0.100	0.960	4
Foreman supervisory skills	0.004	0.100	0.958	5
Crew experience	0.006	0.099	0.947	6
Crew skill level	0.006	0.098	0.939	7
Foreman work planning skills	0.007	0.097	0.930	8
Foreman experience	0.008	0.096	0.922	9
Coordination between labor and equipment operators	0.009	0.096	0.918	10
Material availability	0.009	0.095	0.915	11
Past experience with project configurations	0.009	0.096	0.915	12
Foreman leadership style	0.009	0.095	0.912	13
Late arrival/early quit	0.010	0.095	0.908	14
Appropriateness of equipment	0.012	0.092	0.882	15
Equipment production capacity	0.015	0.089	0.854	16
Project safety plan execution	0.016	0.088	0.843	17
Balance between labor and equipment	0.017	0.087	0.835	18

Factors	Distance to PIS	Distance to NIS	Evaluation score	Rank
Safety training	0.018	0.087	0.830	19
Equipment moving technology	0.021	0.084	0.800	20

The top three critical factors influencing the productivity of equipment-intensive activities are: (1) number of languages spoken in the crew, (2) equipment operator experience, and (3) crew motivation. The 10 categories of the factors in the tradespeople survey are also ranked based on their influence on construction productivity, as presented in Table 3.6. The evaluation score for each category is calculated as the mean value of the evaluation scores of all the factors in that category.

Table 3.6. Tradespeople Survey: Factor categories' rankings

Factor category	Level of details	Mean evaluation score	Rank
Foreman-related factors	Micro-level	0.857	1
Equipment- and tools-related factors	Micro-level	0.698	2
Crew-related factors	Micro-level	0.690	3
Materials and consumables	Micro-level	0.639	4
Project management	Micro-level	0.608	5
Safety	Micro-level	0.581	6
Task-related factors	Micro-level	0.528	7
Engineering and instructions	Micro-level	0.467	8
Location-related factors	Micro-level	0.399	9
Project conditions	Micro-level	0.388	10

The top three critical categories of the factors influencing productivity of equipment-intensive activities are: (1) foreman-related factors, (2) equipment- and tools-related factors, and (3) crew-related factors.

3.6.3. Comparative Study of Project Management and Tradespeople Survey Results

Previous studies by Tsehayae and Fayek (2014) and Dai et al. (2009) compared the perspectives of project management and tradespeople on the most critical factors influencing construction productivity. In this paper, the comparison of the two perspectives is conducted on two different aspects of the surveys: (1) the impact on productivity of the factors common to both surveys and (2) the ranking of the critical categories common to both surveys.

Tsehayae and Fayek (2014) and Dai et al. (2009) compared the perspectives of project management and tradespeople based on the impact score of each factor. The level of information about the existence of each factor in the current project (i.e., the agreement score) is different for the two respondent groups. While the evaluation scores (Equation 3.10) are calculated using the agreement and impact scores, a comparison of the evaluation scores does not represent the differences in respondent perspectives; instead, it represents the differences in their perspectives combined with the amount of information available to them. Accordingly, it was suggested by Tsehayae (2015) to use only the impact score for comparing the two perspectives. A comparison of the two perspectives using only the impact score makes it possible to implement the comparison using data collected from multiple projects. In this paper, a comparison of the two perspectives is implemented using the ANOVA F-test as suggested by Tsehayae and Fayek (2014) and Dai et al. (2009). The ANOVA F-test is a statistical method for testing if the mean values (i.e., the mean impact score of each factor) of two sample populations (i.e., project management survey respondents and tradespeople survey respondents) are significantly different. If the two sample populations to be compared are distinguished by a single classification criterion, as in this paper (i.e., the position of the survey respondents on the project), the F-test is called one-way ANOVA. If there are two classification criteria that distinguish the two sample populations, the F-test is called two-way ANOVA (Lee et al. 2013).

In order to compare the survey respondents' perspectives on the impact of each factor on productivity, the F-test is performed for each individual factor. The null hypothesis for the F-test is that there is no statistically significant difference between the mean values of the impact scores of the project management and tradespeople surveys. The ANOVA F-test is performed with a confidence level of 95% (i.e., a *p*-value of 0.05), which represents a probability of 95% that the null hypothesis is true. Once the confidence level is selected for the F-test, the critical F-value is determined from the F-distribution table using the confidence level and the degree of freedom. The degree of freedom is calculated using the number of responses received for a given factor. Thus the degree of freedom of the factors can be different if some respondents leave the impact score of some factors blank. If the F-value of an individual factor exceeds the critical F-value, the null hypothesis is rejected, confirming that there is a significant difference between the two perspectives regarding the impact of that factor on productivity. Table 3.7 shows the factors for which the null hypothesis is rejected and presents the following information for each factor: the variance and mean value of the impact score evaluated by the two surveys, as well as the F-value and the critical F-value for each factor.

Table 3.7. Factors with Significant Difference between the Perspective of Project Management (PM) and Tradespeople (Trade) Survey Respondents

Factor	Variance: PM survey	Mean: PM Survey	Variance: Trade survey	Mean: Trade survey	F-value (A)	Critical F-value* (B)	$A - B$
Foreman work planning skills	1.600	5.800	0.274	6.200	5.846	2.400	3.446
Activity duration prediction accuracy	0.335	6.214	1.884	3.900	5.622	2.471	3.151
Total volume of work	0.401	5.643	1.292	5.650	3.221	2.471	0.751
Crew skill level	0.924	5.933	0.303	6.250	3.053	2.400	0.653
Time to respond RFIs**	4.132	4.143	1.358	5.100	3.043	2.471	0.572
Communication between trades	3.410	4.867	1.146	5.579	2.975	2.413	0.561
Weather conditions	5.810	3.667	1.989	3.900	2.920	2.400	0.520
Appropriateness of equipment	0.695	5.867	0.261	6.050	2.669	2.400	0.269
Delay in project team payments	3.566	4.786	1.355	5.750	2.631	2.471	0.160
Problems with predecessors	4.154	4.000	1.632	4.500	2.546	2.471	0.075
Project safety plan execution	0.924	5.933	0.366	5.950	2.526	2.400	0.125
Foreman leadership style	0.552	6.133	0.221	6.300	2.499	2.400	0.099
Unseen subsurface conditions	3.912	3.714	1.568	4.100	2.494	2.471	0.023
Crew makeup changes	2.667	4.333	1.103	4.550	2.418	2.400	0.018

* Critical F-value is extracted from the F distribution table assuming for 95% confidence level (i.e., *p*-value=0.05).

** RFI: Request for information.

As shown in Table 3.7, the three factors with the greatest difference between the F-values and the critical F-values are: (1) foreman work planning skills, where the mean impact score is higher in the tradespeople survey than the project management survey; (2) activity duration prediction accuracy, where the mean impact score is higher in the project management survey than the tradespeople survey; and (3) total volume of work, where the mean impact score is slightly higher in the tradespeople survey than the project management survey. Although the mean impact score for “total volume of work” in the project management survey is only slightly less than the tradespeople survey, due to the difference between their variances, the null hypothesis of the F-test is rejected for this factor. Comparing the TOPSIS and F-test results reveals that there are six factors among the top 20 critical factors listed in Table 3.3 and Table 3.5 where the perspectives of the project management and tradespeople survey respondents are significantly different regarding their impact on productivity: foreman work planning skills, crew skill level, communication between trades, appropriateness of equipment, project safety plan execution, and foreman leadership style.

In addition to the impact of each individual factor on productivity, the two perspectives on the rankings of the critical categories influencing productivity are also compared. Table 3.8 shows the results of the comparison between the project management survey respondents and the tradespeople survey respondents. It should be noted that the rankings of the project management survey categories were recalculated once the factors that were not common to both surveys were removed from the list of factors. Thus the rank of any given factor in Table 3.8 may be different from its rank in Table 3.4.

Table 3.8. Comparison of the Perspective of Project Management and Tradespeople Survey Respondents Regarding Rankings of Factor Categories

Factor category	Project management survey rank	Tradespeople survey rank
Crew-related factors	2	3
Engineering and instructions	8	8
Equipment- and tools-related factors	4	2
Foreman-related factors	1	1
Location-related factors	10	9
Materials and consumables	5	4
Project conditions	9	10
Project management	6	5

Factor category	Project management survey rank	Tradespeople survey rank
Safety	3	6
Task-related factors	7	7

The most noticeable difference between the two rankings of categories in Table 3.8 is that of the safety category, which is ranked as the third most critical category by project management survey respondents and the sixth most critical category by tradespeople survey respondents.

3.7. Summary

This chapter presents a list of 221 factors that influence the productivity of equipment-intensive activities, which were identified by reviewing 117 previous research works. This chapter also presents an interview survey and a TOPSIS framework, which were developed for the identification of the most critical factors influencing the productivity of equipment-intensive activities. Finally, a comparative analysis using ANOVA F-test is presented for comparing the perspectives of survey respondents. The list of factors influencing productivity, which are verified by expert knowledge to have either a negative or positive impact on construction productivity, is used to develop the predictive model of productivity as discussed in Chapter 5. As a requirement for developing the FSD model of construction productivity, the next chapter presents a computational method for the implementation of fuzzy arithmetic operations using the extension principle approach.

3.8. References

Bernold, L. E., and AbouRizk, S. M. (2010). *Managing performance in construction.* John Wiley & Sons, Hoboken, NJ.

Bobko, P. (2001). *Correlation and regression: Applications for industrial organizational psychology and management*. Sage, London, UK.

Burns, A. C., and Bush, R. F. (2007). *Basic marketing research using Microsoft Excel data analysis*. Prentice Hall Press, Upper Saddle River, NJ.

Construction Industry Institute (CII). (2006). *Workforce view of construction labor productivity (IR-252-2a).* Report, Construction Industry Institute, University of Texas at Austin, Austin, TX.

Choi, J., and Ryu, H. (2015). "Statistical analysis of construction productivity for highway pavement operations." *KSCE J. of Civil Eng.,* 19(5), 1193-1202.

Dai, J. (2006). "A latent analysis and prototype system to manage jobsite factors impacting construction labor productivity." Doctoral dissertation, University of Kentucky, Lexington, KY.

Dai, J., Goodrum, P. M., and Maloney, W. F. (2009). "Construction craft workers' perceptions of the factors affecting their productivity." *J. Constr. Eng. Manage.,* 135(3), 217-226.

El Amine, M., Pailhes, J., and Perry, N. (2014). "Critical review of multi-criteria decision aid methods in conceptual design phases: Application to the development of a solar collector structure." *Procedia CIRP,* 21, 497-502.

Fellows, R. F., and Liu, A. M. (2015). *Research methods for construction*. John Wiley & Sons, Hoboken, NJ.

Ghoddousi, P., Poorafshar, O., Chileshe, N., and Hosseini, M. R. (2015). "Labour productivity in Iranian construction projects: Perceptions of chief executive officers." *Int. J. of Product. Perform. Manage.,* 64(6), 811-830.

Gkountis, I., and Zayed, T. (2015). "Subway infrastructure condition assessment." *J. Constr. Eng. Manage.,* 141(12), 04015042.

Goodrum, P. M., and Haas, C. T. (2004). "Long-term impact of equipment technology on labor productivity in the US construction industry at the activity level." *J. Constr. Eng. Manage.,* 130(1), 124-133.

Goodrum, P. M., Haas, C. T., Caldas, C., Zhai, D., Yeiser, J., and Homm, D. (2010). "Model to predict the impact of a technology on construction productivity." *J. Constr. Eng. Manage.,* 137(9), 678-688.

Hanna, A., and Heale, D. G. (1994). "Factors affecting construction productivity: Newfoundland versus rest of Canada." *Can. J. of Civil Eng.*, 21(4), 663-673.

Hong, Y., Chan, D. W., Chan, A. P., and Yeung, J. F. (2011). "Critical analysis of partnering research trend in construction journals." *J. Manage. Eng.,* 28(2), 82-95.

Hwang, C., and Yoon, K. (1981). “Methods for multiple attribute decision making.” *Multiple attribute decision making,* Springer, Verlag, New York, NY, 58-191.

Jarkas, A. M. (2010). “Critical investigation into the applicability of the learning curve theory to rebar fixing labor productivity.” *J. Constr. Eng. Manage.,* 136(12), 1279-1288.

Kannan, G. (2011). “Field studies in construction equipment economics and productivity.” *J. Constr. Eng. Manage.,* 137(10), 823-828.

Ke, Y., Wang, S., Chan, A. P., and Cheung, E. (2009). “Research trend of public-private partnership in construction journals.” *J. Constr. Eng. Manage.,* 135(10), 1076-1086.

Knight, K., and Fayek, A. Robinson. (2000). “A preliminary study of the factors affecting the cost escalation of construction projects.” *Can. J. of Civil Eng.,* 27(1), 73-83.

Lee, C. F., Lee, J. C., and Lee, A. C. (2013). *Statistics for business and financial economics (3rd Edition).* Springer, New York, NY.

Mateo, José Ramón San Cristóbal. (2012). *Multi criteria analysis in the renewable energy industry.* Springer Science & Business Media, New York, NY.

Mawdesley, M. J., and Al-Jibouri, S. (2009). “Modelling construction project productivity using systems dynamics approach.” *Int. J. of Product. Perform. Manage.,* 59(1), 18-36.

Naoum, S. G. (2016). “Factors influencing labor productivity on construction sites: A state-of-the-art literature review and a survey.” *Int. J. of Product. Perform. Manage.,* 65(3), 401-421.

Ok, S. C., and Sinha, S. K. (2006). “Construction equipment productivity estimation using artificial neural network model.” *Constr. Manage. Econ.,* 24(10), 1029-1044.

Opricovic, S., and Tzeng, G. (2004). “Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS.” *Eur. J. Oper. Res.,* 156(2), 445-455.

Portas, J., and AbouRizk, S. (1997). “Neural network model for estimating construction productivity.” *J. Constr. Eng. Manage.*, 123(4), 399-410.

Tsai, C., and Wen, M. L. (2005). “Research and trends in science education from 1998 to 2002: A content analysis of publication in selected journals.” *Int. J. Sci. Educ.,* 27(1), 3-14.

Tsehayae, A. A. (2015). “Developing and optimizing context-specific and universal construction labour productivity models.” Doctoral dissertation, University of Alberta, Edmonton, Canada.

Tsehayae, A. A., and Fayek, A. Robinson. (2014). “Identification and comparative analysis of key parameters influencing construction labour productivity in building and industrial projects.” *Can. J. of Civil Eng.,* 41(10), 878-891.

Wing, C. K. (1997). “The ranking of construction management journals.” *Constr. Manage. Econ.,* 15(4), 387-398.

Yi, W., and Chan, A. P. (2013). “Critical review of labor productivity research in construction journals.” *J. Manage. Eng.,* 30(2), 214-225.

Zakeri, M., Olomolaiye, P. O., Holt, G. D., & Harris, F. C. (1996). “A survey of constraints on Iranian construction operatives’ productivity.” *Constr. Manage. Econ.*, *14*(5), 417-426.

Zayed, T. M., and Halpin, D. W. (2005). “Productivity and cost regression models for pile construction.” *J. Constr. Eng. Manage.,* 131(7), 779-789.

Chapter 4. Computational Method for Fuzzy Arithmetic Operations on Triangular Fuzzy Numbers by the Extension Principle

4.1. Introduction

Fuzzy sets theory, developed by Zadeh (1965), is a powerful tool for modeling subjective and imprecise information in different contexts. Introduced by Zadeh (1975), fuzzy numbers are a specific type of fuzzy sets used for representing values of real world parameters when the exact values are not measurable due to a lack of knowledge or incomplete information (Pedrycz and Gomide 2007). Fuzzy numbers have been applied in many different areas, such as engineering problems (see Ross [2009] for review), decision making problems (see Cabrerizo [2015] for review), and control systems (see Lee [1990] for review).In the construction context fuzzy numbers are used to represent the subjective uncertainties of construction variables, such as in applications in simulation techniques (e.g., fuzzy system dynamics [FSD]). In such applications, fuzzy arithmetic is applied to mathematical equations that include fuzzy numbers by using one of the two approaches introduced in the literature: (1) the α-cuts and interval calculations approach, and (2) the extension principle approach using different t-norms. Hereafter, this paper will refer to the α-cuts and interval calculations approach as “standard fuzzy arithmetic” and to the extension principle approach as “extended fuzzy arithmetic”.

Though the literature contains extensive discussion on the mathematical aspects of the two fuzzy arithmetic implementation approaches (see Dubois and Prade [1978] for review), implementing the two approaches mathematically in different applications is not always possible. The mathematical solution of standard fuzzy arithmetic requires the calculation of inverse function for the input fuzzy numbers, which is computationally complex. Moreover, the mathematical solution of extended fuzzy arithmetic is equivalent to solving a non-linear programming problem, which implies that there is not a universal solution for the extended fuzzy arithmetic problem, regardless of the t-norm used. Therefore, there are computational methods developed in the literature for implementing fuzzy arithmetic using one of the two approaches. The computational methods proposed in the literature are commonly focused on standard fuzzy arithmetic, which will be discussed in detail below due to its simplicity (Hanss 2002, Kechagias and Papadopoulos 2007, Chang and hung 2006). However, the standard fuzzy arithmetic approach is criticized for the overestimation of uncertainty, a phenomenon that reduces the interpretability of the resulting fuzzy numbers (Lin et al. 2011). Consequently, the overestimation of uncertainty in the FSD simulation results reduces the ability of users to accurately predict the actual system output (e.g., actual productivity) based on the simulation results. Moreover, the effect of this phenomenon becomes more significant in FSD technique, when consecutive fuzzy arithmetic operations (i.e., applying a fuzzy arithmetic operation on the result of another fuzzy arithmetic operation) are applied on the mathematical equations of the model. The uncertainty overestimation problem can be reduced by implementing extended fuzzy arithmetic, using any t-norm other than the min t-norm. Extended fuzzy arithmetic using the min t-norm returns the same results as standard fuzzy arithmetic (Kechagias and Papadopoulos 2007, Elbarkouky et al. 2016). Therefore, given that min is the highest t-norm (i.e., returns the highest membership value for the results of fuzzy operations), performing extended fuzzy arithmetic using any t-norm other than min reduces the uncertainty overestimation problem (Lin et al. 2011). However, due to its complexity, the existing computational methods for implementing extended fuzzy arithmetic are limited to the use of min and drastic product t-norms. Additionally, implementing extended fuzzy arithmetic using the drastic product t-norm is also criticized for producing resulting fuzzy numbers that are highly sensitivity to changes to the input fuzzy numbers (Pedrycz and Gomide 2007).

This chapter introduces an original computational method for implementing extended fuzzy arithmetic using product and Lukasiewicz t-norms on triangular fuzzy numbers, which reduces the uncertainty overestimation problem in the resulting fuzzy numbers. Given that product and Lukasiewicz t-norms are continuous, using these t-norms for implementing extended fuzzy arithmetic decreases the sensitivity of the resulting fuzzy numbers to changes to the input fuzzy numbers, as compared to the drastic product t-norm. The computational method proposed in this paper is developed for triangular fuzzy numbers, which are commonly used in a wide range of applications (Pedrycz and Gomide 2007, Pedrycz 1994). Finally, the proposed computational method is mathematically proven and an algorithm is suggested for its implementation.

4.2. Preliminaries

4.2.1. Fuzzy Set Theory and Fuzzy Sets

Fuzzy set theory, introduced by Zadeh (1965), is a powerful method for representing subjective or imprecise information in different contexts. Fuzzy sets are represented by their membership functions, which determine the degree of membership of each point in the universe of discourse in the fuzzy set. The *α*-cut of a fuzzy set, denoted as A_α, is an interval of the real numbers including all the members of the universe of discourse whose membership values are equal to or exceed α where $\alpha \in [0,1]$. Referring to the representation theorem, any fuzzy set can be represented by its *α*-cuts (Pedrycz and Gomide 2007). The mathematical form of the representation theorem is below shown in Eq. 4.1.

$$A(x) = \sup_{\alpha \in [0,1]} \left(\alpha A_\alpha(x)\right) \tag{4.1}$$

where $A(x)$ stands for the fuzzy number and A_α represents the *α*-cut of fuzzy number $A(x)$ at the level of *α*. The representation theorem implies that any fuzzy operation performed on fuzzy sets (e.g., fuzzy arithmetic) can be implemented on their *α*-cuts using the classical operations, the latter of which are applicable to crisp intervals (Pedrycz and Gomide 2007).

4.2.2. Fuzzy Numbers

Fuzzy numbers are a specific type of fuzzy sets with membership functions that have the following properties (Nguyen and Walker 2005): (1) bounded supports, (2) are normal (i.e., possess at least one point in the universe of discourse, which has a membership value of 1), (3) are convex, and (4) have *α*-cuts that are closed (i.e., continuous) intervals of real numbers. There are several types of membership functions that meet the above requirements for fuzzy numbers, such as triangular fuzzy numbers, which are common in engineering applications (Lorterapong and Moselhi 1996, Pedrycz and Gomide 2007). Triangular fuzzy numbers are defined by their piecewise linear segments, as presented in Eq. 4.2.

$$A(x;a_1,a_2,a_3) = \begin{cases} \dfrac{x-a_1}{a_2-a_1}, & if\ a_1 < x \leq a_2 \\ \dfrac{a_3-x}{a_3-a_2}, & if\ a_2 < x \leq a_3, \\ 0, & Otherwise \end{cases} \quad a_1 \leq a_2 \leq a_3 \tag{4.2}$$

where a_1 and a_3 stand for the lower and upper bounds of the support (respectively) and a_2 is the core of fuzzy number (i.e., $A(a_2;a_1,a_2,a_3) = 1$). According to Abebe et al. (2000), the wider support of the fuzzy number implies the higher level of uncertainty that the fuzzy number represents. Fig. 4.1 presents a generic form of a triangular fuzzy number.

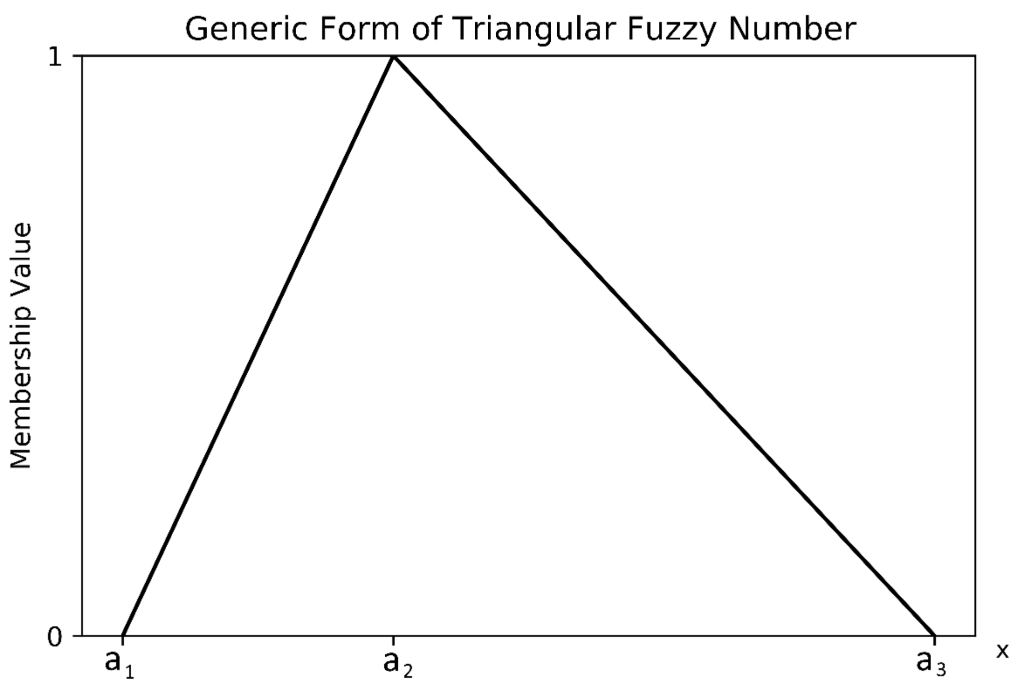

Figure 4.1. Generic form of triangular fuzzy number $\mathbf{A}(\mathbf{x},\mathbf{a_1},\mathbf{a_2},\mathbf{a_3})$

4.2.3. Fuzzy Arithmetic

There are two different approaches for implementing fuzzy arithmetic on fuzzy numbers: (1) the *α*-cuts and interval calculations approach (i.e., standard fuzzy arithmetic), and (2) the extension principle approach (i.e., extended fuzzy arithmetic) using different t-norms. Standard fuzzy arithmetic is implemented through the following steps: (1) the input fuzzy numbers are discretized into a number of α-cuts, (2) interval calculations (as presented in Eq. 4.3) are implemented on the α-cuts of the input fuzzy numbers to find the α-cut of the resulting fuzzy number, and (3) the resulting fuzzy number is constructed as the supremum of its α-cuts, which are the results of step 2. The three steps for implementing fuzzy arithmetic by the α-cuts and interval calculations are presented in Eq. 4.4.

$$\begin{aligned}
&\text{Addition: } [a,b]+[c,d]=[a+c,b+d] \\
&\text{Subtraction: } [a,b]-[c,d]=[a-d,b-c] \\
&\text{Multiplication: } [a,b]\times[c,d]=[\min(ac,ad,bc,bd),\max(ac,ad,bc,bd)] \\
&\text{Division: } \frac{[a,b]}{[c,d]}=\left[\min\left(\frac{a}{c},\frac{a}{d},\frac{b}{c},\frac{b}{d}\right),\max\left(\frac{a}{c},\frac{a}{d},\frac{b}{c},\frac{b}{d}\right)\right], where\ 0\notin[c,d]
\end{aligned} \tag{4.3}$$

$$C(z)=A(x)\circledast B(y)=\sup_{\alpha\in[0,1]}\alpha\big((A_\alpha * B_\alpha)(z)\big) \tag{4.4}$$

where $C(z)$ represents the resulting fuzzy number, $A(x)$ and $B(y)$ represent the input fuzzy numbers, and A_α and B_α represent the α-cuts of the input fuzzy numbers. In addition, $\circledast$ stands for any of the four fuzzy arithmetic operations (i.e., fuzzy addition, fuzzy subtraction, fuzzy multiplication, and fuzzy division), and $*$ stands for any of the four arithmetic operations on crisp intervals (i.e., addition, subtraction, multiplication, and division) presented in Eq. 3. Despite the fact that standard fuzzy arithmetic is used in many different applications, this approach causes overestimation of uncertainties in the resulting fuzzy numbers (Hanss 2002). Moreover, this phenomenon will be intensified by implementing consecutive fuzzy arithmetic operations on fuzzy numbers. Accordingly, in recent applications, extended fuzzy arithmetic has been preferred to standard fuzzy arithmetic (e.g., Lin et al. 2011, Chang et al. 2006). The extended fuzzy arithmetic approach was first introduced by Nguyen (1978) using the min t-norm, as presented in Eq. 4.5.

$$C(z)=A(x)\circledast B(y)=\sup_{z=x*y}\big(\min\big(A(x),B(y)\big)\big) \tag{4.5}$$

where $C(z)$ stands for the resulting fuzzy number, $A(x)$ and $B(y)$ represent the two input fuzzy numbers, $\circledast$ stands for any of the four fuzzy arithmetic operations, and $*$ stands for any of the four arithmetic operations implemented on crisp numbers. In the generalized form of extended fuzzy arithmetic, the min t-norm in Eq.4.5 can be replaced by any t-norm, as presented in Eq. 4.6 (Urbański and Wasowski 2005).

$$C(z) = A(x) \circledast B(y) = \sup_{z=x*y} \Big(t\big(\mathrm{A}(x), B(y)\big)\Big) \tag{4.6}$$

where t represents any t-norm. Thus, the four common t-norms, product, Lukasiewicz, min, and drastic product, can be used to implement extended fuzzy arithmetic in its generalized form. The mathematical representation of the product, Lukasiewicz, min, and drastic product t-norms are presented below in Eq. 4.7, Eq. 4.8, Eq. 4.9, and Eq. 4.10, respectively. The min t-norm is the highest t-norm and drastic product is the lowest t-norm. Additionally, in the literature, the Lukasiewicz t-norm is also referred to as the bounded difference t-norm.

$$t_{product}(x, y) = x \times y \tag{4.7}$$

$$t_{Lukasiewicz}(x, y) = \max(x + y - 1,0) \tag{4.8}$$

$$t_{min}(x, y) = \min(x, y) \tag{4.9}$$

$$t_{drastic\ product}(x, y) = \begin{cases} x, & y = 1 \\ y, & x = 1 \\ 0, & \text{otherwise} \end{cases} \tag{4.10}$$

Implementing extended fuzzy arithmetic using the min t-norm returns the same results as standard fuzzy arithmetic (Kechagias and Papadopoulos 2007, Elbarkouky et al. 2016); consequently, it causes the same level of uncertainty overestimation as standard fuzzy arithmetic. However, using any t-norm other than min for implementing extended fuzzy arithmetic reduces the uncertainty overestimation compared to standard fuzzy arithmetic. Moreover, depending on the strength of the t-norm used for implementing extended fuzzy arithmetic, the level of uncertainty overestimation will be reduced to different levels, as compared to standard fuzzy arithmetic. In other words, the lower the t-norm is, the less overestimation of uncertainty will occur in the resulting fuzzy numbers. Implementing extended fuzzy arithmetic using the lowest t-norm, drastic product, reduces the uncertainty overestimation in the resulting fuzzy numbers to the lowest possible level. However, due to the fact that the drastic product t-norm is not continuous, if it is used for implementing extended fuzzy arithmetic, the resulting fuzzy numbers will be highly sensitive to changes to the input fuzzy numbers (Pedrycz and Gomide 2007). Accordingly, Pedrycz and Gomide (2007) suggest that the drastic product t-norm can be ruled out for fuzzy operations in some applications, such as system modeling, decision making, or optimization problems (refer to Klement and Navara 1999, Jenei 2002, and Jenei 2004 for a full review).

Klement and Navara (1999) introduce an Archimedean t-norm with the following two characteristics: (1) the t-norm is continuous, and (2) the results of the t-norm operation on any x in the range of $(0,1)$ are smaller than the value of x (i.e., $\forall x \in (0,1),\ t(x,x) < x$). Archimedean t-norms are thus appropriate for implementing extended fuzzy arithmetic, as they mitigate the two limitations of implementing extended fuzzy arithmetic using min and drastic product t-norms (i.e., uncertainty overestimation and high sensitivity). Due to the continuity of the Archimedean t-norms, using them for implementing extended fuzzy arithmetic guarantees that the resulting fuzzy numbers are not highly sensitive to changes to the input fuzzy numbers. Moreover, since Archimedean t-norms are lower than the min t-norm, the problem of uncertainty overestimation is guaranteed to be reduced, as compared to standard fuzzy arithmetic. Min and drastic product t-norms cannot be classified as Archimedean t-norms, as the min t-norm does not satisfy the second condition, and the drastic product t-norm does not satisfy the first condition. On the other hand, product and Lukasiewicz t-norms can both be classified as Archimedean t-norms (Klement and Navara 1999). This paper introduces a computational method for implementing extended fuzzy arithmetic, which uses the two common Archimedean t-norms (i.e., product and Lukasiewicz t-norms) to reduce the uncertainty overestimation and sensitivity of the resulting fuzzy numbers to the changes to the input fuzzy numbers.

4.2.4. Computational Methods for Implementation of Fuzzy Arithmetic

As discussed in Section 4.2.3, the mathematical solution of standard fuzzy arithmetic requires that the inverse functions be calculated for the input fuzzy numbers, which is a mathematically complex process (Kechagias and Papadopoulos 2007). Moreover, the exact solution of extended fuzzy arithmetic is equivalent to solving a non-linear programming problem, which implies that there is not a universal solution for the extended fuzzy arithmetic problem, regardless of the t-norm used. Consequently, various computational methods are proposed in the literature to implement fuzzy arithmetic in different applications. For implementing standard fuzzy arithmetic, Dubois and Prade (1980) developed a computational method, which vertically discretizes the input fuzzy numbers (i.e., the supports of the fuzzy numbers) and approximates the membership values for the discrete points of the resulting fuzzy number supports. Dong and Wong (1987) criticized the method proposed by Dubois and Prade (1980) for its low accuracy of approximation when implementing consecutive fuzzy division operations; to remedy this limitation, they proposed a computational method for implementing standard fuzzy arithmetic operations, which horizontally discretizes the fuzzy numbers by creating α-cuts of the input fuzzy numbers. The computational method proposed by Dong and Wong (1987) is a discrete yet exact method, which calculates the exact values of the intervals (i.e., exact method) for a finite number of α-cuts of the resulting fuzzy numbers (i.e., discrete method). Finally, their method uses the representation theorem to construct the resulting fuzzy numbers using their α-cuts.

Due to the uncertainty overestimation issue in standard fuzzy arithmetic, computational methods for implementing extended fuzzy arithmetic have been proposed in the literature. Heshmaty and Kandel (1985) prove that the triangular fuzzy numbers are closed under all extended fuzzy arithmetic operations using drastic product t-norm. In other words, the result of implementing any extended fuzzy arithmetic operation using the drastic product t-norm on two triangular numbers is a triangular number. Thus, the result of implementing an extended fuzzy arithmetic operation using the drastic product t-norm on two triangular fuzzy numbers can be determined by calculating three points of the resulting fuzzy number (i.e., the core, and lower and upper bounds of support). Accordingly, an exact computational method (i.e., a method derived from the mathematical solution) has been developed by Kolesarova (1995), Mesiar (1997), and Hong and Do (1997) for implementing extended fuzzy arithmetic using the drastic product t-norm on triangular fuzzy numbers.

Despite the availability of the computational method, the drastic product t-norm is not appropriate for implementing extended fuzzy arithmetic, since it is not continuous (refer to Section 4.2.3). In contrast, product and Lukasiewicz are two Archimedean t-norms that are appropriate for implementing extended fuzzy arithmetic; however, extended fuzzy arithmetic operations using these two t-norms do not result in triangular fuzzy numbers. Therefore, due to their complexity, there are no available computational methods for implementing extended fuzzy arithmetic using product and Lukasiewicz t-norms. To remedy this gap in the literature, this paper proposes a discrete computational method for implementing extended fuzzy arithmetic on triangular fuzzy numbers using product and Lukasiewicz t-norms. Usually, these computational methods discretize the input fuzzy numbers into a number of discrete points; next, calculations are performed on these points to find the resulting fuzzy number (Dong and Wong 1987). Dong and Wong (1987) explain that discrete methods for implementing extended fuzzy arithmetic are computationally more efficient than using non-linear programing to achieve the exact solution, since unlike the non-linear programing method, the discrete method does not change if the input fuzzy numbers change.

4.3. Computational Method for Extended Fuzzy Arithmetic

This section presents a computational method for implementing extended fuzzy arithmetic using product and Lukasiewicz t-norms. Referring to Eq. 4.6, there are infinite combinations of x and y that produce z if $z = x * y$. The main challenge in developing a computational method for extended fuzzy arithmetic is finding a finite set of (x_f, y_f) values that satisfy the condition presented in Eq. 4.11.

$$\sup_{z=x*y}\Big(t\big(\mathrm{A}(x), B(y)\big)\Big) = \sup_{z=x_f*y_f}\Big(tA\big(x_f\big), B\big(y_f\big)\Big) \tag{4.11}$$

This paper presents finite sets of (x_f, y_f) for implementing extended fuzzy addition and multiplication on triangular fuzzy numbers, using product and Lukasiewicz t-norms. Moreover, where $A \ominus B = A \oplus (-1) \times B$, and $A \oslash B = A \otimes (1)/B$, extended fuzzy subtraction and extended fuzzy division can be implemented using the computational methods presented in this paper. The computational methods presented in this paper are implemented in the following three-step process: firstly, the resulting fuzzy number support is discretized into a finite number of points; secondly, the exact membership value for each point is calculated; and thirdly, the resulting fuzzy number is constructed using the discrete points (determined in the first step) and their membership values (calculated in the second step).

Due to the fact that min is the highest t-norm, regardless of the t-norm implemented, the results of extended fuzzy arithmetic will have a support that is the same length or smaller compared to the results of extended fuzzy arithmetic using the min t-norm (Pedrycz and Gomide 2007). The computational method presented in this paper considers the largest possible support of the extended fuzzy arithmetic results (i.e., results of extended fuzzy arithmetic using the min t-norm); discretizes these results into a finite number of points; and calculates the membership values for each point. Based on the proposal made by Pedrycz and Gomide (2007), this computational method implements fuzzy arithmetic on the increasing and the decreasing parts of the two input fuzzy numbers, and then combines the two parts to develop the resulting fuzzy number.

Consider two generic triangular fuzzy numbers $A(x)$ and $B(y)$, which are presented in Eq. 4.12 and Eq. 4.13 respectively. Section 4.3.1 and Section 4.3.2 present the computational methods for implementing extended fuzzy arithmetic operations on $A(x)$ and $B(y)$ using product and Lukasiewicz t-norms, respectively.

$$A(x) = \begin{cases} \overline{\alpha_a}x + \overline{\beta_a}, & if\ a_1 \le x < a_2 \\ \underline{\alpha_a}x + \underline{\beta_a}, & if\ a_2 \le x \le a_3, \\ 0, & otherwise \end{cases} \qquad \overline{\alpha_a} > 0, \underline{\alpha_a} < 0, a_1 \le a_2 \le a_3 \tag{4.12}$$

$$B(y) = \begin{cases} \overline{\alpha_b}y + \overline{\beta_b}, & if\ b_1 \le y < b_2 \\ \underline{\alpha_b}y + \underline{\beta_b}, & if\ b_2 \le y \le b_3, \\ 0, & otherwise \end{cases} \qquad \overline{\alpha_b} > 0, \underline{\alpha_b} < 0, b_1 \le b_2 \le b_3 \tag{4.13}$$

4.3.1. Computational Method: Extended fuzzy arithmetic using product t-norm

4.3.1.1. Extended fuzzy addition using product t-norm

The mathematical form of extended fuzzy addition using the product t-norm is presented in Eq. 4.14.

$$C(z) = A(x) \oplus B(y) = \sup_{z=x+y} \left(\mathrm{A}(x) \times B(y)\right) \tag{4.14}$$

Membership values for discrete points in the increasing part of the resulting fuzzy number support are calculated using the following method. For each constant value of $z = c$, there is a function $f_c(x)$ that determines all the possible values of $\mathrm{A}(x) \times B(y)$, such that $c = x + y, and\ c \in [a_1 + b_1, a_2 + b_2]$. Therefore, the maximum point of $f_c(x)$ is the membership value of the resulting fuzzy number at point $z = c$. Fig. 4.2(a) and Fig. 4.2(b) present the two input fuzzy numbers, while Fig. 4.2(c) presents function $f_c(x)$, which is mathematically defined in Eq. 4.15.

$$\begin{aligned} f_c(x) = A(x) \times B(y) = A(x) \times B(c-x) &= \left(x\, \overline{\alpha_a} + \overline{\beta_a}\right)\left(\overline{\alpha_b}(c-x) + \overline{\beta_b}\right) \\ &= (\overline{\alpha_a}\, \overline{\alpha_b})(cx - x^2) + x\left(\overline{\alpha_a}\overline{\beta_b}\right) + \left(\overline{\beta_a}\overline{\alpha_b}\right)(c-x) + \left(\overline{\beta_a}\, \overline{\beta_b}\right) \end{aligned} \tag{4.15}$$

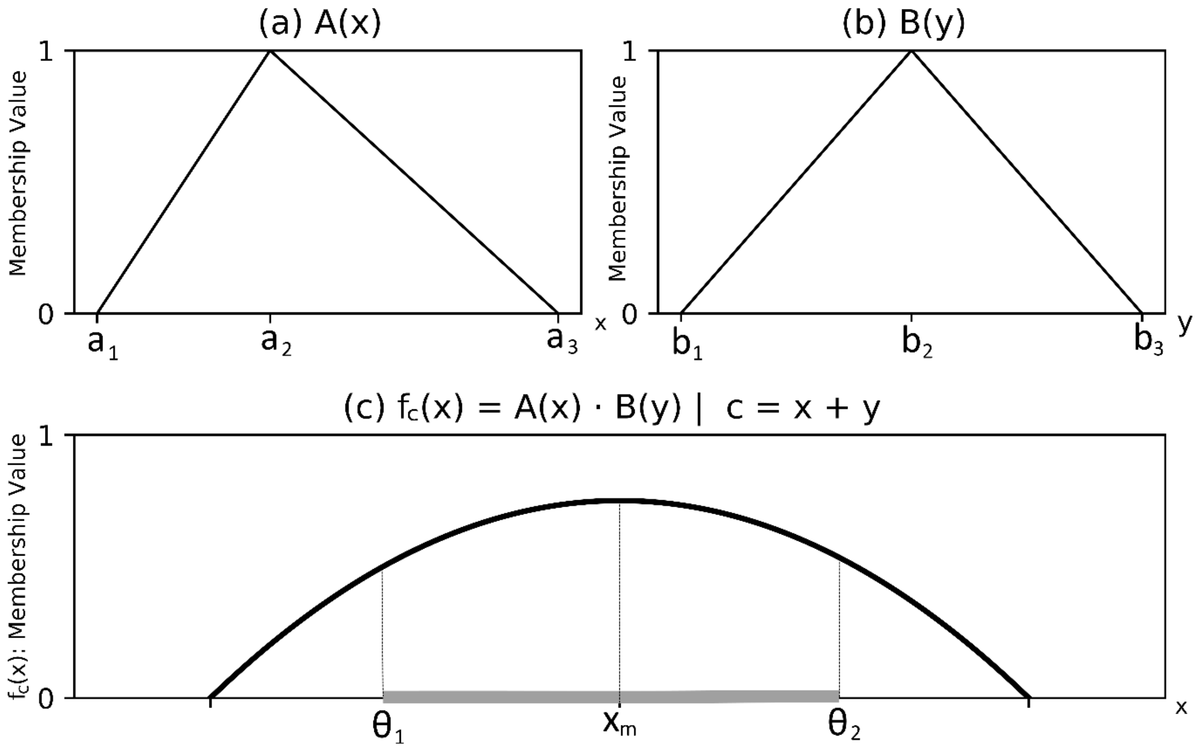

Figure 4.2. Extended fuzzy addition using product t-norm

Fig. 4.2(c) shows that function $f_c(x)$ has an extremum point that is calculated using its first derivative, as shown in Eq. 4.16.

$$\frac{\partial f_c(x)}{\partial x} = (\overline{\alpha_a}\,\overline{\alpha_b})(c - 2x) + \left(\overline{\alpha_a}\overline{\beta_b}\right) - \left(\overline{\beta_a}\overline{\alpha_b}\right)$$

$$\frac{\partial f_c(x)}{\partial x} = 0 \Rightarrow \; x_m = \frac{c}{2} - \frac{\overline{\beta_a}\overline{\alpha_b} - \overline{\alpha_a}\overline{\beta_b}}{2 \times \overline{\alpha_a}\,\overline{\alpha_b}}$$

$$\frac{\partial^2 f_c(x)}{\partial x^2} = -2\overline{\alpha_a}\,\overline{\alpha_b} \begin{cases} \overline{\alpha_a} > 0 \\ \overline{\alpha_b} > 0 \end{cases} \Longrightarrow \; \frac{\partial^2 f_c(x_m)}{\partial x^2} < 0$$

$$\Rightarrow f_c(x = x_m) \text{ is always maximum point of } f_c(x)$$

$$x_m = \frac{c}{2} - \frac{\overline{\beta_a}\overline{\alpha_b} - \overline{\alpha_a}\overline{\beta_b}}{2\overline{\alpha_a}\,\overline{\alpha_b}}, \qquad y_m = c - x_m = \frac{c}{2} + \frac{\overline{\beta_a}\overline{\alpha_b} - \overline{\alpha_a}\overline{\beta_b}}{2\overline{\alpha_a}\,\overline{\alpha_b}} \tag{4.16}$$

For each constant value of $z = c$, the domain of the function $f_c(x)$ is calculated as the intersection of the two boundary conditions of the input fuzzy numbers, as shown in Eq. 4.17.

$$\begin{cases} 1)\ a_1 \leq x \leq a_2 \\ 2)\ b_1 \leq y \leq b_2 \Rightarrow b_1 \leq c - x \leq b_2 \Rightarrow c - b_2 \leq x \leq c - b_1 \\ 3)\ a_1 + b_1 \leq c \leq a_2 + b_2 \end{cases}$$
$$\Rightarrow \underbrace{\max(a_1, c - b_2)}_{\theta_1} \leq x \leq \underbrace{\min(a_2, c - b_1)}_{\theta_2} \tag{4.17}$$

Therefore, membership values for discrete points in the increasing part of the resulting fuzzy number support are calculated using one of the three cases presented in Eq. 4.18 to Eq. 4.20.

$$Case\ 1: if\ \theta_1 \leq x_m \leq \theta_2 : C(c) = \sup_{z=x+y} \big(A(x) \times B(y)\big) = A(x_m) \times B(y_m) \tag{4.18}$$

$$Case\ 2: if\ \theta_2 < x_m : \frac{\partial f_c(x < x_m)}{\partial x} > 0 \Rightarrow f_c(x < x_m) \text{ is increasing}$$
$$C(c) = \sup_{z=x+y} \big(A(x) \times B(y)\big) = A(\theta_2) \times B(c - \theta_2) \tag{4.19}$$

$$Case\ 3: if\ x_m < \theta_1 : \frac{\partial f_c(x > x_m)}{\partial x} < 0 \Rightarrow f_c(x > x_m) \text{ is decreasing}$$
$$C(c) = \sup_{z=x+y} \big(A(x) \times B(y)\big) = A(\theta_1) \times B(c - \theta_1) \tag{4.20}$$

Similarly, the maximum point of function $f_c(x)$ for each constant value of $z = c$ in the decreasing part of the resulting fuzzy number support is calculated using Eq. 4.21.

$$x_m = \frac{c}{2} - \frac{\underline{\beta_a}\,\underline{\alpha_b} - \underline{\alpha_a}\,\underline{\beta_b}}{2\underline{\alpha_a}\,\underline{\alpha_b}}, \qquad y_m = c - x_m = \frac{c}{2} + \frac{\underline{\beta_a}\,\underline{\alpha_b} - \underline{\alpha_a}\,\underline{\beta_b}}{2\underline{\alpha_a}\,\underline{\alpha_b}} \tag{4.21}$$

$$\frac{\partial^2 f_c(x)}{\partial x^2} = -2\underline{\alpha_a}\,\underline{\alpha_b}\begin{cases}\underline{\alpha_a} < 0\\ \underline{\alpha_a} < 0\end{cases} \Longrightarrow \frac{\partial^2 f_c(x_m)}{\partial x^2} < 0$$

$$\Rightarrow f_c(x = x_m)\text{is always maximum point of } f_c(x)$$

For each constant value of $z = c$, the domain of the function $f_c(x)$ is calculated as the intersection of the two boundary conditions of the input fuzzy numbers, as shown in Eq. 4.22.

$$\begin{cases}1)\ a_2 \le x \le a_3\\ 2)\ b_2 \le y \le b_3 \Longrightarrow b_2 \le c - x \le b_3 \Longrightarrow c - b_3 \le x \le c - b_2\\ 3)\ a_2 + b_2 \le c \le a_3 + b_3\end{cases}$$
$$\Longrightarrow \underbrace{\max(a_2, c - b_3)}_{\theta_3} \le x \le \underbrace{\min(a_3, c - b_2)}_{\theta_4} \qquad (4.22)$$

Therefore, membership values for discrete points in the decreasing part of the resulting fuzzy number support are calculated using one of the three cases presented in Eq. 4.23 to Eq. 4.25.

$$Case\ 1{:}\ if\ \theta_3 \le x_m \le \theta_4 : C(c) = \sup_{z=x+y}\big(A(x) \times B(y)\big) = A(x_m) \times B(y_m) \qquad (4.23)$$

$$Case\ 2{:}\ if\ \theta_4 < x_m{:}\ C(c) = \sup_{z=x+y}\big(A(x) \times B(y)\big) = A(\theta_4) \times B(c - \theta_4) \qquad (4.24)$$

$$Case\ 3{:}\ if\ x_m < \theta_3\ :\ C(c) = \sup_{z=x+y}\big(A(x) \times B(y)\big) = A(\theta_3) \times B(c - \theta_3) \qquad (4.25)$$

4.3.1.2. Extended fuzzy multiplication using product t-norm

The mathematical form of extended fuzzy multiplication using the product t-norm is presented in Eq. 4.26. For any two triangular fuzzy numbers of $A(x)$ and $B(x)$ with positive supports (i.e., $a_1 > 0\ and\ b_1 > 0$), extended fuzzy multiplication using the product t-norm can be implemented using the following method:

$$C(z) = A(x) \otimes B(y) = \sup_{z=x\times y} \left(A(x) \times B(y)\right) \tag{4.26}$$

The membership values for the discrete points in the increasing part of the resulting fuzzy number support are calculated using the following method. For each constant value of $z = c$, there is a function $f_c(x)$ that determines all the possible values of $A(x) \times B(y)$, such that $c = x \times y, and\ c \in [a_1 b_1, a_2 b_2]$. Therefore, the maximum point of $f_c(x)$ is the membership value of the resulting fuzzy number at point c. Fig. 4.3(a) and Fig. 4.3(b) present the two input fuzzy numbers, while Fig. 4.3(c) presents function $f_c(x)$, which is mathematically defined in Eq. 4.27.

$$\begin{aligned} f_c(x) = A(x) \times B(y) = A(x) \times B\left(\frac{c}{x}\right) = \left(\overline{\alpha_a}\, x + \overline{\beta_a}\right)\left(\overline{\alpha_b}\left(\frac{c}{x}\right) + \overline{\beta_b}\right) \\ = (\overline{\alpha_a}\, \overline{\alpha_b})c + \left(\overline{\alpha_a}\, \overline{\beta_b}\right)x + \left(\overline{\beta_a}\, \overline{\alpha_b}\right)\left(\frac{c}{x}\right) + \left(\overline{\beta_a}\, \overline{\beta_b}\right), x \neq 0 \end{aligned} \tag{4.27}$$

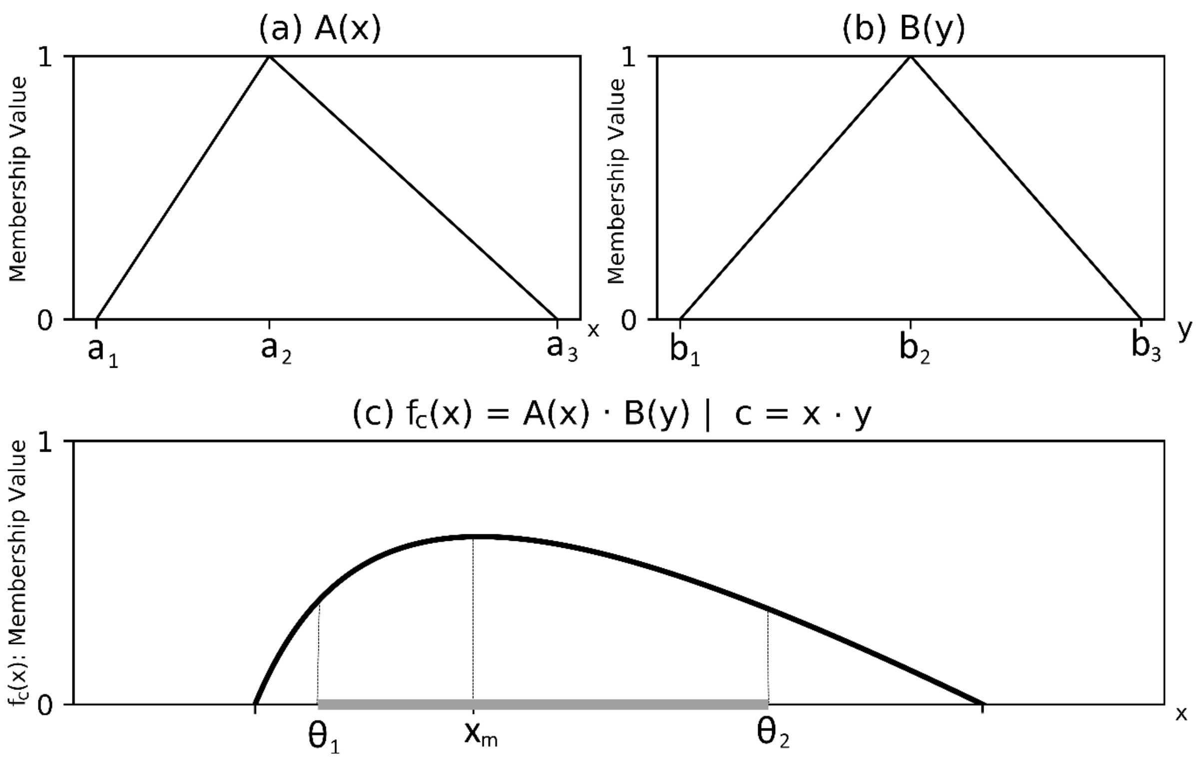

Figure 4.3. Extended fuzzy multiplication using product t-norm

Fig. 4.3(c) shows that function $f_c(x)$ has an extremum point that is calculated using its first derivative, as shown below:

$$\frac{\partial f_c(x)}{\partial x} = \left(\overline{\alpha_a}\,\overline{\beta_b}\right) - \frac{\left(\overline{\beta_a}\,\overline{\alpha_b}\right)c}{x^2}$$

$$\frac{\partial f_c(x)}{\partial x} = 0 \xrightarrow{yields} x = \pm\sqrt{\frac{\overline{\beta_a}\,\overline{\alpha_b}}{\overline{\alpha_a}\,\overline{\beta_b}} \times c}\,, \quad \begin{cases} \overline{\alpha_a} > 0 \\ \overline{\alpha_b} > 0 \\ c > 0 \\ \overline{\beta_a} < 0 \\ \overline{\beta_b} < 0 \end{cases} \Rightarrow \frac{\overline{\beta_a}\,\overline{\alpha_b}}{\overline{\alpha_a}\,\overline{\beta_b}} \times c > 0$$

Thus, function $f_c(x)$ has two extremum points, one of which is always located on the negative side of the universe of discourse, and the other one is always located on the positive side. However, the extremum point that is on the negative side of the universe of discourse is not included in the domain of the function if supports of the two input fuzzy numbers are positive. For each constant value of $z = c$, the domain of the function $f_c(x)$ is calculated as the intersection of the two boundary conditions of the input fuzzy numbers, as shown in Eq. 4.28.

$$\begin{cases} 1)\ a_1 \le x \le a_2 \\ 2)\ b_1 \le y \le b_2 \Rightarrow b_1 \le \frac{c}{x} \le b_2 \Rightarrow \frac{c}{b_2} \le x \le \frac{c}{b_1} \\ 3)\ a_1 b_1 \le c \le a_2 b_2 \end{cases}$$
$$\Rightarrow \underbrace{\max\left(a_1, \frac{c}{b_2}\right)}_{\theta_1} \le x \le \underbrace{\min\left(a_2, \frac{c}{b_1}\right)}_{\theta_2} \qquad (4.28)$$

$$\begin{cases} 0 < \theta_1 \\ -\sqrt{\frac{\overline{\beta_a}\,\overline{\alpha_b}}{\overline{\alpha_a}\,\overline{\beta_b}} \times c} < 0 \end{cases} \Rightarrow -\sqrt{\frac{\overline{\beta_a}\,\overline{\alpha_b}}{\overline{\alpha_a}\,\overline{\beta_b}} \times c} < \theta_1 \Rightarrow -\sqrt{\frac{\overline{\beta_a}\,\overline{\alpha_b}}{\overline{\alpha_a}\,\overline{\beta_b}} \times c} \notin [\theta_1, \theta_2] \Rightarrow$$

$$x_m = \left(\sqrt{\frac{\overline{\beta_a}\,\overline{\alpha_b}}{\overline{\alpha_a}\,\overline{\beta_b}}\, c}\right) \text{ is the only possible extremum point for function } f_c(x) \text{in its domain}$$

Thus, function $f_c(x)$ has only one extremum point that may be included in its domain (presented in Eq. 4.29). The extremum point of function $f_c(x)$ is always a maximum point, as illustrated below (refer to Fig. 4.3(c)).

$$\frac{\partial^2 f_c(x)}{\partial x^2} = 2 \times \frac{(\overline{\beta_a}\,\overline{\alpha_b})c}{x^3}, \begin{cases} \overline{\alpha_b} > 0 \\ c > 0 \\ \overline{\beta_a} < 0 \\ x^3 > 0 \end{cases} \Rightarrow \frac{\partial^2 f_c(x)}{\partial x^2} < 0$$

$$\Rightarrow f_c(x = x_m) \text{ is always maximum point of } f_c(x)$$

$$x_m = \sqrt{\frac{\overline{\beta_a}\,\overline{\alpha_b}}{\overline{\alpha_a}\,\overline{\beta_b}} \times c}, \qquad y_m = \frac{c}{x_m} = \sqrt{\frac{\overline{\alpha_a}\,\overline{\beta_b}}{\overline{\beta_a}\,\overline{\alpha_b}} \times c} \tag{4.29}$$

Therefore, membership values for discrete points in the increasing part of the resulting fuzzy number support are calculated using one of the three cases presented in Eq. 4.30 to Eq. 4.32.

$$Case\ 1{:}\ if\ \theta_1 \le x_m \le \theta_2{:}\ C(c) = \sup_{z=x\times y}\left(\mathrm{A}(x) \times B(y)\right) = A(x_m) \times B(y_m) \tag{4.30}$$

$$Case\ 2{:}\ if\ \theta_2 < x_m{:}\ \frac{\partial f_c(x < x_m)}{\partial x} > 0 \Rightarrow\ f(x < x_m) \text{ is increasing}$$

$$C(c) = \sup_{z=x\times y}\left(\mathrm{A}(x) \times B(y)\right) = A(\theta_2) \times B\left(\frac{c}{\theta_2}\right) \tag{4.31}$$

$$Case\ 3{:}\ if\ x_m < \theta_1\ {:}\ \frac{\partial f_c(x > x_m)}{\partial x} < 0 \Rightarrow f(x > x_m) \text{ is decreasing}$$

$$C(c) = \sup_{z=x\times y}\left(\mathrm{A}(x) \times B(y)\right) = A(\theta_1) \times B\left(\frac{c}{\theta_1}\right) \tag{4.32}$$

Similarly, the maximum point of function $f_c(x)$ for each constant value of $z = c$ in the decreasing part of the resulting fuzzy number support is calculated using Eq. 4.33.

$$\frac{\partial f_c(x)}{\partial x} = 0 \Rightarrow\ x = \pm\sqrt{\frac{\underline{\beta_a}\,\underline{\alpha_b}}{\underline{\alpha_a}\,\underline{\beta_b}} \times c} \Rightarrow\ x_m = \sqrt{\frac{\underline{\beta_a}\,\underline{\alpha_b}}{\underline{\alpha_a}\,\underline{\beta_b}} \times c}$$

$$\frac{\partial^2 f_c(x)}{\partial x^2} = 2 \times \frac{\left(\underline{\beta_a}\,\underline{\alpha_b}\right) c}{x^3}, \begin{cases} \underline{\alpha_b} < 0 \\ c > 0 \\ \underline{\beta_a} > 0 \\ x^3 > 0 \end{cases} \Rightarrow \frac{\partial^2 f_c(x)}{\partial x^2} < 0$$

$$\Rightarrow f_c(x = x_m) \text{ is always maximum point of function } f_c(x)$$

$$x_m = \sqrt{\frac{\underline{\beta_a}\,\underline{\alpha_b}}{\underline{\alpha_a}\,\underline{\beta_b}} \times c}, \qquad y_m = \frac{c}{x} = \sqrt{\frac{\underline{\alpha_a}\,\underline{\beta_b}}{\underline{\beta_a}\,\underline{\alpha_b}} \times c} \tag{4.33}$$

The domain of the function $f_c(x)$ for each constant value of $z = c$ is calculated as the intersection of the two boundary conditions of the input fuzzy numbers, as shown in Eq. 4.34.

$$\begin{cases} 1)\ a_2 \le x \le a_3 \\ 2)\ b_2 \le y \le b_3 \Rightarrow b_2 \le \frac{c}{x} \le b_3 \Rightarrow \frac{c}{b_3} \le x \le \frac{c}{b_2} \\ 3)\ a_2 b_2 \le c \le a_3 b_3 \end{cases}$$
$$\Rightarrow \underbrace{\max\left(\mathrm{a}_2, \frac{c}{b_3}\right)}_{\theta_3} \le x \le \underbrace{\min\left(a_3, \frac{c}{b_2}\right)}_{\theta_4} \tag{4.34}$$

Therefore, membership values for discrete points in the decreasing part of the resulting fuzzy number support are calculated using one of the three cases presented in Eq. 4.35 to Eq. 4.37.

$$Case\ 1: if\ \theta_3 \le x_m \le \theta_4 : C(c) = \sup_{z=x\times y} \left(\mathrm{A}(x) \times B(y)\right) = A(x_m) \times B(y_m) \tag{4.35}$$

$$Case\ 2: if\ \theta_4 < x_m : C(c) = \sup_{z=x\times y} \left(\mathrm{A}(x) \times B(y)\right) = A(\theta_4) \times B\left(\frac{c}{\theta_4}\right) \tag{4.36}$$

$$Case\ 3: if\ x_m < \theta_3 :\ C(c) = \sup_{z=x\times y} \left(\mathrm{A}(x) \times B(y)\right) = A(\theta_3) \times B\left(\frac{c}{\theta_3}\right) \tag{4.37}$$

If the two input fuzzy numbers (i.e., $A(x)$ and $B(x)$) have negative supports (i.e., $a_3 < 0\ and\ b_3 < 0$), then there exists an $A'(x) = -1 \otimes A(x)$ and a $B'(x) = -1 \otimes B(y)$ where $A'(x)$ and $B'(y)$ are two triangular fuzzy numbers with positive supports (i.e., ${a'}_1 > 0$ and ${b'}_1 > 0$). Due to the associativity and commutativity of extended fuzzy multiplication (Dubois and Prade 1980, Pedrycz and Gomide 2007), the resulting fuzzy number can be computed using $A'(x)$ and $B'(y)$ through the method presented in this section; where

$$A(x) \otimes B(y) = \left(-1 \otimes A'(x)\right) \otimes \left(-1 \otimes B'(y)\right) = \left((-1) \otimes (-1)\right) \otimes \left(A'(x) \otimes B'(y)\right)$$
$$= A'(x) \otimes B'(y)$$

Moreover, if one of the two input triangular fuzzy numbers has a negative support, and the other one has a positive support (i.e., $a_3 < 0\ and\ b_1 > 0$), then there exists some $A'(x) = -1 \otimes A(x)$ such that $A'(x)$ is a triangular fuzzy number that has a positive support (i.e., ${a'}_3 < 0$). Due to the associativity of extended fuzzy multiplication (Dubois and Prade 1980), the resulting fuzzy number can be computed using $A'(x)$ and $B(y)$ through the method presented in this section, where:

$$A(x) \otimes B(y) = \left((-1) \otimes A'(x)\right) \otimes B(y) = (-1) \otimes \left(A'(x) \otimes B(y)\right)$$

4.3.2. Computational Method: Extended fuzzy arithmetic using Lukasiewicz t-norm

4.3.2.1. Extended fuzzy addition using Lukasiewicz t-norm

The mathematical form of extended fuzzy addition using the Lukasiewicz t-norm is presented in Eq. 4.38.

$$\begin{aligned} C(z) = A(x) \oplus B(y) &= \sup_{z=x+y} \left(A(x) t (B(y))\right) \\ &= \sup_{z=x+y} \left(\max(A(x) + B(y) - 1, 0)\right) \end{aligned} \tag{4.38}$$

Membership values for discrete points in the increasing part of the resulting fuzzy number support are calculated using the following method. For each constant value of $z = c$, there is a function $f_c(x)$ that determines all the possible values of $A(x) + B(y) - 1$, such that $c = x + y, and\ c \in [a_1 + b_1, a_2 + b_2]$. Therefore, the maximum point of $f_c(x)$ is the membership value of the resulting fuzzy number at point c. Fig. 4.4(a) and Fig. 4.4(b) present the two input fuzzy numbers, while Fig. 4.4(c) presents function $f_c(x)$, which is mathematically defined in Eq. 4.39:

$$\begin{aligned} f_c(x) = A(x) + B(y) - 1 &= A(x) + B(c - x) - 1 \\ &= \left(\overline{\alpha_a}\, x + \overline{\beta_a}\right) + \left(\overline{\alpha_b}\, (c - x) + \overline{\beta_b}\right) - 1 \end{aligned} \tag{4.39}$$

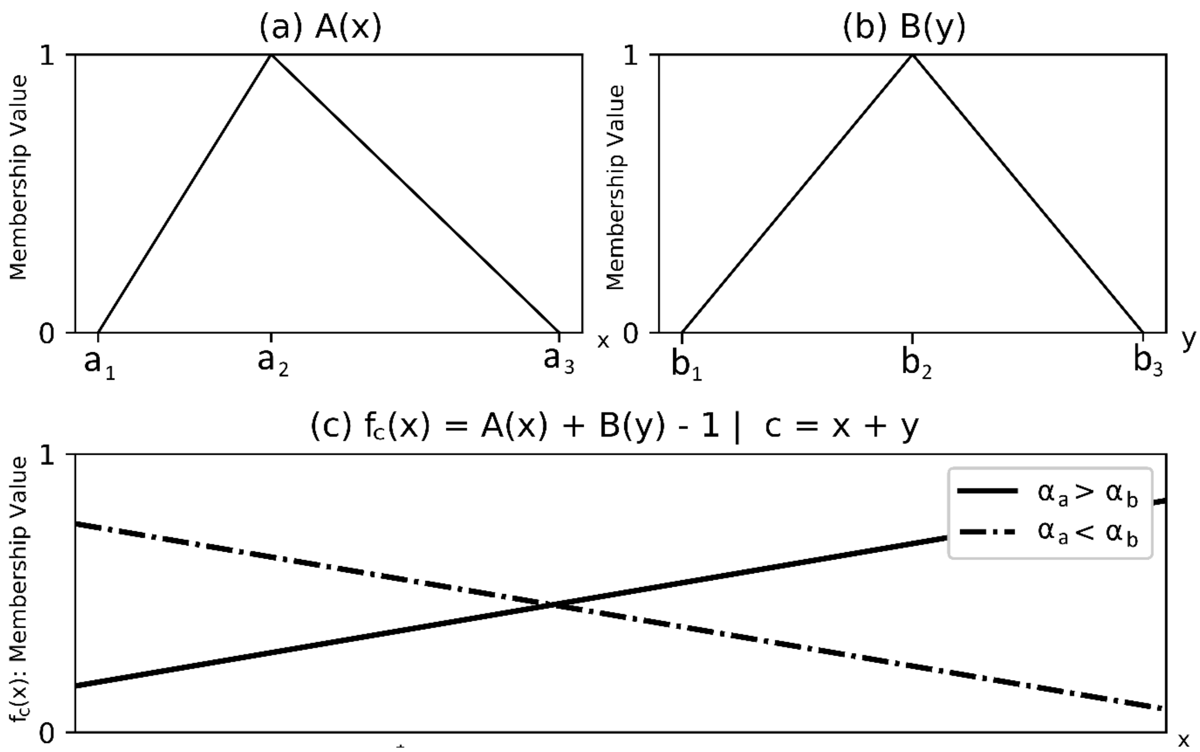

Figure 4.4. Extended fuzzy addition using Lukasiewicz t-norm

For each constant value of $z = c$, the domain of the function $f_c(x)$ is calculated as the intersection of the two boundary conditions of the input fuzzy numbers, as shown in Eq. 4.40.

$$\begin{cases} 1)\ a_1 \le x \le a_2 \\ 2)\ b_1 \le y \le b_2 \Rightarrow b_1 \le c - x \le b_2 \Rightarrow c - b_2 \le x \le c - b_1 \\ 3)\ a_1 + b_1 \le c \le a_2 + b_2 \end{cases} \tag{4.40}$$

$$\Rightarrow \underbrace{\max(a_1, c - b_2)}_{\theta_1} \leq x \leq \underbrace{\min(a_2, c - b_1)}_{\theta_2}$$

$$\frac{\partial f_c(x)}{\partial x} = \overline{\alpha_a} - \overline{\alpha_b}$$

As shown in Fig. 4.4(c), function $f_c(x)$ is either increasing or decreasing depending on the values of $\overline{\alpha_a}$ and $\overline{\alpha_b}$, as described below. Therefore, the maximum point for function $f_c(x)$ occurs in one of the two boundary points of its domain. Accordingly, membership values for the discrete points in the increasing part of the resulting fuzzy number support are calculated using one of the three cases presented in Eq. 4.41 to Eq. 4.43.

$$\begin{aligned} &Case\ 1{:}\ if\ \ \overline{\alpha_a} > \overline{\alpha_b} \Rightarrow f_c(x) \text{ is increasing} \Rightarrow \\ &\qquad C(c) = sup(max(A(x) + B(y) - 1{,}0)) \\ &\qquad\qquad = \max(A(\theta_2) + B(c - \theta_2) - 1{,}0) \end{aligned} \tag{4.41}$$

$$\begin{aligned} &Case\ 2{:}\ if\ \ \overline{\alpha_a} < \overline{\alpha_b} \Rightarrow f_c(x) \text{ is decreasing} \Rightarrow \\ &\qquad C(c) = sup(max(A(x) + B(y) - 1{,}0)) \\ &\qquad\qquad = \max(A(\theta_1) + B(c - \theta_1) - 1{,}0) \end{aligned} \tag{4.42}$$

$$\begin{aligned} &Case\ 3{:}\ if\ \ \overline{\alpha_a} = \overline{\alpha_b} \Rightarrow f_c(x) \text{ is constant} \Rightarrow C(c) \\ &\qquad = sup(max(A(x) + B(y) - 1{,}0)) \\ &\qquad C(c) = \max(A(\theta_2) + B(c - \theta_2) - 1{,}0) \\ &\qquad\qquad = \max(A(\theta_1) + B(c - \theta_1) - 1{,}0) \end{aligned} \tag{4.43}$$

Similarly, the membership values for the discrete points in the decreasing part of the resulting fuzzy number support are calculated using the following method:

$$\frac{\partial f_c(x)}{\partial x} = \underline{\alpha_a} - \underline{\alpha_b}$$

For each constant value of $z = c$ the domain of the function $f_c(x)$ is calculated using the two boundary conditions of the input fuzzy numbers, as shown Eq. 4.44.

$$\begin{cases} 1)\ a_2 \le x \le a_3 \\ 2)\ b_2 \le y \le b_3 \Rightarrow b_2 \le c - x \le b_3 \Rightarrow c - b_3 \le x \le c - b_2 \\ 3)\ a_2 + b_2 \le c \le a_3 + b_3 \end{cases}$$

$$\Rightarrow \underbrace{\max(a_2, c - b_3)}_{\theta_3} \le x \le \underbrace{\min(a_3, c - b_2)}_{\theta_4} \quad (4.44)$$

Therefore, membership values for the discrete points in the decreasing part of the resulting fuzzy number support in are calculated using one of the three cases presented in Eq. 4.45 to Eq. 4.47.

$$Case\ 1{:}\ if\ \ \underline{\alpha_a} > \underline{\alpha_b} \Rightarrow f_c(x) \text{ is increasing} \Rightarrow$$

$$\begin{aligned} C(c) &= \sup(\max(A(x) + B(y) - 1{,}0)) \\ &= \max(A(\theta_4) + B(c - \theta_4) - 1{,}0) \end{aligned} \quad (4.45)$$

$$Case\ 2{:}\ if\ \ \underline{\alpha_a} < \underline{\alpha_b} \Rightarrow f_c(x) \text{ is decreasing} \Rightarrow$$

$$\begin{aligned} C(c) &= \sup(\max(A(x) + B(y) - 1{,}0)) \\ &= \max(A(\theta_3) + B(c - \theta_3) - 1{,}0) \end{aligned} \quad (4.46)$$

$$Case\ 3{:}\ if\ \ \underline{\alpha_a} = \underline{\alpha_b} \Rightarrow f_c(x) \text{ is constant} \Rightarrow C(c)$$

$$= \sup(\max(A(x) + B(y) - 1{,}0))$$

$$\begin{aligned} C(c) &= \max(A(\theta_4) + B(c - \theta_4) - 1{,}0) \\ &= \max(A(\theta_3) + B(c - \theta_3) - 1{,}0) \end{aligned} \quad (4.47)$$

Discussion

The mathematical proof presented in this section shows that implementing extended fuzzy addition using the Lukasiewicz t-norm on triangular fuzzy numbers returns the same results as the drastic product t-norm. The mathematical form of extended fuzzy addition using the drastic product t-norm is presented in Eq. 4.48.

$$C(z) = A(x) \oplus B(y) = \sup_{z=x+y} (A(x) t_d B(y)) \tag{4.48}$$

Membership values for the discrete points in the increasing part of the resulting fuzzy number support are calculated using the following method. For each constant value of $z = c$, there is a function $g_c(x)$ that determines all the possible values of $\left(A(x) t_d B(y)\right)$, such that $c = x + y, and\ c \in [a_1 + b_1, a_2 + b_2]$ and t_d stands for the drastic product t-norm. Therefore, the maximum point for function $g_c(x)$ occurs in one of the two boundary points of its domain. Function $g_c(x)$ is mathematically defined in Eq. 4.49.

$$g_c(x) = \begin{cases} A(c - b_2), & if\ a_1 \le c - b_2 \\ B(c - a_2), & if\ b_1 \le c - a_2 \\ 0, & Otherwise \end{cases} \Rightarrow C(c) = \sup_{z=x+y} \left(\mathrm{A}(x) t B(y)\right) = \max\left(g_c(x)\right) \tag{4.49}$$

For the Lukasiewicz t-norm, there is a function $h_c(x)$ that determines a finite number of values of $\left(A(x) t_L B(y)\right)$ at the point $c = x + y, and\ c \in [a_1 + b_1, a_2 + b_2]$, where t_L stands for the Lukasiewicz t-norm. The maximum value determined by function $h_c(x)$ is the membership value for of the resulting fuzzy number at point c. Function $h_c(x)$ is mathematically defined in Eq. 4.50.

$$h_c(x) = \begin{cases} \max(A(\theta_2) + B(c - \theta_2) - 1{,}0), & \theta_2 = \min(a_2, c - b_1) \\ \max(A(\theta_1) + B(c - \theta_1) - 1{,}0), & \theta_1 = \max(a_1, c - b_2) \\ 0, & Otherwise \end{cases} \tag{4.50}$$

Now, let us assume that $\theta_2 = \min(a_2, c - b_1) = c - b_1$; then;

$$\begin{aligned} \max(A(\theta_2) + B(c - \theta_2) - 1{,}0) &= \max(A(c - b_1) + B(b_1) - 1{,}0) \\ &= \max(A(c - b_1) + 0 - 1{,}0) = 0 \end{aligned}$$

Similarly, if $\theta_1 = \max(a_1, c - b_2) = a_1$, then, $\max(A(\theta_1) + B(c - \theta_1) - 1{,}0) = 0$. Now, let us assume that $\theta_2 = \min(a_2, c - b_1) = a_2$; then,

$$\begin{aligned} \max(A(\theta_2) + B(c - \theta_2) - 1{,}0) &= \max(A(a_2) + B(c - a_2) - 1{,}0) \\ &= \max(1 + B(c - a_2) - 1{,}0) = B(c - a_2) \end{aligned}$$

Similarly, if $\theta_1 = \max(a_1, c - b_2) = c - b_2$, then, $\max(A(\theta_1) + B(c - \theta_1) - 1{,}0) = A(c - b_2)$. Therefore, function $h_c(x)$ can be written (as presented below), and the maximum point for function $h_c(x)$ can be calculated as follows:

$$h_c(x) = \begin{cases} A(c - b_2), & if\ a_1 \le c - b_2 \\ B(c - a_2), & if\ b_1 \le c - a_2 \\ 0, & Otherwise \end{cases} \Rightarrow C(c) = \sup_{z=x+y} \big(\mathrm{A}(x)tB(y)\big)$$

$$= \sup(max(A(c - b_2), 0), max(B(c - a_2), 0), 0)$$

Thus, for any point in the universe of discourse, if the fuzzy number resulting from extended fuzzy addition has a membership value greater than zero, its membership value is equal for both Lukasiewicz and drastic product t-norms. Similarly, membership values for the decreasing part of the fuzzy number resulting from extended fuzzy addition are equal for Lukasiewicz and drastic product t-norms.

4.3.2.2. Extended fuzzy multiplication using Lukasiewicz t-norm

The mathematical form of extended fuzzy multiplication using Lukasiewicz t-norm is presented in Eq. 4.51. For any two triangular fuzzy numbers of $A(x)$ and $B(x)$ with positive supports (i.e., $a_1 > 0\ and\ b_1 > 0$) extended fuzzy multiplication using the Lukasiewicz t-norm can be implemented using the following method:

$$C(z) = A(x) \otimes B(y) = \sup_{z=x\times y} \big(\mathrm{A}(x)tB(y)\big) = \sup_{z=x\times y} (\max(A(x) + B(y) - 1{,}0)) \quad (4.51)$$

The membership values for discrete points in the increasing part of the resulting fuzzy number support are calculated using the following method. For each constant value of $z = c$, there is a function $f_c(x)$ that determines all the possible values of $\mathrm{A}(x) + B(y) - 1$, such that $c = x \times y, and\ c \in [a_1 b_1, a_2 b_2]$. Therefore, the maximum point of $f_c(x)$ is the membership value for of the resulting fuzzy number at point c. Fig. 5(a) and Fig. 5(b) present the two input fuzzy numbers, while Fig. 5(c) presents function $f_c(x)$, which is mathematically defined in Eq. 4.52.

$$f_c(x) = A(x) + B(y) - 1 = A(x) + B\left(\frac{c}{x}\right) - 1$$
$$= \left(\overline{\alpha_a}x + \overline{\beta_a}\right) + \left(\overline{\alpha_b}\left(\frac{c}{x}\right) + \overline{\beta_b}\right) - 1 \quad (4.52)$$

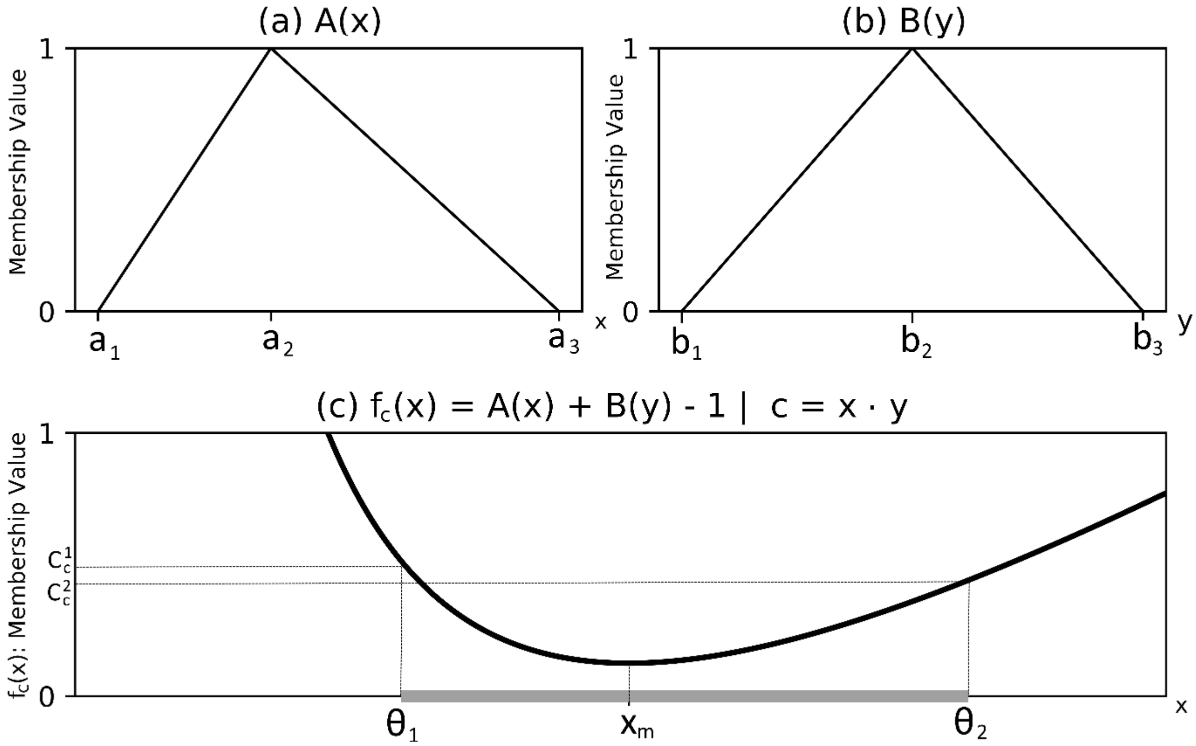

Figure 4.5. Extended fuzzy multiplication using Lukasiewicz t-norm (increasing part)

Fig. 4.5(c) shows that function $f_c(x)$ has an extremum point that is calculated using its first derivative, as shown below:

$$\frac{\partial f_c(x)}{\partial x} = \overline{\alpha_a} - \frac{\overline{\alpha_b}c}{x^2}$$

$$\frac{\partial f_c(x)}{\partial x} = 0 \Longrightarrow x = \pm\sqrt{\frac{\overline{\alpha_b}\,c}{\overline{\alpha_a}}}, \begin{cases} \overline{\alpha_b} > 0 \\ \overline{\alpha_a} > 0 \\ c > 0 \end{cases} \Longrightarrow \frac{\overline{\alpha_b}\,c}{\overline{\alpha_a}} > 0$$

Function $f_c(x)$ has two extremum points, one of which is always located on the negative side of the universe of discourse, while the other one is always located on the positive side. However, the extremum point that is on the negative side of the universe of discourse is not included in the domain of the function if the supports of the two input fuzzy numbers are positive. For each constant value of $z = c$, the domain of the function $f_c(x)$ is calculated as the intersection of the two boundary conditions of the input fuzzy numbers, as shown in Eq. 4.53.

$$\begin{cases} 1)\ a_1 \le x \le a_2 \\ 2)\ b_1 \le y \le b_2 \Rightarrow b_1 \le \dfrac{c}{x} \le b_2 \Rightarrow \dfrac{c}{b_2} \le x \le \dfrac{c}{b_1} \\ 3)\ a_1 b_1 \le c \le a_2 b_2 \end{cases}$$

$$\Rightarrow \underbrace{\max\left(a_1, \frac{c}{b_2}\right)}_{\theta_1} \le x \le \underbrace{\min\left(a_2, \frac{c}{b_1}\right)}_{\theta_2} \tag{4.53}$$

$$\begin{cases} 0 < \theta_1 \\ -\sqrt{\dfrac{\overline{\alpha_b}\ c}{\overline{\alpha_a}}} < 0 \end{cases} \Rightarrow -\sqrt{\frac{\overline{\alpha_b}\ c}{\overline{\alpha_a}}} < \theta_1 \Rightarrow -\sqrt{\frac{\overline{\alpha_b}\ c}{\overline{\alpha_a}}} \notin [\theta_1, \theta_2] \Rightarrow$$

$$x_m = \left(\sqrt{\frac{\overline{\alpha_b}\ c}{\overline{\alpha_a}}}\right) \text{ is the only possible extremum point for function } f(x) \text{ in its domain}$$

Function $f_c(x)$ has only one extremum point that may be included in its domain (presented in Eq. 4.54). The extremum point of function $f_c(x)$ is always a minimum point, as proven below (refer to Fig. 4.5(c)).

$$\frac{\partial^2 f_c(x)}{\partial x^2} = 2 \times \frac{\overline{\alpha_b}\ c}{x^3}, \begin{cases} \overline{\alpha_b} > 0 \\ c > 0 \\ x^3 > 0 \end{cases} \Rightarrow \frac{\partial^2 f_c(x)}{\partial x^2} > 0$$

$$\Rightarrow f_c(x = x_m) \text{ is always minimum point of function } f_c(x)$$

$$x_m = \sqrt{\frac{\overline{\alpha_b}\ c}{\overline{\alpha_a}}}, \qquad y_m = \frac{c}{x_m} = \sqrt{\frac{\overline{\alpha_a}\ c}{\overline{\alpha_b}}} \tag{4.54}$$

Therefore, membership values for discrete points in the increasing part of the resulting fuzzy number support are calculated using one of the three cases presented in Eq. 4.55 to Eq. 4.57.

$$Case\ 1: if\ \theta_1 \leq x_m \leq \theta_2 \Rightarrow \begin{cases} \dfrac{\partial f_c(x < x_m)}{\partial x} < 0\ f_c(x < x_m) is\ decreasing \\ \dfrac{\partial f_c(x > x_m)}{\partial x} < 0\ f_c(x > x_m) is\ increasing \end{cases}$$

$$\begin{cases} C_c^1 = \max\left(A(\theta_1) + B\left(\dfrac{c}{\theta_1}\right) - 1{,}0\right) \\ C_c^2 = \max\left(A(\theta_2) + B\left(\dfrac{c}{\theta_2}\right) - 1{,}0\right) \end{cases} \tag{4.55}$$

$$\Rightarrow C(c) = \sup_{z=x\times y} \big(A(x)tB(y)\big) = \max(C_c^1, C_c^2)$$

$$Case\ 2: if\ \theta_2 < x_m: \frac{\partial f_c(x < x_m)}{\partial x} < 0 \Rightarrow f_c(x < x_m) \text{ is decreasing}$$

$$C(c) = \sup_{z=x\times y} \big(A(x)tB(y)\big) = \max\left(A(\theta_1) + B\left(\frac{c}{\theta_1}\right) - 1{,}0\right) \tag{4.56}$$

$$Case\ 3: if\ x_m < \theta_1: \frac{\partial f_c(x > x_m)}{\partial x} > 0 \Rightarrow f_c(x > x_m) \text{ is increasing}$$

$$C(c) = \sup_{z=x\times y} \big(A(x)tB(y)\big) = \max\left(A(\theta_2) + B\left(\frac{c}{\theta_2}\right) - 1{,}0\right) \tag{4.57}$$

The membership values for the discrete points in the decreasing part of the resulting fuzzy number support are calculated using the following method. For each constant value of $z = c$, there is a function $f_c(x)$ that determines all the possible values of $A(x) + B(y) - 1$, such that $c = x \times y, and\ c \in [a_2 b_2, a_3 b_3]$. Therefore, the maximum point of $f_c(x)$ is the membership value of the resulting fuzzy number at point c. Fig. 4.6(a) and Fig. 4.6(b) present the two input fuzzy numbers, while Fig. 4.6(c) presents function $f_c(x)$, which is mathematically defined in Eq. 4.58:

$$
\begin{aligned}
f_c(x) &= A(x) + B(y) - 1 = A(x) + B\left(\frac{c}{x}\right) - 1 \\
&= \left(\underline{\alpha_a}\, x + \underline{\beta_a}\right) + \left(\underline{\alpha_b}\left(\frac{c}{x}\right) + \underline{\beta_b}\right) - 1
\end{aligned}
\tag{4.58}
$$

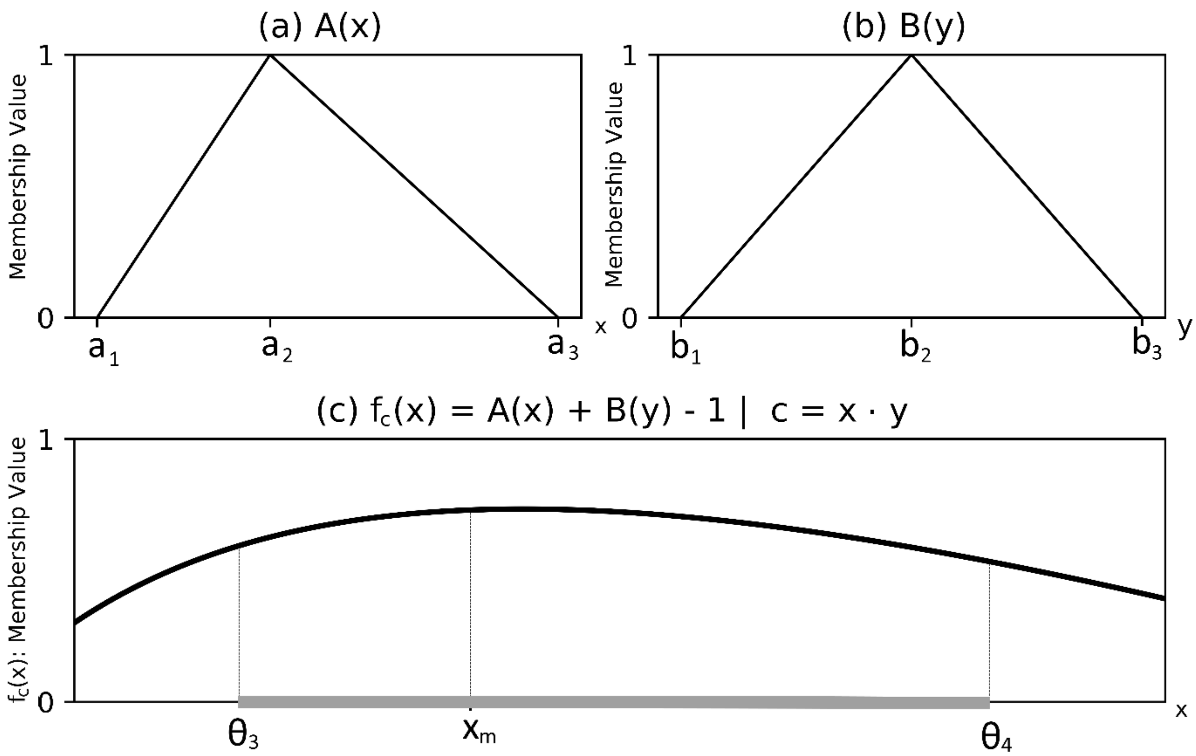

Figure 4.6. Extended fuzzy multiplication using Lukasiewicz t-norm (decreasing part)

Fig. 4.6(c) shows that function $f_c(x)$ has an extremum point that is calculated using its first derivative, as shown below:

$$
\frac{\partial f_c(x)}{\partial x} = \underline{\alpha_a} - \frac{\underline{\alpha_b}\, c}{x^2}
$$

$$
\frac{\partial f_c(x)}{\partial x} = 0 \Longrightarrow x = \pm\sqrt{\frac{\underline{\alpha_b}\, c}{\underline{\alpha_a}}}, \begin{cases} \underline{\alpha_b} < 0 \\ \underline{\alpha_a} < 0 \\ c > 0 \end{cases} \Longrightarrow \frac{\overline{\alpha_b}\, c}{\overline{\alpha_a}} > 0
$$

Function $f_c(x)$ has two extremum points, one of which is always located on the negative side of the universe of discourse, while the other is always located on the positive side. However, the extremum point that is on the negative side of the universe of discourse is not included in the domain of the function if the supports of the two input fuzzy numbers are positive. For each constant value of $z = c$, the domain of the function $f_c(x)$ is calculated as the intersection of the two boundary conditions of the input fuzzy numbers, as shown in Eq. 4.59.

$$\begin{cases} 1)\ a_2 \le x \le a_3 \\ 2)\ b_2 \le y \le b_3 \Rightarrow b_2 \le \dfrac{c}{x} \le b_3 \Rightarrow \dfrac{c}{b_3} \le x \le \dfrac{c}{b_3} \\ 3)\ a_2 b_2 \le c \le a_3 b_3 \end{cases}$$

$$\Rightarrow \underbrace{\max\left(\mathrm{a}_2, \frac{c}{b_3}\right)}_{\theta_3} \le x \le \underbrace{\min\left(a_3, \frac{c}{b_2}\right)}_{\theta_4} \tag{4.59}$$

$$\begin{cases} 0 < a_2 \\ -\sqrt{\dfrac{\underline{\alpha_b}\ c}{\underline{\alpha_a}}} < 0 \end{cases} \Rightarrow -\sqrt{\frac{\underline{\alpha_b}\ c}{\underline{\alpha_a}}} < a_2 \Rightarrow -\sqrt{\frac{\underline{\alpha_b}\ c}{\underline{\alpha_a}}} \notin [a_2, a_3] \Rightarrow$$

$$x_m = \left(\sqrt{\frac{\underline{\alpha_b}\ c}{\underline{\alpha_a}}}\right) \text{ is the only possible extremum point of function } f_c(x) \text{ in its domain}$$

Thus, function $f_c(x)$ has only one extremum point that may be included in its domain (presented in Eq. 4.60). The extremum point of function $f_c(x)$ is always a maximum point, as proven below (refer to Fig. 4.6(c)):

$$\frac{\partial^2 f_c(x)}{\partial x^2} = 2 \times \frac{\underline{\alpha_b}\ c}{x^3}, \begin{cases} \underline{\alpha_b} < 0 \\ c > 0 \\ x^3 > 0 \end{cases} \Rightarrow \frac{\partial^2 f_c(x)}{\partial x^2} < 0$$

$$\Rightarrow f_c(x = x_m) \text{ is always maximum point of function } f_c(x)$$

$$x_m = \sqrt{\frac{\underline{\alpha_b}\ c}{\underline{\alpha_a}}}, \qquad y_m = \frac{c}{x_m} = \sqrt{\frac{\underline{\alpha_a}\ c}{\underline{\alpha_b}}} \tag{4.60}$$

Therefore, membership values for discrete points in the increasing part of the resulting fuzzy number support are calculated using one of the three cases presented in Eq. 4.61 to Eq. 4.63.

$$Case\ 1: if\ \theta_3 \leq x_m \leq \theta_4$$
$$\Rightarrow C(c) = \sup_{z=x\times y} \big(\mathrm{A}(x)tB(y)\big) = \max(A(x_m) + B(y_m) - 1{,}0) \quad (4.61)$$

$$Case\ 2: if\ \theta_4 < x_m: \ \frac{\partial f_c(x < x_m)}{\partial x} > 0 \Rightarrow\ f_c(x < x_m) \text{ is increasing}$$
$$C(c) = \sup_{z=x\times y} \big(\mathrm{A}(x)tB(y)\big) = \max\left(A(\theta_4) + B\left(\frac{c}{\theta_4}\right) - 1{,}0\right) \quad (4.62)$$

$$Case\ 3: if\ \ x_m < \theta_3\ \Rightarrow \frac{\partial f_c(x > x_m)}{\partial x} < 0 \Rightarrow\ f_c(x < x_m) \text{ is decreasing}$$
$$C(c) = \sup_{z=x\times y} \big(\mathrm{A}(x)tB(y)\big) = \max\left(A(\ \theta_3) + B\left(\frac{c}{\theta_3}\right) - 1{,}0\right) \quad (4.63)$$

If the two input fuzzy numbers, $A(x)$ and $B(x)$, have negative supports (i.e., $a_3 < 0 \text{ and } b_3 < 0$), then there exists an $A'(x) = -1 \otimes A(x)$ and a $B'(x) = -1 \otimes B(y)$, where $A'(x)$ and $B'(y)$ are two triangular fuzzy numbers with positive supports (i.e., $a'_1 > 0\ and\ b'_1 > 0$). Due to the associativity and commutativity of extended fuzzy multiplication (Dubois and Prade 1980, Pedrycz and Gomide 2007), the resulting fuzzy number can be computed using $A'(x)$ and $B'(y)$ through the method presented in this section; where

$$A(x) \otimes B(y) = \big(-1 \otimes A'(x)\big) \otimes \big(-1 \otimes B'(y)\big) = \big((-1) \otimes (-1)\big) \otimes \big(A'(x) \otimes B'(y)\big)$$
$$= A'(x) \otimes B'(y)$$

If one of the two input triangular fuzzy numbers has a negative support and the other one has positive support (i.e., $a_3 < 0 \text{ and } b_1 > 0$), then there exists some $A'(x) = -1 \otimes A(x)$, such that $A'(x)$ is a triangular fuzzy number that has a positive support (i.e., $a'_3 < 0$). Therefore, due to the associativity of extended fuzzy multiplication (Dubois and Prade 1980), the resulting fuzzy number can be computed using $A'(x)$ and $B(y)$ through the method presented in this section; where

$$A(x)\otimes B(y) = \left((-1)\otimes A'(x)\right)\otimes B(y) = (-1)\otimes\left(A'(x)\otimes B(y)\right)$$

Discussion

The mathematical proof presented in this section shows that for the increasing part of the resulting fuzzy number, implementing extended fuzzy multiplication using the Lukasiewicz t-norm on triangular fuzzy numbers returns the same results as implementing extended fuzzy multiplication using the drastic product t-norm. The mathematical form of extended fuzzy multiplication using the drastic product t-norm is presented in Eq. 4.64:

$$C(z) = A(x)\otimes B(y) = \sup_{z=x\times y}\left(A(x)t_d B(y)\right) \tag{4.64}$$

Membership values for discrete points in the increasing part of the resulting fuzzy number support are calculated using the following method. For each constant value of $z = c$, there is a function $g_c(x)$ that determines all the possible values of $\left(A(x)t_d B(y)\right)$, such that $c = x \times y, and\ c \in [a_1b_1, a_2b_2]$ and t_d stands for the drastic product t-norm. Therefore, the maximum point for function $g_c(x)$ occurs in one of the two boundary points of its domain. Function $g_c(x)$ is mathematically defined in Eq. 4.65.

$$g_c(x) = \begin{cases} A\left(\frac{c}{b_2}\right), & if\ a_1 \le \frac{c}{b_2} \\ B\left(\frac{c}{a_2}\right), & if\ b_1 \le \frac{c}{a_2} \\ 0, & Otherwise \end{cases} \Longrightarrow C(c) = \sup_{z=x\times y}\left(\mathrm{A}(x)tB(y)\right) = \max\left(g_c(x)\right) \tag{4.65}$$

For the Lukasiewicz t-norm, there is a function $h_c(x)$ that determines a finite number of values of $\left(A(x)t_L B(y)\right)$ at point $c = x \times y, and\ c \in [a_1b_1, a_2b_2]$, where t_L stands for Lukasiewicz t-norm. The maximum value determined by function $h_c(x)$ is the membership value for of the resulting fuzzy number at point c. Function $h_c(x)$ is mathematically defined in Eq. 4.66

$$h_c(x) = \begin{cases} \max\left(A(\theta_2) + B\left(\frac{c}{\theta_2}\right) - 1{,}0\right), & \theta_2 = \min\left(a_2, \frac{c}{b_1}\right) \\ \max\left(A(\theta_1) + B\left(\frac{c}{\theta_1}\right) - 1{,}0\right), & \theta_1 = \max\left(a_1, \frac{c}{b_2}\right) \\ 0, & Otherwise \end{cases} \tag{4.66}$$

Let us assume that $\theta_2 = \min\left(a_2, \frac{c}{b_1}\right) = \frac{c}{b_1}$; then,

$$\max\left(A(\theta_2) + B\left(\frac{c}{\theta_2}\right) - 1{,}0\right) = \max\left(A\left(\frac{c}{b_1}\right) + B(b_1) - 1{,}0\right) = \max\left(A\left(\frac{c}{b_1}\right) + 0 - 1{,}0\right) = 0$$

Similarly, if $\theta_1 = \max\left(a_1, \frac{c}{b_2}\right) = a_1$, then; $\max\left(A(\theta_1) + B\left(\frac{c}{\theta_1}\right) - 1{,}0\right) = 0.$

Let us assume that $\theta_2 = \min\left(a_2, \frac{c}{b_1}\right) = a_2$; then,

$$\max\left(A(\theta_2) + B\left(\frac{c}{\theta_2}\right) - 1{,}0\right) = \max\left(A(a_2) + B\left(\frac{c}{a_2}\right) - 1{,}0\right) = \max\left(1 + B\left(\frac{c}{a_2}\right) - 1{,}0\right)$$
$$= B\left(\frac{c}{a_2}\right)$$

Similarly, if $\theta_1 = \max\left(a_1, \frac{c}{b_2}\right) = \frac{c}{b_2}$, then, $\max\left(A(\theta_1) + B\left(\frac{c}{\theta_1}\right) - 1{,}0\right) = A\left(\frac{c}{b_2}\right)$

Therefore, function $h_c(x)$ can be written (as presented below), and the maximum point for function $h_c(x)$ can be calculated as follows:

$$h_c(x) = \begin{cases} A\left(\frac{c}{b_2}\right), & if\ a_1 \le \frac{c}{b_2} \\ B\left(\frac{c}{a_2}\right), & if\ b_1 \le \frac{c}{a_2} \\ 0, & Otherwise \end{cases} \Rightarrow C(c) = \sup_{z=x+y}\left(\mathrm{A}(x)tB(y)\right)$$
$$= \sup\left(\max\left(A\left(\frac{c}{b_2}\right), 0\right), \max\left(B\left(\frac{c}{a_2}\right), 0\right), 0\right)$$

Thus, if any point in the increasing part of the resulting fuzzy number support has a membership value greater than zero, its membership value is equal for both Lukasiewicz and drastic product t-norms. However, the membership values in the decreasing parts of the resulting fuzzy numbers are not necessarily equal for Lukasiewicz and drastic product t-norms. Finally, if one of the two input triangular fuzzy numbers has a negative support and the other one has positive support, it can be proven that the decreasing parts of the fuzzy numbers resulting from extended fuzzy multiplication using Lukasiewicz and drastic product t-norms overlap.

4.4. Programming Algorithm and Numerical Examples

This section presents the programming algorithms for the computational methods presented in Section 4.3, as well as numerical examples of extended fuzzy arithmetic implemented on triangular fuzzy numbers. The numerical examples use the computational methods proposed in section 4.3 to illustrate the results of implementing extended fuzzy addition and multiplication using product and Lukasiewicz t-norms on triangular fuzzy numbers. Moreover, extended fuzzy arithmetic using the min t-norm is performed using the computational method proposed by Klir (1997), while a computational method proposed by Lin et al. (2011) is used to implement extended fuzzy arithmetic using the drastic product t-norm.

4.4.1. Programming Algorithm for Extended Fuzzy Arithmetic

The algorithm for implementing extended fuzzy addition and fuzzy multiplication on triangular fuzzy numbers using the product t-norm is presented below in Fig. 4.7.

```
Input:Fuzzy Number A(a1,a2,a3) , Fuzzy Number B(b1,b2,b3)
Output: Fuzzy Number C([z_values],[membership_values])
    for c in [z_values]:
        if (a1+b1)<= c <= (a2+b2):
            xm=...; ym=...
            tmin=...; tmax=...
            select case:
                case 1: tmin<= xm <=tmax:
                        membership_value[i]=...
                case 2: tmax< xm:
                        membership_value[i]=...
                case 3: xm< tmin:
                        membership_value[i]=...
            end select
        else if (a2+b2)<= c <= (a3+b3):
            xm=...; ym=...
            tmin=...; tmax=...
            select case:
                case 1: tmin<= xm <=tmax:
                        membership_value[i]=...
                case 2: tmax< xm:
                        membership_value[i]=...
                case 3: xm< tmin:
                        membership_value[i]=...
            end select
        end if
   end for
```

Figure 4.7. Programming algorithm for extended fuzzy addition and multiplication using product t-norm

The algorithm presented in Fig. 4.7 calculates the exact membership values for a finite number of points in the resulting fuzzy number support. The membership values, extremum points, and domain of $f_c(x)$ (shown in Fig. 4.7) are calculated using the equations presented in Section 4.3.1.1 (extended fuzzy addition) and Section 4.3.1.2 (extended fuzzy multiplication).

In addition, the programming algorithms for implementing extended fuzzy addition and multiplication on triangular fuzzy numbers using the Lukasiewicz t-norm are presented in Fig. 4.8 and Fig. 4.9 respectively.

```
Input:Fuzzy Number A(a1,a2,a3) , Fuzzy Number B(b1,b2,b3)
Output: Fuzzy Number C([z_values],[membership_values])
    for c in [z_values]:
        if (a1+b1)<= c <= (a2+b2):
            select case:
                case 1: alpha_a1 > alpha_b1
                        membership_value[i]=...
                case 2: alpha_a1 < alpha_b1
                        membership_value[i]=...
                case 3: alpha_a1 = alpha_b1
                        membership_value[i]=...
            end select
        else if (a2+b2)<= c <= (a3+b3):
            select case:
                case 1: alpha_a2 > alpha_b2
                        membership_value[i]=...
                case 2: alpha_a2 < alpha_b2
                        membership_value[i]=...
                case 3: alpha_a2 = alpha_b2
                        membership_value[i]=...
            end select
        end if
   end for
```

Figure 4.8. Programming algorithm for extended fuzzy addition using Lukasiewicz t-norm

```
Input:Fuzzy Number A(a1,a2,a3) , Fuzzy Number B(b1,b2,b3)
Output: Fuzzy Number C([z_values],[membership_values])
    for c in [z_values]:
        xm=...; ym=...
        tmin=...; tmax=...
        if (a1.b1)<= c <= (a2.b2):
            xm=...; ym=...

                select case:
                    case 1: tmin<= xm <=tmax:
                            temp1=...
                            temp2=...
                            membership_value[i]=max(temp1,temp2)
                    case 2: tmax< xm:
                            membership_value[i]=...
                    case 3: xm< tmin:
                            membership_value[i]=...
                end select
        else if (a2.b2)<= c <= (a3.b3):
            xm=...; ym=...
            tmin=...; tmax=...
                select case:
                    case 1: tmin<= xm <=tmax:
                            membership_value[i]=...
                    case 2: tmax< xm:
                            membership_value[i]=...
                    case 3: xm< tmin:
                            membership_value[i]=...
                end select
        end if
   end for
```

Figure 4.9. Programming algorithm for extended fuzzy multiplication using Lukasiewicz t-norm

The programming algorithms presented in Fig. 4.8 and Fig. 4.9 calculate the exact membership values for a finite number of points in the resulting fuzzy number support. The membership values, extremum points, and domain of $f_c(x)$ function, as shown in Fig. 4.8 and Fig. 4.9, are calculated using the equations presented in Section 4.3.2.1 (extended fuzzy addition) and Section 4.3.2.2 (extended fuzzy multiplication).

4.4.2. Numerical Examples of Extended Fuzzy Arithmetic Operations

This section presents numerical examples for implementing extended fuzzy arithmetic on triangular fuzzy numbers.

Example 1: Consider two triangular fuzzy numbers $A(x)$ and $B(y)$ that both have positive supports. The mathematical forms of the two fuzzy numbers are presented in Eq. 4.67 and Eq. 4.68 respectively. Fig. 4.10(a) and Fig. 4.10(b) show the graphical representations of $A(x)$ and $B(y)$ respectively.

$$A(x) = \begin{cases} \frac{1}{3}x - \frac{1}{3}, & if\ 1 \leq x < 4 \\ -\frac{1}{5}x + \frac{9}{5}, & if\ 4 \leq x \leq 9 \\ 0, & otherwise \end{cases} \tag{4.67}$$

$$B(y) = \begin{cases} y - 5, & if\ 5 \leq y < 6 \\ -\frac{1}{7}y + \frac{13}{7}, & if\ 6 \leq y \leq 13 \\ 0, & otherwise \end{cases} \tag{4.68}$$

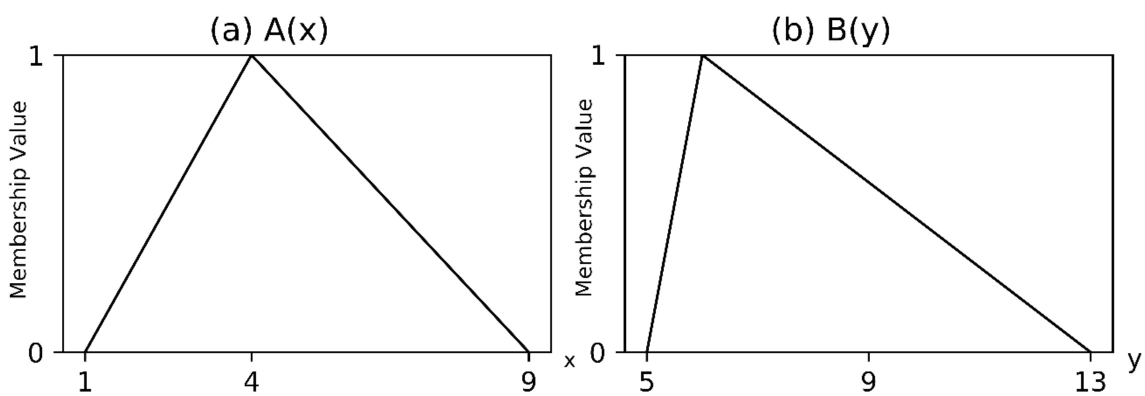

Figure 4.10. Triangular input fuzzy numbers $\boldsymbol{A(x, 1, 4, 9)}$ and $\boldsymbol{B(y, 5, 6, 13)}$

To perform extended fuzzy addition using the product t-norm on the two fuzzy numbers, the membership values for 10 points of the resulting fuzzy number support are calculated. Table 4.1 presents the 10 points, the membership value for each point, and the values of x, y, $A(x)$, and $B(y)$.

Table 4.1. Extended fuzzy addition results for $\boldsymbol{A(x)} \oplus \boldsymbol{B(y)}$ using product t-norm

$\boldsymbol{c = x + y}$	$\boldsymbol{x}$	$\boldsymbol{A(x)}$	$\boldsymbol{y}$	$\boldsymbol{B(y)}$	**Membership Value** $\boldsymbol{C(c) = A(x) \times B(y)}$
6.00	1.00	0.00	5.00	0.00	0.00
7.78	1.89	0.30	5.89	0.89	0.26
9.56	3.56	0.85	6.00	1.00	0.85
11.33	4.00	1.00	7.33	0.81	0.81
13.11	4.56	0.89	8.56	0.63	0.56
14.89	5.44	0.71	9.44	0.51	0.36
16.67	6.33	0.53	10.33	0.38	0.20
18.44	7.22	0.36	11.22	0.25	0.09
20.22	8.11	0.18	12.11	0.13	0.02
22.00	9.00	0.00	13.00	0.00	0.00

Similarly, membership values for 10 points of the resulting fuzzy number support are calculated in order to implement extended fuzzy addition using the Lukasiewicz t-norm. Table 4.2 presents the 10 points, the membership value for each point, and values of x, y, $A(x)$, and $B(y)$. Fig. 4.11 presents the results of implementing extended fuzzy addition using the four most common t-norms (i.e., product, Lukasiewicz, min, and drastic product t-norms) on the two triangular fuzzy numbers.

Table 4.2. Extended fuzzy addition results for $\boldsymbol{A(x)} \oplus \boldsymbol{B(y)}$using Lukasiewicz t-norm

$\boldsymbol{c = x + y}$	$\boldsymbol{x}$	$\boldsymbol{A(x)}$	$\boldsymbol{y}$	$\boldsymbol{B(y)}$	**Membership Value** $\boldsymbol{C(c) = max(A(x) + B(y) - 1, 0)}$
6.00	1.00	0.00	5.00	0.00	0.00
7.23	1.23	0.08	6.00	1.00	0.08
8.46	2.46	0.49	6.00	1.00	0.49
9.69	3.69	0.90	6.00	1.00	0.90
10.92	4.00	1.00	6.92	0.87	0.87
12.15	4.00	1.00	8.15	0.69	0.69
13.38	4.00	1.00	9.38	0.52	0.52
14.62	4.00	1.00	10.62	0.34	0.34
15.85	4.00	1.00	11.85	0.16	0.16
17.00	4.00	1.00	13.00	0.00	0.00

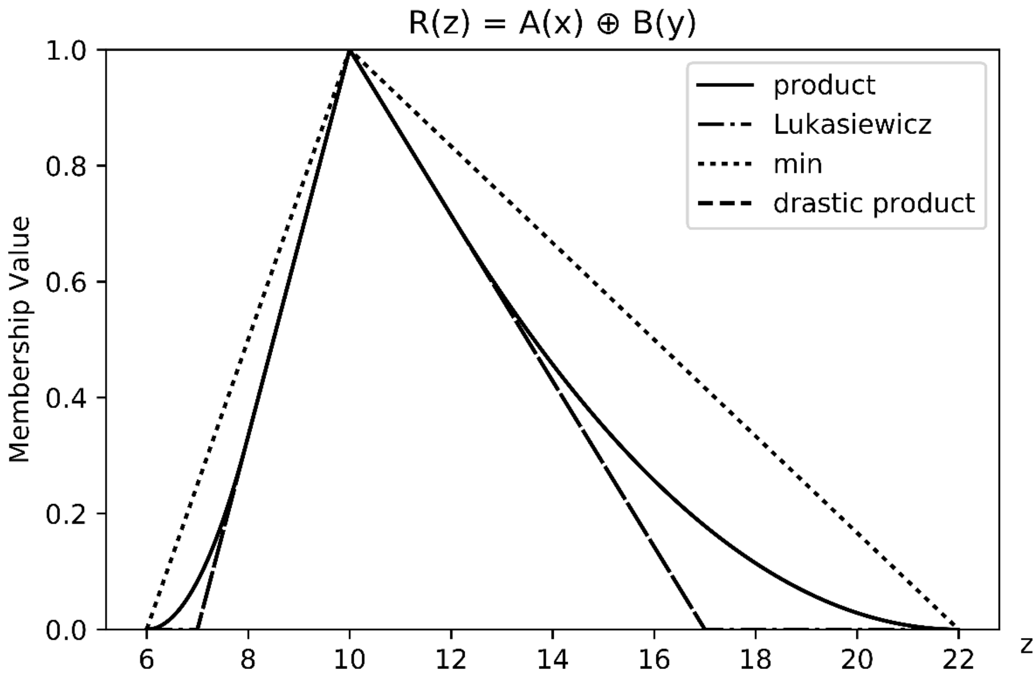

Figure 4.11. Extended fuzzy addition $\boldsymbol{A}(\boldsymbol{x}) \oplus \boldsymbol{B}(\boldsymbol{y})$ using different t-norms

The min t-norm is the highest t-norm, which implies that the resulting fuzzy number has the largest membership value for each point of the support if extended fuzzy addition is implemented using the min t-norm (refer to Fig. 4.11). Conversely, the drastic product t-norm is the lowest t-norm, thus the resulting fuzzy number has the smallest membership value for each point of the support if extended fuzzy addition is implemented using the drastic product t-norm. Finally, as presented in Fig. 4.11, the fuzzy numbers resulting from the implementation of extended fuzzy addition using the Lukasiewicz and drastic product t-norms are overlapping for all points of the support.

In order to implement extended fuzzy multiplication using the product t-norm on the two fuzzy numbers, the membership values for 10 points of the resulting fuzzy number support are calculated. Table 4.3 presents the 10 points, the membership value for each point, and values of x, y, $A(x)$, and $B(y)$.

Table 4.3. Extended fuzzy multiplication results for $\boldsymbol{A(x)} \otimes \boldsymbol{B(y)}$ using product t-norm

$\boldsymbol{c = x \times y}$	$\boldsymbol{x}$	$\boldsymbol{A(x)}$	$\boldsymbol{y}$	$\boldsymbol{B(y)}$	**Membership Value** $\boldsymbol{C(c) = A(x) \times B(y)}$
5.00	1.00	0.00	5.00	0.00	0.00
17.44	2.91	0.64	6.00	1.00	0.64
29.89	4.55	0.89	6.57	0.92	0.82
42.33	5.41	0.72	7.82	0.74	0.53
54.78	6.16	0.57	8.90	0.59	0.33
67.22	6.82	0.44	9.85	0.45	0.20
79.67	7.43	0.31	10.73	0.32	0.10
92.11	7.99	0.20	11.53	0.21	0.04
104.56	8.51	0.10	12.29	0.10	0.01
117.00	9.00	0.00	13.00	0.00	0.00

Similarly, membership values for the 10 points of the resulting fuzzy number support are calculated in order to implement extended fuzzy multiplication using the Lukasiewicz t-norm on the two fuzzy numbers. Table 4.4 presents the 10 points, the membership value for each point, and the values of x, y, $A(x)$, and $B(y)$. Fig. 4.12 presents the results of implementing extended fuzzy multiplication using the four common t-norms (i.e., product, Lukasiewicz, min, and drastic product t-norms) on the two triangular fuzzy numbers.

Table 4.4. Extended fuzzy multiplication results for $\boldsymbol{A(x)} \otimes \boldsymbol{B(y)}$ using Lukasiewicz t-norm

$\boldsymbol{c = x \times y}$	$\boldsymbol{x}$	$\boldsymbol{A(x)}$	$\boldsymbol{y}$	$\boldsymbol{B(y)}$	**Membership Value** $\boldsymbol{C(c) = max(A(x) + B(y) - 1, 0)}$
5.00	1.00	0.00	5.00	0.00	0.00
12.47	2.08	0.36	6.00	1.00	0.36
19.93	3.32	0.77	6.00	1.00	0.77
24.00	4.00	1.00	6.00	1.00	1.00
27.40	4.42	0.92	6.19	0.97	0.89
34.87	4.99	0.80	6.99	0.86	0.66
42.33	5.50	0.70	7.70	0.76	0.46
49.80	5.96	0.61	8.35	0.66	0.27
57.27	6.40	0.52	8.95	0.58	0.10
64.73	6.80	0.44	9.52	0.50	0.00

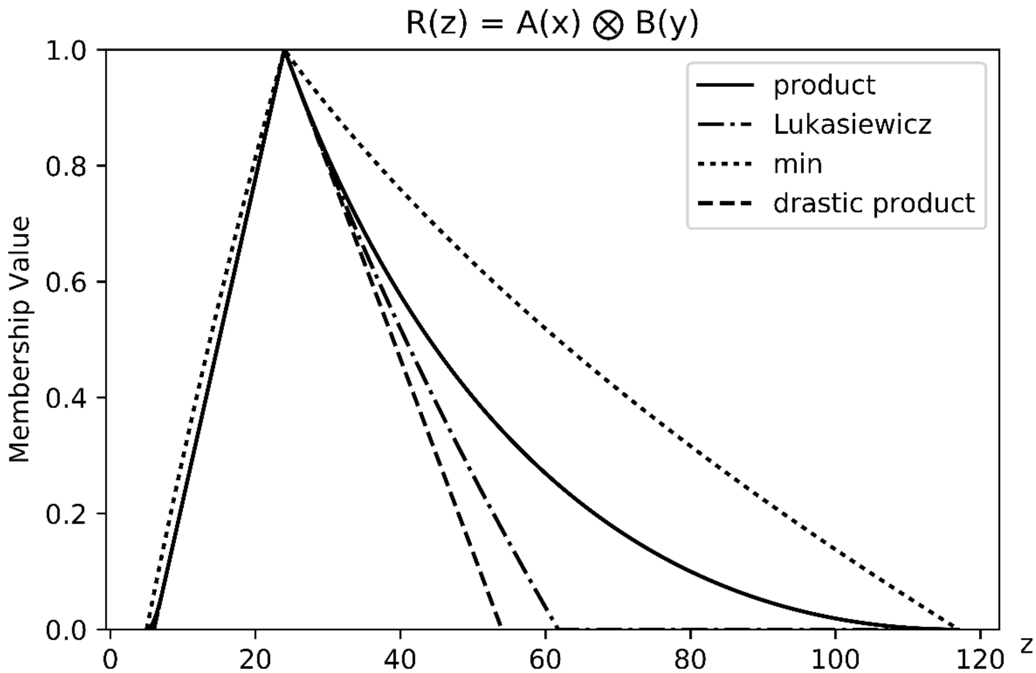

Figure 4.12. Extended fuzzy multiplication $\boldsymbol{A}(\boldsymbol{x})\otimes\boldsymbol{B}(\boldsymbol{y})$ using different t-norms

Fig. 4.12 shows that the increasing parts of the resulting fuzzy numbers overlap for the Lukasiewicz and drastic product t-norms. However, there is no overlap on the decreasing parts of the resulting fuzzy numbers.

Example 2: Consider the two triangular fuzzy numbers, $C(x)$ and $D(y)$, where $C(x)$ has a negative support and $D(y)$ has a positive support. The two fuzzy numbers are mathematically defined as presented in Eq. 4.69 and Eq. 4.70, and the graphical representations of $C(x)$ and $D(y)$ are illustrated in Fig. 4.13(a) and Fig. 4.13(b) respectively.

$$C(x) = \begin{cases} \frac{1}{7}x + \frac{12}{7}, & if -12 \le x < -5 \\ -\frac{1}{4}x - \frac{1}{4}, & if -5 \le x \le -1 \\ 0, & otherwise \end{cases} \tag{4.69}$$

$$D(y) = \begin{cases} \frac{1}{3}y - \frac{1}{3}, & if\ 1 \leq y < 4 \\ -\frac{1}{4}y + 2, & if\ 4 \leq y \leq 8 \\ 0, & otherwise \end{cases} \tag{4.70}$$

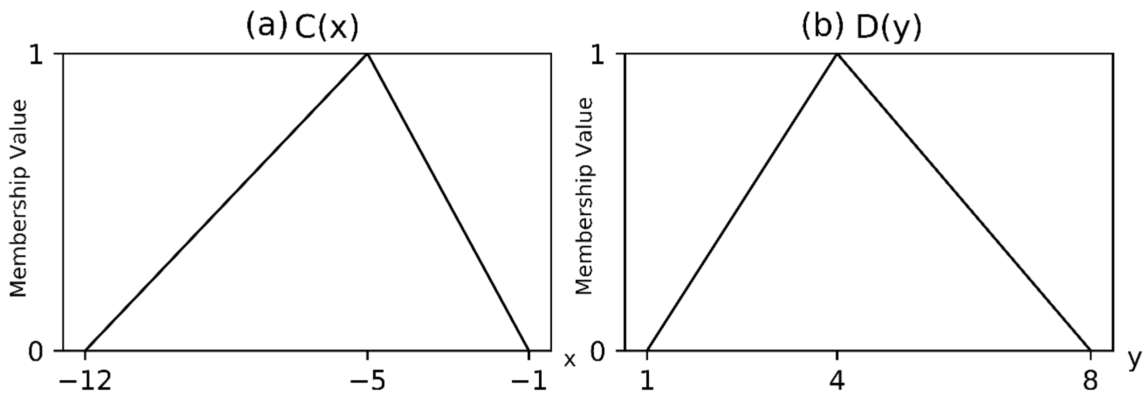

Figure 4.13. Triangular input fuzzy numbers $\boldsymbol{C(x, 1, 4, 9)}$ and $\boldsymbol{D(y, 5, 6, 13)}$

In order to implement extended fuzzy addition using the product t-norm, the membership values for 10 points in the resulting fuzzy number support are calculated using the method presented in Section 4.3.1.2. Table 4.5 presents the 10 points, the membership value for each point, and values of x, y, $C(x)$, and $D(y)$.

Table 4.5. Extended fuzzy addition results for $\boldsymbol{C(x)} \oplus \boldsymbol{D(y)}$ using product t-norm

$\boldsymbol{c = x + y}$	$\boldsymbol{x}$	$\boldsymbol{A(x)}$	$\boldsymbol{y}$	$\boldsymbol{B(y)}$	**Membership Value** $\boldsymbol{C(c) = A(x) \times B(y)}$
-11.00	-12.00	0.00	1.00	0.00	0.00
-9.00	-11.00	0.14	2.00	0.33	0.36
-7.00	-10.00	0.29	3.00	0.67	0.77
-5.00	-9.00	0.43	4.00	1.00	1.00
-3.00	-7.00	0.71	4.00	1.00	0.89
-1.00	-5.00	1.00	4.00	1.00	0.66
1.00	-4.00	0.75	5.00	0.75	0.46
3.00	-3.00	0.50	6.00	0.50	0.27
5.00	-2.00	0.25	7.00	0.25	0.10
7.00	-1.00	0.00	8.00	0.00	0.00

Similarly, in order to implement extended fuzzy addition using the Lukasiewicz t-norm, the membership values for 10 points of the resulting fuzzy number support are calculated using the method presented in Section 4.3.2.2. Table 4.6 presents the 10 points, the membership value for each point, and values of x, y, $C(x)$, and $D(y)$. Fig. 4.14 shows the results of implementing extended fuzzy addition using the four common t-norms (i.e., product, Lukasiewicz, min, and drastic product t-norms) on the two triangular fuzzy numbers.

Table 4.6. Extended fuzzy addition results for $\boldsymbol{C(x)} \oplus \boldsymbol{D(y)}$ using Lukasiewicz t-norm

$\boldsymbol{c = x + y}$	$\boldsymbol{x}$	$\boldsymbol{A(x)}$	$\boldsymbol{y}$	$\boldsymbol{B(y)}$	**Membership Value** $\boldsymbol{C(c) = max(A(x) + B(y) - 1, 0)}$
-8.23	-12.00	0.00	3.77	-1.23	0.00
-6.85	-10.85	0.16	4.00	1.00	0.16
-5.46	-9.46	0.36	4.00	1.00	0.36
-4.08	-8.08	0.56	4.00	1.00	0.56
-2.69	-6.69	0.76	4.00	1.00	0.76
-1.31	-5.31	0.96	4.00	1.00	0.96
0.08	-3.92	0.73	4.00	1.00	0.73
1.46	-2.54	0.38	4.00	1.00	0.38
2.85	-1.15	0.04	4.00	1.00	0.04
4.23	-1.00	0.00	5.23	0.69	0.00

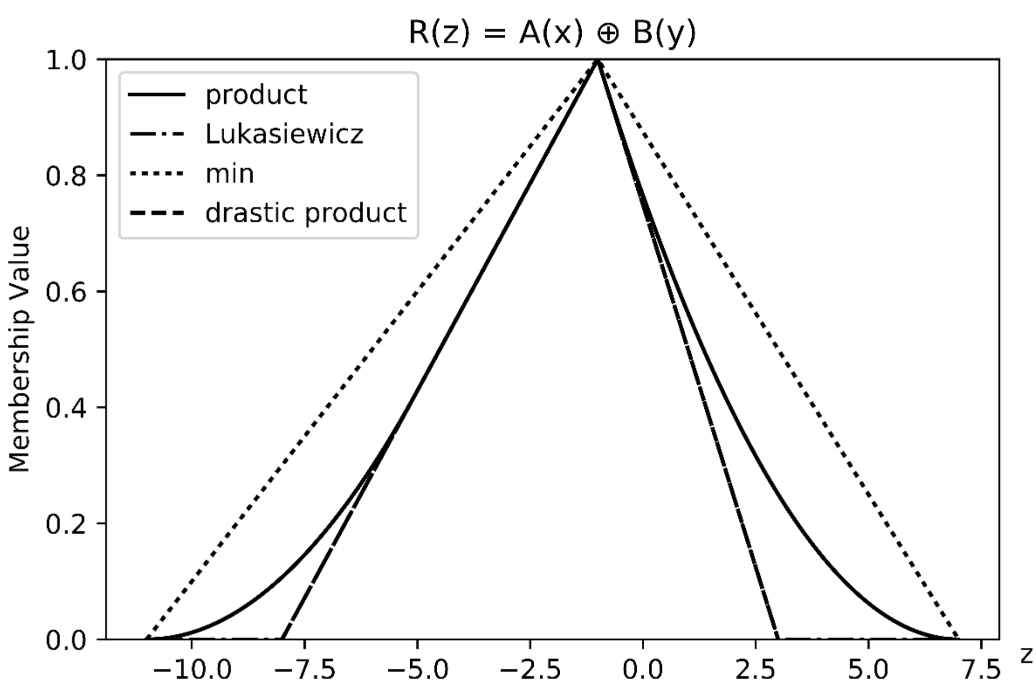

Figure 4.14. Extended fuzzy addition $\boldsymbol{C(x)} \oplus \boldsymbol{D(y)}$ using different t-norms

As presented in Fig. 4.14, the fuzzy number resulting from implementing extended fuzzy addition using the Lukasiewicz and drastic product t-norms overlap for all points of the support.

In order to implement extended fuzzy multiplication on the two fuzzy numbers using the computational methods presented in Section 4.3.1.2 and 4.3.2.2, a triangular fuzzy number $C'(x) = -1 \otimes C(x)$ is developed; this number as presented mathematically in Eq. 4.71. Next, extended fuzzy multiplication is implemented on $C'(x)$ and $D(y)$ using the computational methods presented in Section 4.3.1.2 and 3.2.2, where the two fuzzy numbers have positive supports. Finally, the resulting fuzzy number is multiplied by -1 to calculate the result of the extended fuzzy multiplication implemented on $C(x)$ and $D(y)$.

$$C'(x) = \begin{cases} \frac{1}{4}x - \frac{1}{4}, & if\ 1 \leq x < 5 \\ -\frac{1}{7}x + \frac{12}{7}, & if\ 5 \leq x \leq 12 \\ 0, & otherwise \end{cases} \tag{4.71}$$

Table 4.7 presents the results of implementing extended fuzzy multiplication using the product t-norm, while Table 4.8 presents the results of implementing extended fuzzy multiplication using the Lukasiewicz t-norm. Finally, Fig. 4.15 shows the results of implementing extended fuzzy multiplication using the four most common t-norms (i.e., product, Lukasiewicz, min, and drastic product t-norms) on the two triangular fuzzy numbers.

Table 4.7. Extended fuzzy multiplication results for $\boldsymbol{C(x) \otimes D(y)}$ using Lukasiewicz t-norm

$\boldsymbol{c = x \times y}$	$\boldsymbol{x}$	$\boldsymbol{A(x)}$	$\boldsymbol{y}$	$\boldsymbol{B(y)}$	**Membership Value** $\boldsymbol{C(c) = A(x) \times B(y)}$
-96.00	-12.00	0.00	8.00	0.00	0.00
-85.44	-11.32	0.10	7.55	0.11	0.01
-74.89	-10.60	0.20	7.07	0.23	0.05
-64.33	-9.82	0.31	6.55	0.36	0.11
-53.78	-8.98	0.43	5.99	0.50	0.22
-43.22	-8.05	0.56	5.37	0.66	0.37
-32.67	-7.00	0.71	4.67	0.83	0.60
-22.11	-5.53	0.92	4.00	1.00	0.92

-11.56	-3.40	0.60	3.40	0.80	0.48
-1.00	-1.00	0.00	1.00	0.00	0.00

Table 4.8. Extended fuzzy multiplication results for $\boldsymbol{C(x)} \otimes \boldsymbol{D(y)}$ using Lukasiewicz t-norm

$\boldsymbol{c = x \times y}$	$\boldsymbol{x}$	$\boldsymbol{A(x)}$	$\boldsymbol{y}$	$\boldsymbol{B(y)}$	**Membership Value** $\boldsymbol{C(c) = max(A(x) + B(y) - 1, 0)}$
-54.20	-9.74	0.32	5.57	0.61	0.00
-46.60	-9.03	0.42	5.16	0.71	0.13
-42.80	-8.65	0.48	4.95	0.76	0.24
-39.00	-8.26	0.53	4.72	0.82	0.35
-35.20	-7.85	0.59	4.48	0.88	0.47
-31.40	-7.41	0.66	4.24	0.94	0.60
-27.60	-6.90	0.73	4.00	1.00	0.73
-23.80	-5.95	0.86	4.00	1.00	0.86
-20.00	-5.00	1.00	4.00	1.00	1.00
-16.20	4.05	0.00	4.00	1.00	0.00

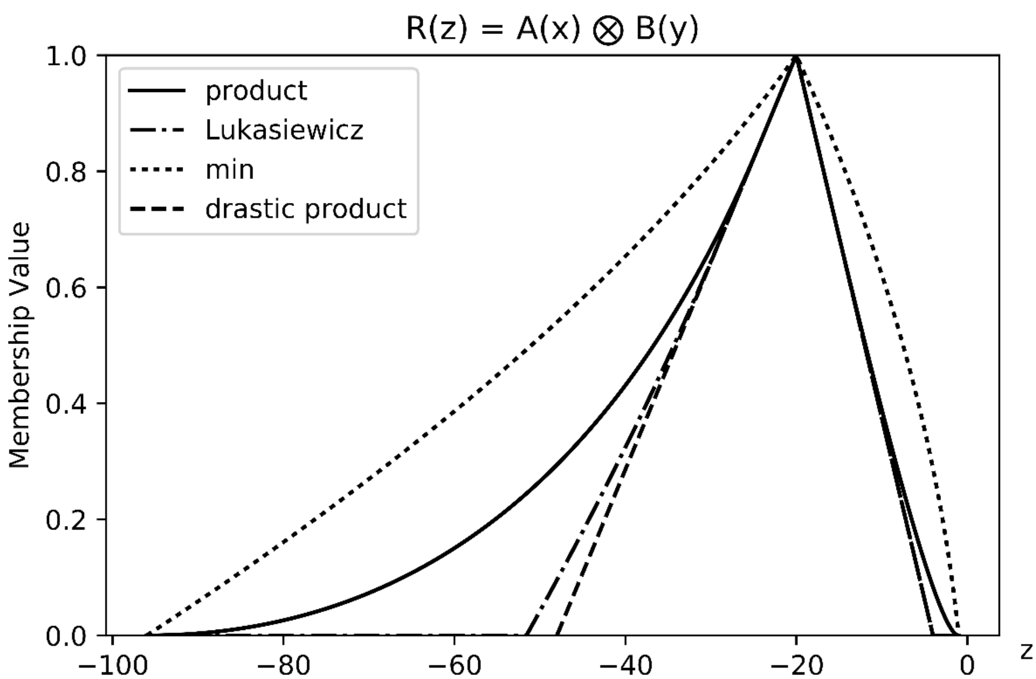

Figure 4.15. Extended fuzzy multiplication $\boldsymbol{C(x)} \otimes \boldsymbol{D(y)}$ using different t-norms

As presented in Fig. 4.15, the decreasing parts of the resulting fuzzy numbers overlap for the Lukasiewicz and drastic product t-norms. However, there is no overlap on the increasing parts of the resulting fuzzy numbers.

4.5. Summary

This chapter presents computational methods for the implementation of extended fuzzy arithmetic using product and Lukasiewicz t-norms on triangular fuzzy numbers. These computational methods can be used for implementation of fuzzy arithmetic operations in different applications of fuzzy numbers including fuzzy system dynamics technique. These computational methods are exact discrete methods that calculate the exact membership values of a finite number of points in the resulting fuzzy number support. This chapter also presents numerical examples for the implementation of fuzzy arithmetic operations using Fuzzy Calculator class. Fuzzy Calculator class is developed in Python programming language as a component of the FSD model of construction productivity; it is capable of implementing standard fuzzy arithmetic and the extended fuzzy arithmetic, the latter of which uses the min, product, Lukasiewicz, and drastic product t-norms. In the next chapter the qualitative FSD model of construction productivity is presented.

4.6. References

Abebe, A., Guinot, V., & Solomatine, D. (2000). Fuzzy alpha-cut vs. Monte Carlo techniques in assessing uncertainty in model parameters. In Proceedings of the 4th International Conference on Hydroinformatics, Iowa.

Cabrerizo, F. J., Chiclana, F., Al-Hmouz, R., Morfeq, A., Balamash, A. S., & Herrera-Viedma, E. (2015). Fuzzy decision making and consensus: Challenges. Journal of Intelligent & Fuzzy Systems, 29(3), 1109-1118.

Chang, P., & Hung, K. (2006). *α*-cut fuzzy arithmetic: Simplifying rules and a fuzzy function optimization with a decision variable. IEEE Transactions on Fuzzy Systems, 14(4), 496-510.

Chang, P., Pai, P., Lin, K., & Wu, M. (2006). Applying fuzzy arithmetic to the system dynamics for the customer–producer–employment model. International Journal of Systems Science, 37(10), 673-698.

Dong, W., & Wong, F. (1987). Fuzzy weighted averages and implementation of the extension principle. Fuzzy Sets and Systems, 21(2), 183-199.

Dubois, D., & Prade, H. (1978). Operations on fuzzy numbers. International Journal of Systems Science, 9(6), 613-626.

Dubois, D., & Prade, H. (1980). Fuzzy sets and systems: Theory and applications. Academic press, Massachusetts.

Elbarkouky, M. M., Fayek, A. R., Siraj, N. B., & Sadeghi, N. (2016). Fuzzy arithmetic risk analysis approach to determine construction project contingency. Journal of Construction Engineering and Management, 142(12), 04016070.

Hanss, M. (2002). The transformation method for the simulation and analysis of systems with uncertain parameters. Fuzzy Sets and Systems, 130(3), 277-289.

Heshmaty, B., & Kandel, A. (1985). Fuzzy linear regression and its applications to forecasting in uncertain environment. Fuzzy Sets and Systems, 15(2), 159-191.

Hong, D. H., & Do, H. Y. (1997). Fuzzy system reliability analysis by the use of Tω (the weakest t-norm) on fuzzy number arithmetic operations. Fuzzy Sets and Systems, 90(3), 307-316.

Jenei, S. (2002). A note on the ordinal sum theorem and its consequence for the construction of triangular norms. Fuzzy Sets and Systems, 126(2), 199-205.

Jenei, S. (2004). How to construct left-continuous triangular norms—state of the art. Fuzzy Sets and Systems, 143(1), 27-45.

Kechagias, P., & Papadopoulos, B. K. (2007). Computational method to evaluate fuzzy arithmetic operations. Applied Mathematics and Computation, 185(1), 169-177.

Klement, E. P., & Navara, M. (1999). A survey on different triangular norm-based fuzzy logics. Fuzzy Sets and Systems, 101(2), 241-251.

Klir, G. J. (1997). Fuzzy arithmetic with requisite constraints. Fuzzy Sets and Systems, 91(2), 165-175.

Kolesárová, A. (1995). Additive preserving the linearity of fuzzy intervals. Tatra Mountains Mathematical Publications, 6, 75-81.

Lee, C. (1990). Fuzzy logic in control systems: Fuzzy logic controller. I. IEEE Transactions on Systems, Man, and Cybernetics, 20(2), 404-418.

Lin, K., Wen, W., Chou, C., Jen, C., & Hung, K. (2011). Applying fuzzy GERT with approximate fuzzy arithmetic based on the weakest t-norm operations to evaluate repairable reliability. Applied Mathematical Modelling, 35(11), 5314-5325.

Lorterapong, P., & Moselhi, O. (1996). Project-network analysis using fuzzy sets theory. Journal of Construction Engineering and Management, 122(4), 308-318.

Mesiar, R. (1997). Shape preserving additions of fuzzy intervals. Fuzzy Sets and Systems, 86(1), 73-78.

Moore R. (1966). Interval Analysis. Prentice-Hall, Englewood Cliffs, New Jersey.

Moore, R. E. (1979). Methods and applications of interval analysis. SIAM, Philadelphia.

Nguyen, H. T. (1978). A note on the extension principle for fuzzy sets. Journal of Mathematical Analysis and Applications, 64(2), 369-380.

Nguyen, H. T., & Walker, E. A. (2005). A first course in fuzzy logic. CRC press, New York.

Pedrycz, W., & Gomide, F. (2007). Fuzzy systems engineering: Toward human-centric computing John Wiley & Sons, New Jersey.

Ross, T. J. (2009). Fuzzy logic with engineering applications. John Wiley & Sons, West Sussex.

Urbański, M. K., & Wasowski, J. (2005). Fuzzy arithmetic based on boundary weak t-norms. International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 13(01), 27-37.

Zadeh, L. A. (1965). Fuzzy Sets, Information and Control, 8(3), 338-353.

Zadeh, L. A. (1975). The concept of a linguistic variable and its application to approximate reasoning—I. Information Sciences, 8(3), 199-249.

Chapter 5. Dynamic Modeling of Construction Productivity[1]

5.1. Introduction

Previous research on construction productivity has often focused on labour-intensive activities for the identification of factors influencing activity-level productivity or the development of predictive models for activity-level productivity. Construction equipment is now the driver of productivity for some activities, so called equipment-intensive activities. Since the driver of productivity for labour- and equipment-intensive activities is different, the factors that influence the productivity of these activities are different as well. As a result, predictive models that are developed to measure the productivity of labour-intensive activities are not appropriate for measuring the productivity of equipment-intensive activities, since these models do not include all the factors influencing the productivity of equipment-intensive activities. Chapter 3 presented a comprehensive list of factors influencing the productivity of equipment-intensive activities. These factors are used to develop the predictive model of productivity for equipment-intensive activities discussed in this chapter.

The existing predictive models of activity-level construction productivity often measure construction labour productivity (CLP). However. CLP is not an appropriate measure of productivity for equipment-intensive activities, since it does not provide any information regarding the resource input (equipment) that is the main driver of productivity for these activities. Accordingly, in this research, the predictive model of productivity for equipment-intensive activities determines the multi-factor productivity (MFP) of these activities and provides information regarding the three input resources of these activities: labour, equipment, and material. The MFP of equipment-intensive activities can be calculated using Eq. 5.1.

$$\mathrm{MFP}\left(\frac{\$}{\mathrm{unit}}\right)=\frac{\mathrm{Labour}\ (\$)+\mathrm{Equipment}(\$)+\mathrm{Material}(\$)}{\mathrm{Outputs}\ (\mathrm{unit})} \quad (5.1)$$

[1] Parts of this chapter have been submitted for publication in the Journal of Construction Engineering and Management, ASCE, on November 09, 2017.

Moreover, as discussed in Chapter 2, the existing predictive models of construction productivity often fail to capture the dynamism of construction productivity, or fail to capture the subjective uncertainty of the factors influencing productivity. Accordingly, Nojedehi and Nasirzadeh (2017) suggested the use of fuzzy system dynamics technique for modeling construction productivity, since this technique captures the dynamism of construction systems and the interactions between the factors influencing productivity, while simultaneously representing the probabilistic and subjective uncertainty of these factors. Nojedehi and Nasirzadeh (2017) developed a predictive model for construction productivity using FSD to determine CLP. However, their predictive model is for labour-intensive activities and predicts CLP, which is not an appropriate measure of productivity for equipment-intensive activities, as discussed earlier. Accordingly, there is a need within the existing body of construction research to develop a predictive model of the MFP for equipment-intensive activities using FSD technique. This chapter presents the FSD model of construction productivity developed in this research for measuring the MFP of equipment-intensive activities.

In order to develop the predictive model of construction productivity using FSD technique, the qualitative and quantitative FSD models were developed. The qualitative FSD model, which is also referred to as system thinking in the literature (Sterman 2000, Wolstenholme 1999), helps the users to identify the system behaviour. In contrast, the quantitative FSD model helps users to simulate system behaviour and predict the state of the system (e.g., construction productivity) dynamically. Accordingly, the qualitative FSD model of construction productivity helps users to identify the factors influencing construction productivity and the relationships between these factors. Moreover, the quantitative FSD model of construction productivity makes dynamic predictions (i.e., tracks the changes of productivity throughout the project life cycle), while considering the interactions between the factors influencing construction productivity.

5.2. Methodology

Developing the predictive model of construction productivity using the FSD technique is accomplished in the following five steps: (1) identification of the factors influencing construction productivity, (2) reduction of the dimensionality of the factors by feature selection, (3) development of the qualitative FSD model, (4) development of the quantitative FSD model, and (5) validation of the full FSD model. These five steps are presented in Fig. 5.1.

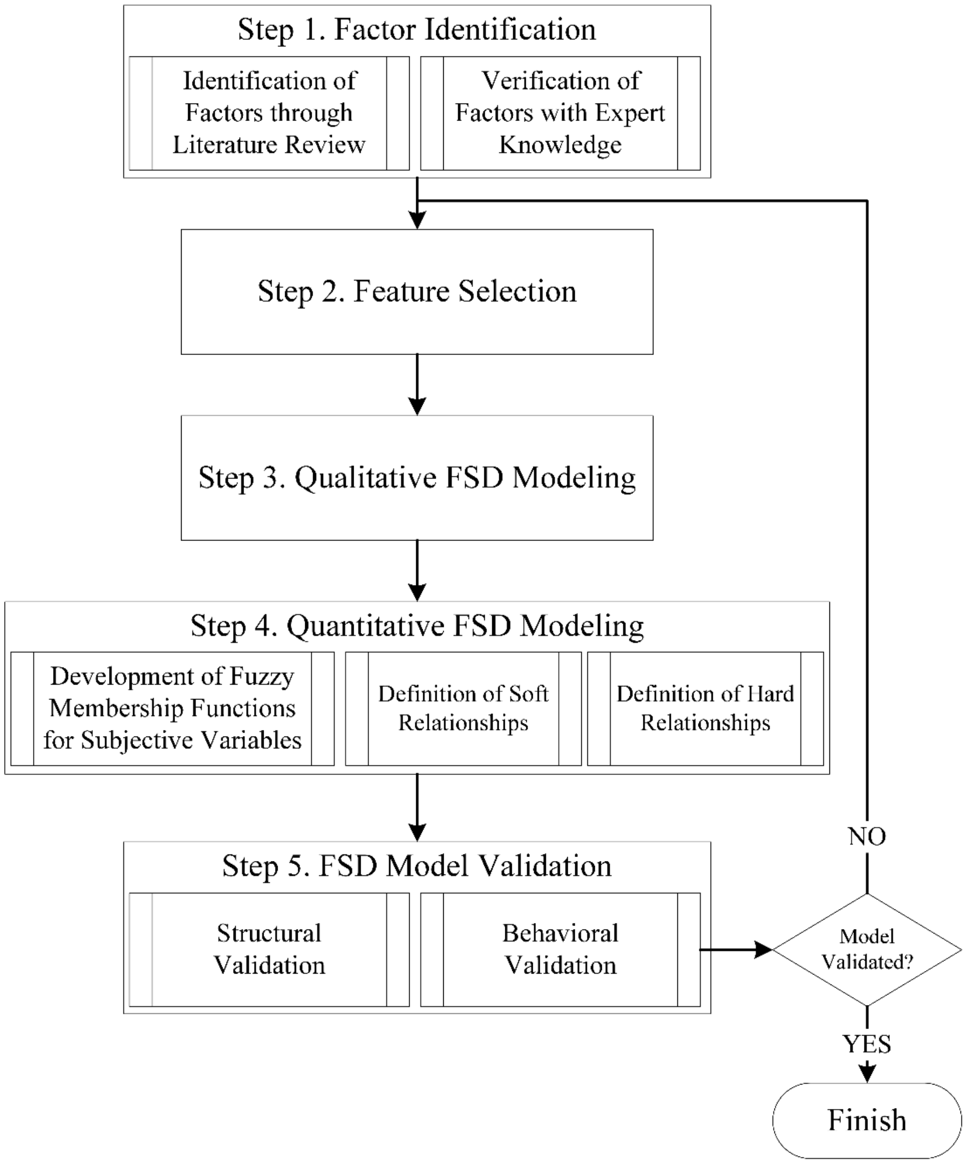

Figure 5.1. Methodology for construction productivity modeling by FSD technique

5.2.1. Factor Identification

As discussed in Chapter 3, in the first step, the factors influencing activity-level productivity of equipment-intensive activities were identified through a literature review;

then the identified factors were verified by expert knowledge using interview surveys. Construction productivity naturally tends to be a micro-level issue, where a group of organized workers are required to transform a set of inputs into tangible project outputs (Bernold and AbouRizk 2010). In addition to micro-level factors (i.e., crew-level, activity-level, and project-level), macro-level factors (i.e., organizational-level, provincial-level, national-level, and global-level) may directly or indirectly influence construction productivity (Tsehayae and Fayek 2014). However, due to the fact that project-level and macro-level factors are constant at the activity-level, these factors are excluded for developing the FSD model of construction productivity. While the crew-level and activity-level factors are required for developing the FSD model of productivity, the project-level and macro-level factors are required to represent the context of the construction project. Construction productivity models are context-dependant, where the influence of the factors on productivity varies from one context to another (Gerek et al. 2015, Heravi and Eslamdoost 2015, Tsehayae and Fayek 2016a). An explicit representation of the project context enables the users to adapt and use the predictive model in new contexts (Tsehayae and Fayek 2016a). Thus, in this research, a comprehensive list of the factors influencing productivity is identified; the crew-level and activity-level factors are used for developing the FSD model of productivity, and the project-level and macro-level factors are used for representing the project context. Consequently, 72 activity-level factors were identified through the literature review and were verified by expert knowledge to have either a negative or positive impact on construction productivity; these factors are referred to as the system variables in the following steps.

5.2.2. Feature Selection

Once the factors influencing construction productivity are selected, the number of system variables must be reduced by feature selection to increase the accuracy of the predictive model of construction productivity (Guyon and Elisseeff 2003, Ahmad and Pedrycz 2011). There are different feature selection methods that can be used for reducing the dimensionality of datasets; these methods are categorized into the three following categories (Guyon and Elisseeff 2003): filter methods that rank the features based on their correlation coefficient and select the best subset of the data based on the ranking; wrapper methods that use evolutionary search methods (e.g., genetic algorithms) to identify the best subset of data, for which the predictive model has the highest accuracy (e.g., the lowest root mean square error); and embedded methods that are specific to given machine learning techniques and that select the best features as a part of the training process. Correlation-based feature selection (CFS) that is a filter method, is the most common approach, due to its simplicity (Hall 1999). The CFS method reduces the dimensionality of the dataset by selecting the subset of the factors that have the highest Pearson correlation coefficient with the system output (e.g., productivity), and that have the lowest Pearson correlation coefficient with the other factors of the subset. While CFS is appropriate for developing mathematical equations by the statistical regression method (Guyon et al. 2006), for developing fuzzy rule-based systems (FRBS), Ahmad and Pedrycz (2011) proposed the use of the wrapper method. In this research, as discussed in quantitative FSD modeling (Step 4), the soft relationships between the system variables were defined by either data-driven FRBS or by statistically-developed mathematical equations. As a result, feature selection was implemented using the following two approaches: the CFS method, which is applied to soft relationships that are defined by statistically-developed mathematical equations, and the wrapper method, using a genetic algorithm (GA) search method, which is applied to soft relationships that are defined by data-driven FRBS. The CFS method calculates the Pearson's correlation coefficient for every pair of system variables as presented in Eq. 5.2.

$$r_{xy} = \frac{cov(X, Y)}{\sigma_x \sigma_y} \tag{5.2}$$

where r_{xy} is the Pearson correlation coefficient, and $cov(X, Y)$ is the covariance between the system variable X and system variable Y. Also, σ_x is the standard deviation of system variable X, and σ_y is the standard deviation of system variable Y. Once the Pearson correlation coefficients are calculated, the evaluation scores of all subsets of system variables are calculated using Eq. 5.3.

$$M_i = \frac{k\,\overline{r_{cf}}}{\sqrt{k + k(k-1)\overline{r_{ff}}}} \tag{5.3}$$

where M_s is the CFS evaluation score for the subset i, and k is the number of features in the subset. Also, $\overline{r_{cf}}$ is the mean Pearson correlation coefficient between the variables of subset and the output, $\overline{r_{ff}}$ is the mean Pearson correlation coefficient between all pairs of variables in the subset. CFS selects the subset of data with the maximum evaluation score, which simultaneously maximizes the numerator (i.e., correlation between the variables of the subset and the output) and minimizes the denominator (i.e., correlation between the variables of the subset).

Wrapper methods use evolutionary optimization methods such as genetic algorithms (GA) to search for the best subset of system variables for development of the most accurate predictive model for the output (e.g., productivity). GA is an evolutionary optimization method inspired by evolutionary processes observed in nature (Whitley 1994); it has been successfully applied to the wrapper method feature selection problem by Li et al. (2011), Guo et al. (2011), and Sadeghi (2015). Wrapper method feature selection using GA is implemented through the following four steps:

1. Random subsets of system variables are generated, and each subset is used to develop a FRBS. Each subset is called a “chromosome”, and the number of chromosomes generated in each step is called a “population”. The population size plays a key role in the efficiency and performance of a GA (Grefensette 1986). When implemented with a population size smaller than 60, GA may not identify an optimized solution (i.e., it may become trapped in local sub-optimum solution); conversely, for population sizes larger than 110, the efficiency of GA decreases (Grefensette 1986). In this research, the population size of GA is equal to 100, a value which is recommended by Roeva et al. (2013).
2. GA optimization method minimizes the value of a “fitness function”, which is calculated for each chromosome. Since in wrapper method feature selection, the objective is selecting the subset of data that develops the most accurate FRBS, the accuracy of the FRBSs are considered equivalent to the “fitness function”.

3. The chromosomes are ranked based on their fitness functions, and a number of chromosomes are then selected to produce the next generation of chromosomes using the crossover operator. The higher the accuracy of the chromosome, the higher the chance that the chromosome will be selected for the crossover operation. The crossover operator combines two chromosomes (i.e., parent chromosomes) and generates two new chromosomes (i.e., children), as presented in Fig. 5.2.
4. The three previous steps are repeated until the termination condition is satisfied. The termination condition is satisfied in the event that one or more of the following constraints is met: the maximum number of generations is achieved, the improvement of the best fitness function in two sequential generations is less than the threshold, or the fitness function achieves a satisfactory value. Finally, the chromosome with the highest accuracy in the last generation is selected as the best subset of system variables to develop the FRBS.

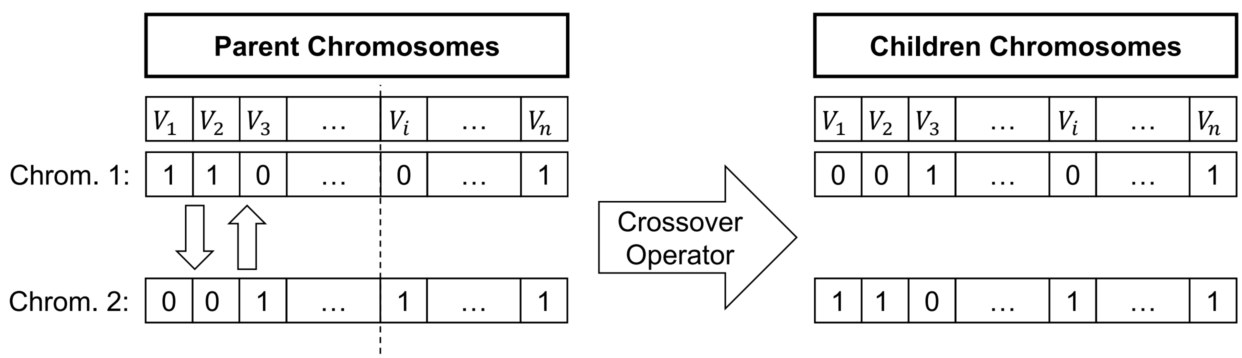

Figure 5.2. Crossover operator for GA method

Chrom. 1 and Chrom. 2 stand for the parent chromosome 1 and parent chromosome 2, respectively. Also, V_i shows the system variable i, and the value of zero written in parent chromosome 1 under V_i refers to the exclusion of variable i in this chromosome. In contrast, the value of one written in parent chromosome 2 under V_i refers to the inclusion of variable V_i in this chromosome.

5.2.3. Qualitative FSD Modeling

Once feature selection is completed, the qualitative FSD model is developed by identifying the relationships between the system variables. There are two types of relationships between the system variables: hard relationships, where the mathematical form of the relationship is known, and soft relationships, where the mathematical form of the relationship is unknown (Coyle 2000). As proposed by Sterman (2000), soft relationships were identified based on the existing knowledge about real-world systems, which was acquired by reviewing previous studies on construction productivity and by using expert judgment. The soft relationships between the system variables and activity-level productivity (i.e., having either a negative or positive impact on productivity) were identified through a literature review and were confirmed by expert knowledge through interview surveys (referring to Chapter 3). On the other hand, the hard relationships between the system variables were identified using the equations, which define the relationships. Eq. 5.4 presents an example of the hard relationship between "crew size", "planned crew size," and "absenteeism":

$$\text{Crew Size} = \text{Planned Crew Size} - \text{Absenteeism}. \tag{5.4}$$

5.2.4. Quantitative FSD Modeling

For developing the quantitative FSD model, first, the objective and the subjective system variables were identified; objective system variables were represented by crisp numbers, and fuzzy membership functions were developed to represent the subjective system variables. Next, the soft and hard relationships of the system were defined quantitatively. The objective and subjective system variables were identified based on their scales of measure. The objective system variables were evaluated by crisp numerical values, such as 10 years for equipment operator experience, while the subjective system variables were evaluated using subjective scales, such as "HIGH" crew motivation (Tsehayae and Fayek 2016b).

Once the objective and the subjective system variables were identified, the subjective variables were represented by fuzzy membership functions. These fuzzy membership functions can be developed by one of several approaches proposed in the literature that use either data or expert knowledge. FCM clustering, an iterative machine learning method, is a data-driven method, which is commonly used for developing fuzzy membership functions (Bezdek 1981, Pedrycz and Reformat 2006). Moreover, FCM is a clustering method based on fuzzy set theory, in which the membership value of each data point in any given cluster can vary between $[0,1]$ (Dunn 1973). Development of the fuzzy membership functions using FCM clustering is accomplished through the following four steps (Pedrycz and Gomide 2007):

1. Random cluster centers are generated. The number of cluster centers —shown as k—is equal to the number of membership functions selected to represent the subjective variables. While increasing the number of fuzzy membership functions increases their coverage (i.e., more data points are covered by at least one of the fuzzy membership functions), the interpretability of the membership functions will decrease by increasing their number (Sadeghi 2015). Accordingly, previous research has suggested representing the subjective variables by three, five, or seven membership functions (Pedrycz 2013).
2. The membership degree of data point i in cluster j for the iteration number t ($u_{i,j}^{t}$) is calculated using Eq. 5.5.

$$u_{i,j}^{t} = \frac{1}{\sum_{k=1}^{c}\left(\frac{\|x_i, c_j\|}{\|x_i, c_k\|}\right)^{\frac{2}{m-1}}} \quad \textbf{(5.5)}$$

   where $\|x_i, c_j\|$ stands for the distance between data point i and cluster center j, and m represents the fuzzification coefficient, which is larger than 1. Pedrycz and Gomide (2007) suggested that $m = 2$ is appropriate for the application of FCM clustering.
3. The new cluster centers for iteration $t + 1$ are calculated using Eq. 5.6.

$$c_k^{t+1} = \frac{\sum_{k=1}^{N} u_{i,k}^{m} \times x_k}{\sum_{k=1}^{N} u_{i,k}^{m}} \quad \textbf{(5.6)}$$

where N stands for the total number of data points.

4. Step 2 and Step 3 are repeated until the termination condition is satisfied. The termination condition that is presented in Eq. 5.7 is satisfied.

$$\max\left(u_{i,j}^{t+1} - u_{i,j}^{t}\right) \leq \varepsilon \quad \textbf{(5.7)}$$

where ε is the minimum improvement in the location of the cluster centers.

The FCM clustering algorithm maximizes the membership degree of each data point in the cluster with the closest cluster center, while minimizing the membership degrees of the data points in other clusters. This method is able to develop data-driven FRBS for defining the relationships between two sets of variables (input variables and output variables) by projecting the clusters into the input space (e.g., the values of the factors influencing construction productivity) and the output space (e.g., the value of construction productivity) (Pedrycz and Gomide 2007). Accordingly, Delgado et al. (1997) concluded that FCM clustering is an efficient approach for developing fuzzy membership functions in order to represent subjective variables and to define the relationships between these variables by data-driven FRBS. In this research, the membership functions, which represent the subjective variables of the system, were developed using the FCM clustering method.

Once the subjective system variables were represented by fuzzy membership functions, the soft relationships of the system were defined quantitatively. Soft relationships are characterized by the fact that their mathematical form is unknown (e.g., the relationship between crew motivation and absenteeism). In this research, the soft relationships in the FSD model were defined either by data-driven FRBS developed using the FCM clustering method or by mathematical equations developed through the linear regression method. Previous research has suggested the use of the linear regression method for developing the mathematical equations that define the soft relationships in FSD models (Khanzadi et al. 2012, Nasirzadeh et al. 2013). The performance of the two methods in defining the soft relationships of the system was evaluated using the root mean square error (RMSE); the method with the lowest RMSE was then chosen for defining each relationship. FCM clustering and linear regression methods were implemented using 90% cross validation, which uses 90% of the data for training and 10% of the data for validation (i.e., measuring RMSE). Since the mathematical form of hard relationships was known, unlike soft relationships, these relationships were defined using mathematical equations. Fuzzy arithmetic was then used to solve both the soft relationships defined using mathematical equations as well as all the hard relationships, since they both contain subjective system variables represented by fuzzy numbers. In this research, the α-cut method and the extension principle method using four common t-norms (min, product, Lukasiewicz and drastic product) were evaluated for the purpose of implementing the fuzzy arithmetic operations on the mathematical equations of the system. The computational methods for the implementation of fuzzy arithmetic operations are presented in Chapter 4.

5.2.5. FSD Model Validation

Finally, in the fifth step, the FSD model was validated. Senge and Forrester (1980) asserted that the common validation tests such as the statistical hypothesis test are not appropriate for the validation of SD (and FSD) models. Barlas (1994) introduced two approaches for validation of the SD (and FSD) models: structure validity and behaviour validity. Structural validity tests confirm that the system variables and the relationships between these variables represent the structure of the real-world system correctly. The behavioral validity tests confirm that the FSD model can replicate the behaviour of the real-world system correctly. In this research the structural and behavioural validity of the FSD model of construction productivity are tested using a case study of earthmoving operations, as discussed in Chapter 6.

5.3. FSD Model of Multi-Factor Productivity for Equipment-Intensive Activities

Seventy-two activity-level factors influencing the productivity of equipment-intensive activities, hereafter referred to as system variables, were identified through the literature review and were verified by expert knowledge. In order to increase the accuracy of the

FSD model of construction productivity, the number of system variables was reduced by feature selection, as discussed in the methodology. Twenty-five system variables, divided into six categories (i.e., crew-related factor), were selected for the development of the FSD model, which are presented below in Table 5.1.

Table 5.1. System variables for FSD model of activity-level construction productivity

Category	Factors
Equipment-related Factors	Number of Equipment, Equipment Capacity, Equipment Ownership, Equipment Functional Range, Operator Experience, Labour and Equipment Balance
Location-related Factors	Distance, Site Restrictions, Underground Facilities, Groundwater Level, Soil Type, Soil Moisture
Weather-related Factors	Gust Speed, Temperature, Total Precipitation
Task-related Factors	Daily Overtime Work, Total Work Volume
Crew-related Factors	Crew Experience, Crew Composition, Crew Size, Crew Motivation, Absenteeism, Foreman Experience
Material-related Factors	Material Pre-Installation Requirements, Material Quality

Once the system variables were selected, the qualitative FSD model of construction productivity was developed by identifying the relationships between the variables. For presentation clarity, the qualitative FSD model of construction productivity in this research is broken into two components: a stock and flow diagram, and a cause and effect diagram. Fig. 5.3 presents the stock and flow diagram that measures the MFP of the system using its three inputs (i.e., labour direct cost, equipment direct cost, and material direct cost), and it measures the total cost rate and the total activity direct cost using the MFP and the production rate of the activity.

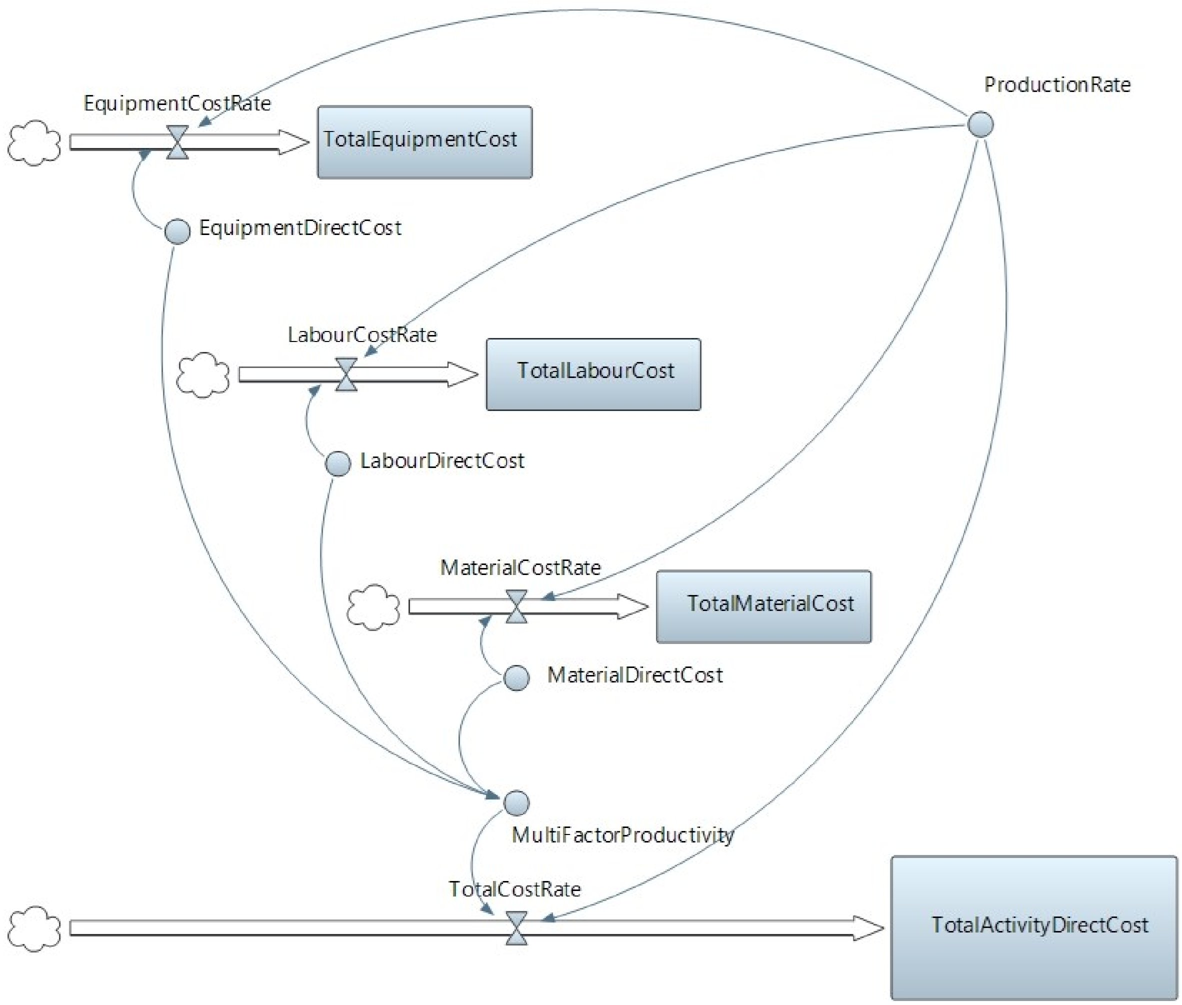

Figure 5.3. Stock and flow diagram of qualitative FSD model of construction productivity

There are four stock variables (i.e., representing accumulation in FSD models) in Fig. 5.3, which represent the cumulative costs of the three input resources "total equipment cost", "total labour cost", and "total material cost", and the total direct cost of the activity "total activity direct cost". There are four flow variables (i.e., representing the rate of increase/decrease in the stock variables of FSD models) in Fig. 5.3, which represent the daily cost of the three input resources (i.e., "equipment cost rate", "labour cost rate", and "material cost rate") and the total daily direct cost of the activity (i.e., "total cost rate"). The MFP, the three inputs of MFP (i.e., "labour direct cost", "equipment direct cost", and "material direct cost"), and the "production rate" of the activity are presented as dynamic variables, where their values are determined by the cause and effect diagram presented in Fig. 5.4. In FSD models, the dynamic variables represent the variables that change in value due to their relationships with other variables. All relationships between the variables of the stock and flow diagram (represented by arrows in Fig. 5.3) are hard relationships, for which their mathematical form is known. Accordingly, these relationships were identified using mathematical equations. Fig. 5.4 presents the cause and effect diagram that measures the three inputs of MFP, and the production rate of the activity (inputs of the stock and flow diagram) using the system variables (refer to Table 5.1).

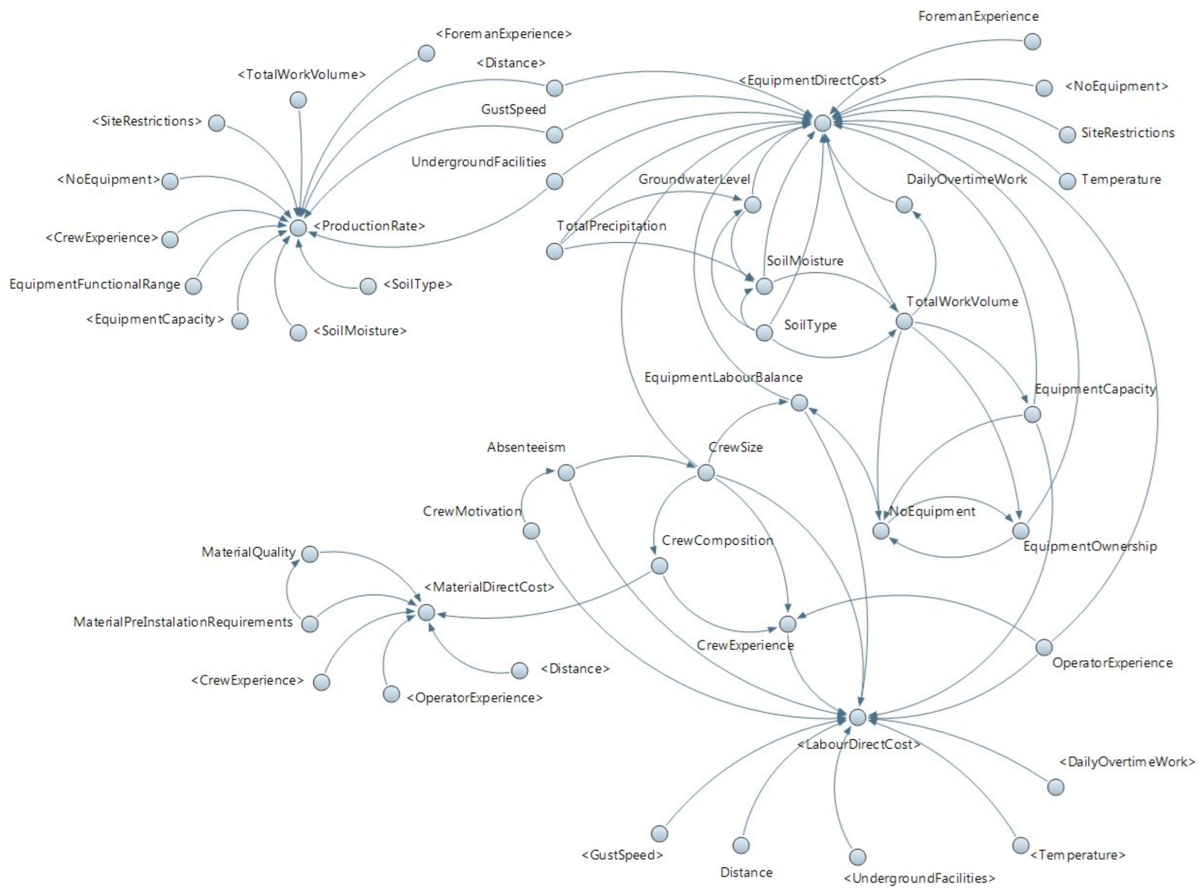

Figure 5.4. Cause and effect diagram of qualitative FSD model of construction productivity

The system variables that are selected for predicting the productivity of equipment-intensive activities (refer to Table 5.1) are presented in Fig. 5.4 as dynamic variables. These variables are used in the cause and effect diagram to predict the value of the three inputs of MFP (i.e., “labour direct cost”, “equipment direct cost”, and “material direct cost”), as well as the “production rate” of the activity. There are also two types of relationships that exist between the system variables in the cause and effect diagram:

soft relationships, such as the relationship between “crew motivation” and “equipment direct cost”, and hard relationships, such as the relationship between “absenteeism” and “crew size”. The soft relationships in the cause and effect diagram were identified based on existing knowledge about the real-world system, which was acquired through a literature review and through interview surveys; the hard relationships were defined using the mathematical equations. The relationships between the system variables can also represent delays, where there is a lag between the changes in the input of the relationship and the changes in the output (Sterman 2000). In the cause and effect diagram presented in Fig. 5.4, there is a delay in the relationship between “Total Precipitation” and “Soil Moisture”, which accounts for the time required for drainage of the water from soil.

In order to develop the quantitative FSD model of construction productivity, the objective and subjective system variables were identified based on their scale of measure. Referring to Table 5.1, there are 20 objective system variables and 5 subjective system variables. The subjective variables of the system include site restrictions, soil moisture, crew motivation, material quality, and material pre-installation requirements. Soil moisture can be also an objective system variable if it is measured numerically using soil tests; however, this factor is considered as a subjective system variable in this paper since it may also be measured by subjective expert judgment if the test results are not available. Once the objective and subjective system variables were identified, the subjective system variables were represented by fuzzy membership functions. In order to develop fuzzy membership functions, the number of fuzzy membership functions must first be selected. In the case of developing data-driven fuzzy membership functions, increasing the number of fuzzy membership function increases their coverage (i.e., more data points are covered by at least one of the fuzzy membership functions). However, the interpretability of the membership functions will be decreased by increasing their number (Sadeghi 2015). Accordingly, previous research has suggested representing the subjective variables by three, five, or seven membership functions (Sadeghi 2015, Pedrycz 2013). Once the number of fuzzy membership functions is selected, the type of membership function must be specified. There are different types of fuzzy membership functions, of which triangular membership functions is the most common in engineering applications (Pedrycz and Gomide 2007). Finally, FCM clustering method was implemented to develop the fuzzy membership functions. In this paper, the subjective system variables are represented by five triangular fuzzy membership functions.

Once the subjective variables of the system were represented by fuzzy membership functions, the soft relationships between the system variables were defined quantitatively. The soft relationships of the system may be defined by one of two approaches suggested in the literature: mathematical equations developed by linear regression (proposed by Nasirzadeh et al. 2014), or data-driven FRBS developed by FCM clustering (proposed by Gerami Seresht and Fayek 2015). As discussed in Section 5.2.4, these two approaches were evaluated, and the approach with the lowest RMSE was selected for defining the soft relationships of the system. Table 5.2 shows these soft relationships and the approach by which each soft relationship was defined.

Table 5.5. Soft relationships of FSD model of activity-level construction productivity

Relationship Output	Relationship Inputs	Numerical Definition Approach
Equipment Direct Cost	Distance, Number of Equipment, Site Restrictions, Underground Facilities, Operator Experience, Equipment Ownership, Equipment Capacity, Daily Overtime Work, Total Work Volume, Soil Type, Soil Moisture, Groundwater Level, Total Precipitation, Temperature, Gust Speed, Foreman Experience, Labour and Equipment Balance, Crew Size	Linear Regression
Labour Direct Cost	Crew Motivation, Crew Size, Crew Experience, Absenteeism, Gust Speed, Distance, Underground Facilities, Temperature, Daily Overtime Work, Operator Experience, Equipment Capacity, Labour and Equipment Balance	Linear Regression
Material Direct Cost	Material Quality, Material Pre-Installation Requirements, Crew Experience, Crew Composition, Operator Experience, Distance	Linear Regression
Production Rate	Site Restrictions, Number of Equipment, Equipment Functional Range, Equipment Capacity, Soil moisture, soil Type, Gust Speed	Linear Regression
Number of Equipment	Equipment Ownership, Equipment Capacity, Total Volume of Work	FCM Clustering
Equipment Capacity	Total Volume of Work	FCM Clustering
Equipment Ownership	Number of Equipment, Total Volume of Work	FCM Clustering
Groundwater Level	Total Precipitation	FCM Clustering

Relationship Output	Relationship Inputs	Numerical Definition Approach
Soil Moisture	Total Precipitation, Soil Type, Groundwater Level	FCM Clustering
Daily Overtime Work	Total Volume of Work	FCM Clustering
Total Work Volume	Soil Moisture, Soil Type	FCM Clustering
Crew Experience	Crew Size, Crew Composition, Operator Experience	FCM Clustering
Crew Composition	Crew Size	FCM Clustering
Absenteeism	Crew Motivation	FCM Clustering
Material Quality	Material Pre-Installation Requirements	FCM Clustering

As presented in Table 5.2, 11 soft relationships in the FSD model were defined by FRBS, and four of those relationships were defined by statistically-developed mathematical equations. Accordingly, in some cases, defining the soft relationships of FSD models using data-driven FRBS developed by FCM clustering can increase the accuracy of FSD models compared to the statistically-developed mathematical equations. However, neither of the two methods is universally the best approach for defining the soft relationships of the system. In order to simulate the FSD model and predict the productivity of any given equipment-intensive activity, the soft relationships of the system (presented in Table 5.2) were evaluated at each time step (i.e., daily). Once the soft relationships were defined, the hard relationships were defined quantitatively using mathematical equations, as discussed in the methodology. There are nine hard relationships in the FSD model, which were defined by the mathematical equations presented in Table 5.3.

Table 5.3. Hard relationships of FSD model of activity-level construction productivity

Relationship Output	Mathematical Equation
Labour Cost Rate	$\text{Labour Cost Rate}\left(\frac{\$}{\text{day}}\right) = \text{Labour Direct Cost}\left(\frac{\$}{\text{units}}\right) \times \text{Production Rate}\left(\frac{\text{units}}{\text{day}}\right)$
Equipment Cost Rate	$\text{Equipment Cost Rate}\left(\frac{\$}{\text{day}}\right) = \text{Equipment Direct Cost}\left(\frac{\$}{\text{units}}\right) \times \text{Production Rate}\left(\frac{\text{units}}{\text{day}}\right)$
Material Cost Rate	$\text{Material Cost Rate}\left(\frac{\$}{\text{day}}\right) = \text{Material Direct Cost}\left(\frac{\$}{\text{units}}\right) \times \text{Production Rate}\left(\frac{\text{units}}{\text{day}}\right)$

Total Labour Cost*	$\text{Total Labour Cost (\$)} = \int \text{Labour Cost Rate}\left(\frac{\$}{\text{day}}\right).dt\ \text{(day)}$
Total Equipment Cost*	$\text{Total Equipment Cost (\$)} = \int \text{Equipment Cost Rate}\left(\frac{\$}{\text{day}}\right).dt\ \text{(day)}$
Total Material Cost*	$\text{Total Material Cost (\$)} = \int \text{Material Cost Rate}\left(\frac{\$}{\text{day}}\right).dt\ \text{(day)}$
Multi Factor Productivity	$\text{Multi Factor Productivity}\left(\frac{\$}{\text{units}}\right) = \text{Labour Direct Cost}\left(\frac{\$}{\text{units}}\right) + \text{Equipment Direct Cost}\left(\frac{\$}{\text{units}}\right) + \text{Material Direct Cost}\left(\frac{\$}{\text{units}}\right)$
Labour and Equipment Balance**	$\text{Labour and Equipment Balance} = \frac{\text{Crew Size (Person)}}{\text{Number of Equipment (Count)}}$
Crew Size***	$\text{Crew Size (Person)} = \text{Planned Crew Size (Person)} - \text{Absenteeism(Person)}$

* dt stands for the time step's duration used for simulation of FSD model that is equal to one day in this paper.

** Number of equipment represents the number of equipment, which are working on the activity.

*** Planned crew size stands for the crew size that is specified for execution of the activity in planning phase, and absenteeism represent the number of absent crew members.

In order to simulate the FSD model and predict the productivity of any given equipment-intensive activity, the mathematical equations presented in Table 5.3 were solved at each time step (i.e., daily).

5.4. Summary

This chapter presents the predictive model of construction productivity developed by FSD technique. The predictive model is developed through the five following steps: factor identification, features selection, qualitative and quantitative FSD modeling, and FSD model validation. The first step for developing the FSD model of productivity (i.e., factor identification) was presented in Chapter 3. This chapter addresses three steps: feature selection, qualitative FSD modeling and quantitative FSD modeling. The next chapter validates the FSD model of construction productivity using field data collected from a case study of earthmoving operations. The details of the case study, field data collection methodology and forms, and validation of the FSD model are presented in the next chapter.

5.5. References

Ahmad, S. S. S., and Pedrycz, W. (2011). "Feature and Instance selection via cooperative PSO." *Systems, Man, and Cybernetics (SMC), 2011 IEEE International Conference on,* IEEE, 2127-2132.

Barlas, Y. (1994). "Model validation in system dynamics." *Proc., 1994 international system dynamics conference,* Sterling, Scotland, 1-10.

Bernold, L. E., and AbouRizk, S. M. (2010). *Managing performance in construction.* John Wiley & Sons.

Bezdek, J. (1981). "Pattern Recognition with Fuzzy Objective Function Algorithms." Plenum Press, NY.

Coyle, G. (2000). "Qualitative and quantitative modelling in system dynamics: some research questions." *Sys. Dynam. Rev.,*16 (3), 225.

Delgado, M., Gómez-Skarmeta, A. F., and Martín, F. (1997). "A fuzzy clustering-based rapid prototyping for fuzzy rule-based modeling." *IEEE Trans. Fuzzy Syst.,* 5(2), 223-233.

Dunn, J. C. (1973). "A fuzzy relative of the ISODATA process and its use in detecting compact well-separated clusters." *Journal of Cybernetics,* 3(3), 32-57.

Gerami Seresht, N, and Fayek, A. Robinson. (2015). "Application of fuzzy logic integrated with system dynamics in construction modeling. *Proc., of the 5th International Construction Specialty Conference of the Canadian Society for Civil Engineering,* 050-01-050-10.

Gerek, I. H., Erdis, E., Mistikoglu, G., and Usmen, M. (2015). "Modelling masonry crew productivity using two artificial neural network techniques." *J. Civ. Eng. Manage.*, 21 (2), 231–238.

Grefenstette, J. J. (1986). "Optimization of control parameters for genetic algorithms." *IEEE Transactions on systems, man, and cybernetics*, *16*(1), 122-128.

Guo, J., White, J., Wang, G., Li, J., & Wang, Y. (2011). “A genetic algorithm for optimized feature selection with resource constraints in software product lines.” *Journal of Systems and Software*, 84(12), 2208-2221.

Guyon, I., & Elisseeff, A. (2003). “An introduction to variable and feature selection.” *Journal of machine learning research*, *3*(Mar), 1157-1182.

Guyon, I., Gunn, S., Nikravesh, M., & Zadeh, L. (2006). Feature extraction, foundations and applications. Springer, Berlin.

Hall, M. A. (1999). *Correlation-Based Feature Selection for Machine Learning* (Doctoral Dissertation University of Waikato). Retrieved from http://www.cs.waikato.ac.nz/~mhall/thesis.pdf.

Heravi, G., and Eslamdoost, E. (2015). "Applying Artificial Neural Networks for Measuring and Predicting Construction-Labor Productivity." *J. Constr. Eng. Manage.,* 141(10), 04015032.

Khanzadi, M., Nasirzadeh, F., and Alipour, M. (2012). "Integrating system dynamics and fuzzy logic modeling to determine concession period in BOT projects." *Automat. Constr.,* 22 368-376.

Li, S., Wu, H., Wan, D., & Zhu, J. (2011). “An effective feature selection method for hyperspectral image classification based on genetic algorithm and support vector machine.” *Knowledge-Based Systems*, *24*(1), 40-48.

Nasirzadeh, F., Khanzadi, M., Afshar, A., and Howick, S. (2013). "Modeling quality management in construction projects." *Int. J. Civ. Eng.,* 11(1), 14-22.

Nasirzadeh, F., Khanzadi, M., and Rezaie, M. (2014). "Dynamic modeling of the quantitative risk allocation in construction projects." *Int. J. Project Manage.,* 32(3), 442-451.

Nojedehi, P., and Nasirzadeh, F. (2017). “A hybrid simulation approach to model and improve construction labor productivity.” *KSCE Journal of Civil Engineering*, 21(5), 1516-1524.

Pedrycz, W. (2013). Granular computing: analysis and design of intelligent systems. CRC press, Boca Raton, FL, USA.

Pedrycz, W., and Gomide, F. (2007). *Fuzzy systems engineering: toward human-centric computing.* John Wiley & Sons.

Pedrycz, A., Reformat,M. (2006). “Hierarchical FCM in a stepwise discovery of structure in data.” *Soft Comput.* 10, 244–256.

Roeva, O., Fidanova, S., & Paprzycki, M. (2013). “Influence of the population size on the genetic algorithm performance in case of cultivation process modelling.” In *Computer Science and Information Systems (FedCSIS), 2013 Federated Conference on* (pp. 371-376). IEEE.

Sadeghi, N. (2015). "A Hybrid Fuzzy Discrete Event Simulation Framework for Analysis of Stochastic and Subjective Uncertainties in Construction Projects” (Doctoral dissertation university of Alberta). Retrieved from https://doi.org/10.7939/R34084.

Senge, P. M., and Forrester, J. W. (1980). "Tests for building confidence in system dynamics models." *System Dynamics, TIMS Studies in Management Sciences*, 14 209-228.

Sterman, J. D. (2000). *Business dynamics: systems thinking and modeling for a complex world.* Irwin/McGraw-Hill Boston, USA.

Tsehayae, A. A., and Fayek, A. Robinson (2014). "Identification and comparative analysis of key parameters influencing construction labour productivity in building and industrial projects." *Can. J. Civil Eng.,* 41(10), 878-891.

Tsehayae, A. A., and Fayek, A. Robinson (2016a). "Developing and Optimizing Context-Specific Fuzzy Inference System-Based Construction Labor Productivity Models." *J. Constr. Eng. Manage.,* 142(7), 04016017.

Tsehayae, A. A., and Fayek, A. Robinson (2016b). "System model for analyzing construction labour productivity." *Construction Innovation,* 16(2), 203-228.

Whitley, D. (1994). “A genetic algorithm tutorial.” *Statistics and computing*, *4*(2), 65-85.

Wolstenholme, E. F. (1999). "Qualitative vs quantitative modelling: the evolving balance." *J. Oper. Res. Soc.,* 422-428.

Chapter 6. FSD Model Validation and Construction Application[1]

6.1. Introduction

Validation stands in contrast with verification although they are used have been interchangeably in managerial literature (Lucko et al., 2010). Sargent (1991) describes verification as an internal task which is done by researchers and confirms the technical correctness of the research product. In contrast, validation process determines if the research product reflects the behavior of the real world systems properly. Lucko et al. (2010) asserted that verification process is concerned with "doing things right" and validation process is concerned with "doing the right things". However, the SD and FSD models can not be verified and validated using the common validation methods as statistical hypothesis test are not appropriate for the validation of SD (and FSD) models (Senge and Forrester 1980).

Barlas (1994) introduced two approaches for validation of the SD (and FSD) models: structure validity and behavior validity, where the structural validity tests is equivalent to the common verification tests and behavioural validity tests are equivalent to the common validation tests. The structural validation of FSD models can be determined using different tests, such as the dimensional consistency test and the structure verification test (Barlas 1994, Senge and Forrester 1980, Barlas 1985, Barlas 1996, Bala et al. 2017). The dimensional consistency test, introduced by Senge and Forrester (1980), is a simple dimensional analysis of the mathematical equations of the FSD models that is appropriate for validation of hard relationships. On the other hand, soft relationships of FSD models can be validated by the structure verification test (Bala et al. 2017), which compares the structure of the model with the real-world system empirically using expert knowledge or theoretically using relevant literature. In this research, the structural validation tests of the FSD model was implemented using the dimensional consistency test for the hard relationships and the structure verification test for the soft relationships. Moreover, the

[1] Parts of this chapter have been submitted for publication in the Journal of Construction Engineering and Management, ASCE, on November 09, 2017.

behavioral validity test of the FSD model was evaluated using the behaviour reproduction test, as suggested by Barlas (1994), Senge and Forrester (1980), Barlas (1985), and Bala et al. (2017). The behaviour reproduction test compares the pattern of system results (e.g., number of peaks of the simulation results, frequency) to field data. Accordingly, in order to validate the FSD model of construction productivity, field data were collected from earthmoving operations on a pipeline maintenance project in Alberta, Canada. This chapter, presents the details of data collection, as well as presenting the validation of the FSD model of productivity using the field data.

6.2. Field Data Collection

Field data were collected from earthmoving operations on a pipeline maintenance project in Alberta, Canada. The project included 79 work packages (i.e., digs) executed by eight earthmoving crews. Field data were collected from October 11, 2016 to December 11, 2016 for two equipment-intensive activities, excavation and backfilling, through documentation of values of the factors influencing construction productivity, as well as determining the actual activity-level MFP of the two activities. In order to collect field data for the factors influencing construction productivity, a systematic approach was used to collect data at different levels (i.e., micro-level and macro-level factors). First, the details of the factors that influence productivity are identified including: description, scale of measure, data collection cycle, and data source of the factors, as Table 6.1 presents an example for these details. The details for the full list of factors influencing productivity of equipment intensive activities are presented in Appendix B.1.

Table 6.1. Example for the details of the factors influencing productivity

Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
Crew Size	The total size of the crew performing the actual task will have an effect on the production rate of the construction operations.	Integer number	Daily	Foreman

Next, the value for each factor was documented by the researcher using the field data collection forms. Four field data collection forms were developed for documenting the values of the factors influencing construction productivity: daily, weekly, monthly, and one-off data collection forms. Based on the data collection cycle of each factor, as shown in Table 6.1 and Appendix B.1, each factor is included in one of the four data collection forms, depending on its frequency of collection. Then, for documenting the actual value of MFP, the daily progress of the activity and the total daily resource inputs of the activity were documented using the MFP data collection form. The four data collection forms for the factors influencing productivity, as well as the MFP data collection form, are provided in Appendix B.2. The field data regarding the factors influencing productivity and actual MFP are collected using different data sources including the project staff, project documents, and external sources, as shown in Table 6.1 and Appendix B.1. The field data were collected from October 11, 2016 to December 11, 2016 from 79 work packages, and eight earthmoving crews. The field data were used to validate the FSD model of productivity, as discussed in this chapter.

6.3. FSD Model Validation

The FSD model of construction productivity in this research was developed by integrating AnyLogic®, Matlab®, and a Fuzzy Calculator class, which was developed in the Python programming language. AnyLogic® was used to develop the SD component of the model; and Matlab® and the Fuzzy Calculator class were used to develop the fuzzy components of the model. AnyLogic® calculates the results of the mathematical equations, in which all system variables are objective. The Fuzzy Calculator class calculates the results of the mathematical equations that include subjective system variables, and Matlab® calculates the results of the FRBS. The Fuzzy Calculator class was developed by the authors for implementing fuzzy arithmetic on triangular fuzzy numbers using the α-cut method and the extension principle method, the latter of which uses min, product, Lukasiewicz, and drastic product t-norms. Fig. 6.1 presents the FSD model of productivity, developed by AnyLogic®, Matlab®, and the Fuzzy Calculator class.

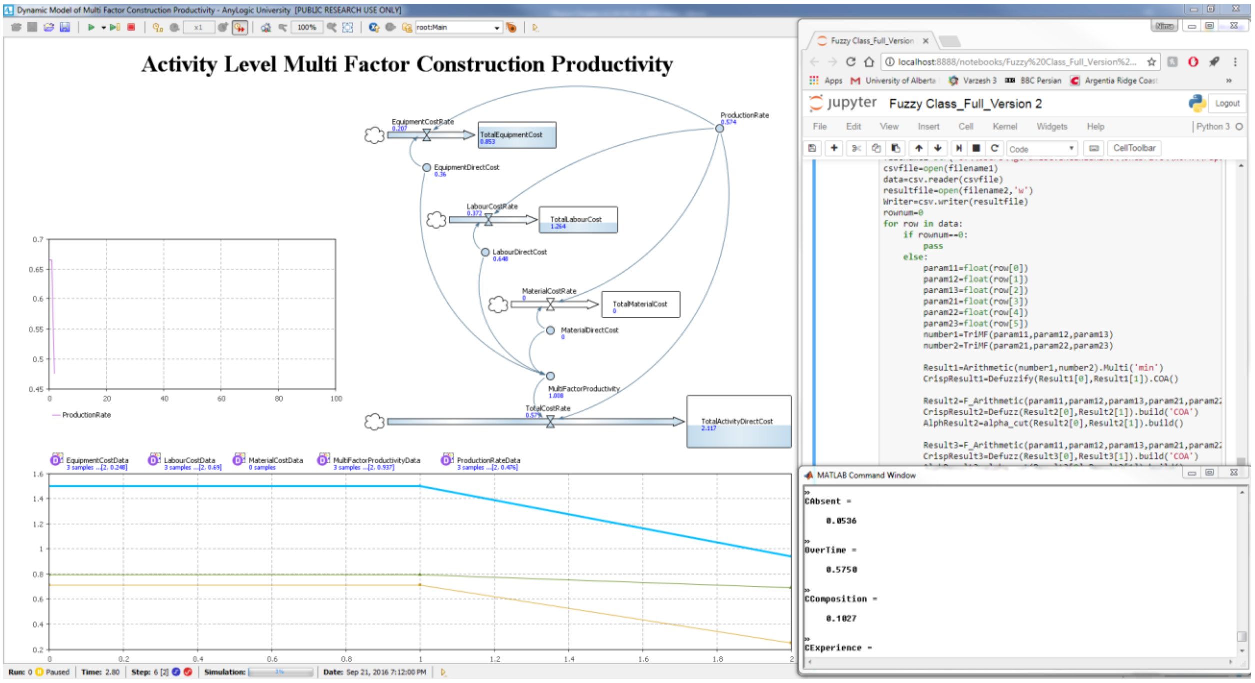

Figure 6.1. Software environment for simulating the activity-level MFP

The structural validity of the FSD model was evaluated using the dimensional consistency test and the structure verification test. The dimensional consistency test is implemented by dimensional analysis of the mathematical equations, which defines the hard relationships of the system. The dimensional consistency test determines if the units of measure on both sides of each equation are consistent or not. This test was implemented on all the hard relationships of the FSD model that are presented in Table 6.2.

Table 6.1. Hard relationships of FSD model of activity-level construction productivity

Relationship Output	Mathematical Equation
Labor Cost Rate	$\text{Labor Cost Rate}\left(\frac{\$}{\text{day}}\right) = \text{Labor Direct Cost}\left(\frac{\$}{\text{units}}\right) \times \text{Production Rate}\left(\frac{\text{units}}{\text{day}}\right)$
Equipment Cost Rate	$\text{Equipment Cost Rate}\left(\frac{\$}{\text{day}}\right) = \text{Equipment Direct Cost}\left(\frac{\$}{\text{units}}\right) \times \text{Production Rate}\left(\frac{\text{units}}{\text{day}}\right)$
Material Cost Rate	$\text{Material Cost Rate}\left(\frac{\$}{\text{day}}\right) = \text{Material Direct Cost}\left(\frac{\$}{\text{units}}\right) \times \text{Production Rate}\left(\frac{\text{units}}{\text{day}}\right)$
Total Labor Cost*	$\text{Total Labor Cost }(\$) = \int \text{Labor Cost Rate}\left(\frac{\$}{\text{day}}\right).dt\ (\text{day})$

Relationship Output	Mathematical Equation
Total Equipment Cost*	$\text{Total Equipment Cost (\$)} = \int \text{Equipment Cost Rate} \left(\frac{\$}{\text{day}}\right).\,dt\ \text{(day)}$
Total Material Cost*	$\text{Total Material Cost (\$)} = \int \text{Material Cost Rate} \left(\frac{\$}{\text{day}}\right).\,dt\ \text{(day)}$
Multi Factor Productivity	$\text{Multi Factor Productivity} \left(\frac{\$}{\text{units}}\right) = \text{Labor Direct Cost} \left(\frac{\$}{\text{units}}\right) + \text{Equipment Direct Cost} \left(\frac{\$}{\text{units}}\right) + \text{Material Direct Cost} \left(\frac{\$}{\text{units}}\right)$
Labor and Equipment Balance**	$\text{Labor and Equipment Balance} = \frac{\text{Crew Size (Person)}}{\text{Number of Equipment (Count)}}$
Crew Size***	$\text{Crew Size (Person)} = \text{Planned Crew Size (Person)} - \text{Absenteeism(Person)}$

For example, in Eq. 6.1, the unit of measure for the left side of the equation is $\left(\frac{\$}{\text{day}}\right)$, and the unit of measure for the right side of the equation is $\left(\frac{\$}{\text{units}}\right) \times \left(\frac{\text{units}}{\text{day}}\right) = \left(\frac{\$}{\text{day}}\right)$, which shows that Eq. 6.1 has dimensional consistency.

$$\text{Labour Cost Rate} \left(\frac{\$}{\text{day}}\right) = \text{Labour Direct Cost} \left(\frac{\$}{\text{units}}\right) \times \text{Production Rate} \left(\frac{\text{units}}{\text{day}}\right). \qquad \textbf{(6.1)}$$

The structure verification test was implemented by verifying the list of the system variables (i.e., factors influencing construction productivity) and the soft relationships of the system through expert knowledge, which was acquired by the interview surveys, as discussed in the methodology section.

The behaviour validity of the FSD model is evaluated using the field data collected on the case study of earthmoving operations. Field data were collected for two equipment-intensive activities, excavation and backfilling, through documentation of values of the factors influencing construction productivity, as well as by determining the actual activity-level MFP of the two activities. Due to confidentiality constraints, all field data were normalized into the range of $[0,1]$ using Eq. 6.2.

$$V_{i,normalized} = \frac{V_i - \min(V_i)}{\max(V_i) - \min(V_i)}, \quad \textbf{(6.2)}$$

where $V_{i,normalized}$ stands for the normalized value of any system variable and V_i represents the original value of the system variable. Table 6.3 presents the results of simulation for the MFP for earthmoving operations in a 30-day period and compares the results to the actual field data; Fig. 6.2 presents these results graphically.

Table 6.3. Simulation results and actual field data for MFP

Simulation Time (day)	Simulation Results	Actual Field Data	Error $\lvert$simulation result − actual Field data$\rvert$
1	0.321	0.365	0.044
2	0.552	0.582	0.03
3	0.858	0.775	0.083
4	0.949	0.978	0.029
5	0.738	0.749	0.011
6	0.911	0.978	0.067
7	0.798	0.775	0.023
8	0.714	0.500	0.214
9	0.692	0.775	0.083
10	0.320	0.206	0.114
11	0.273	0.146	0.127
12	0.824	0.929	0.105
13	0.810	0.765	0.045
14	0.633	0.765	0.132
15	0.933	0.929	0.004
16	0.857	0.765	0.092
17	0.540	0.765	0.225
18	0.000	0.054	0.054
19	0.234	0.039	0.195
20	0.744	0.926	0.182
21	0.873	0.926	0.053
22	0.873	0.912	0.039
23	0.988	0.912	0.076
24	0.942	0.912	0.03
25	0.551	0.504	0.047
26	0.630	0.450	0.18
27	0.823	1.000	0.177
28	0.949	1.000	0.051
29	0.898	1.000	0.102

Simulation Time (day)	Simulation Results	Actual Field Data	Error $\lvert \text{simulation result} - \text{actual Field data} \rvert$
30	0.903	0.894	0.009

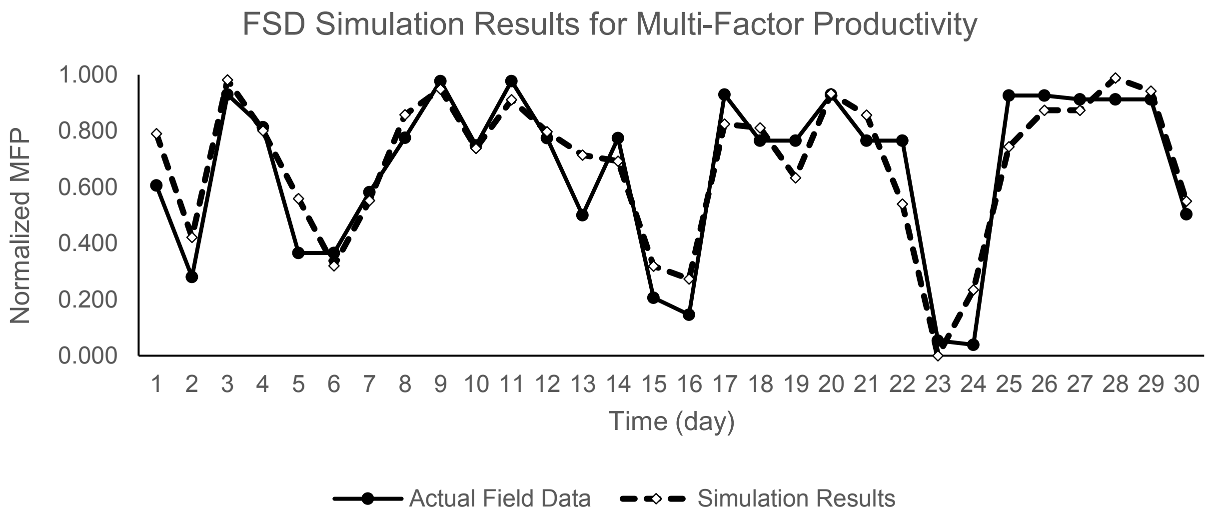

Figure 6.2. Simulation results for MFP in comparison to actual field data

The *y*-axis in Fig. 6.2 shows the normalized value of the MFP of the earthmoving operations, and the *x*-axis shows the duration of earthmoving operations measured in days. The simulation results can be presented as fuzzy numbers or defuzzified values. Defuzzification is the process of converting a fuzzy number to a crisp number. In order to present the simulation results as fuzzy numbers, the results need to be presented at each time step. In order to evaluate the behaviour validity of the FSD model using the behaviour reproduction test, changes in the results over the simulation time need to be compared to the actual field data. The simulation results presented in Fig. 6.1 are the defuzzified values of MFP for the earthmoving operations. These simulation results were defuzzified using the center of area (COA) method, which is a common defuzzification method. Referring to Fig. 4, behavioural validity of the FSD model may be evaluated by the behaviour reproduction test, which shows the following: the trends in the actual MFP values (i.e., an increase or decrease of productivity between any two consecutive points) are predicted correctly by the simulation results in 70% of cases (refer to Table 6.3); and the turning points in the actual MFP values (i.e., the points in which the trend of productivity changes) are predicted correctly by the simulation results in 70% of cases (refer to Table 6.3). Finally, the accuracy of the simulation results is evaluated using two statistical measures: root mean square error (RMSE) and normalized root mean square error (NRMSE). RMSE is a common statistical measure, which is appropriate for evaluating the accuracy of predictive models, since it calculates the error of model in the same scale as the output of the model (Hyndman and Koehler 2006). Accordingly, RMSE measure can represent the uncertainty of the forecasts that are provided based on the results of the predictive model. Although RMSE is an appropriate measure for evaluation of the predictive models, due to its scale-dependency (calculating the error in the same scale as the output), this error measure cannot be used for comparing different predictive models. Accordingly, in this research the accuracy of the predictive model is also evaluated by a non scale-dependent measure, NRMSE as suggested by Shcherbakov et al. (2013). NRMSE compares the RMSE of the data to the average value of the actual field data. RMSE of the simulation results is 0.11, which is calculated using Eq. 6.3.

$$\mathrm{RMSE} = \sqrt{\frac{\sum(\mathrm{simulation\ result} - \mathrm{actual\ field\ data})^2}{\mathrm{n}}}. \qquad \textbf{(6.3)}$$

In addition, NRMSE of the simulation results is 15% calculated by Eq. 6.4.

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{\mathrm{Mean(actual\ field\ data)}}. \qquad \textbf{(6.4)}$$

By implementing fuzzy arithmetic operations on the mathematical equations of the FSD model, the support of the resulting fuzzy numbers grows rapidly, which is interpreted as an overestimation of uncertainty. In general, an increase in the length of the support of a fuzzy number shows an increase in the amount of uncertainty represented by that fuzzy number. The overestimation of uncertainty in FSD models is affected by the chosen fuzzy arithmetic implementation method, which is used to solve the mathematical equations of the FSD model. Accordingly, the effect of fuzzy arithmetic implementation methods on the simulation results were evaluated to determine the most appropriate method. Fig. 6.3 shows the results of the simulation for the “Total Cost Rate” of the activity for the first time step of simulation, calculated using the α-cut method and the extension principle method with the min, product, Lukasiewicz*,* and drastic product t-norms.

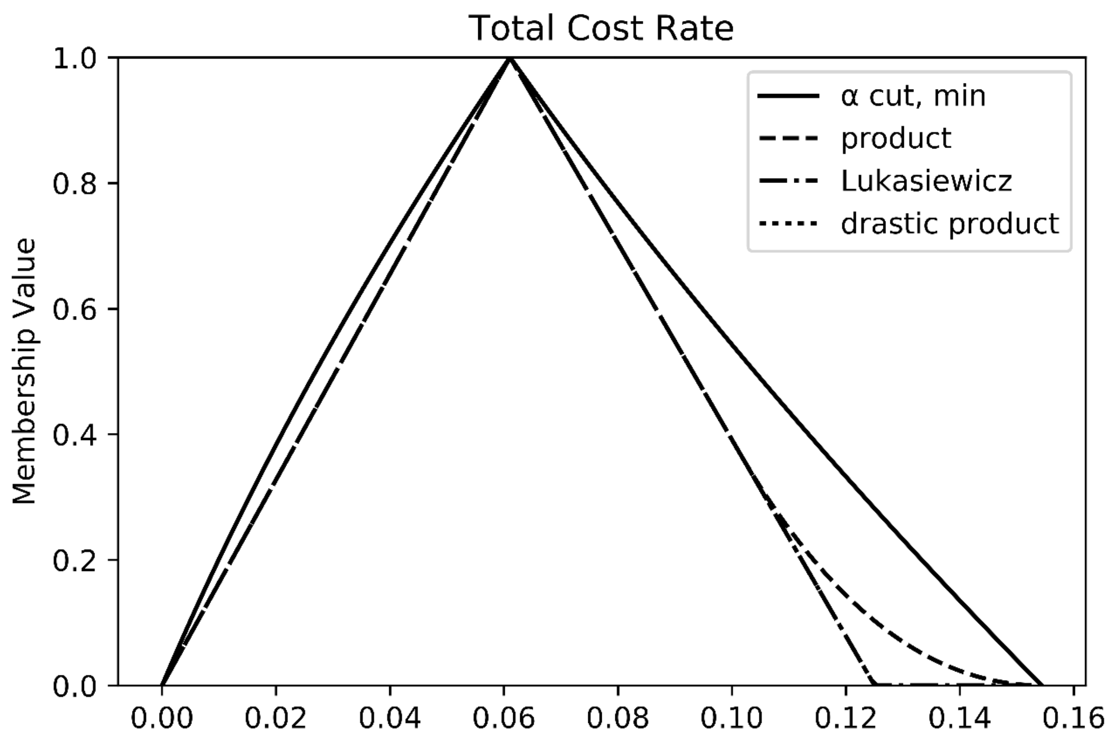

Figure 6.3. Simulation results for Total Cost Rate for the first time step

The simulation results presented in Fig. 6.3 show that the implementation of fuzzy arithmetic operations using the *α*-cut method and using the extension principle method with the min t-norm provide the same results. Moreover, the length of the support of the four fuzzy numbers represented in Fig. 6.3 are 0.154, 0.154, 0.125, 0.125 for the min, product, Lukasiewicz, and drastic product t-norms respectively. Accordingly, the implementation of fuzzy arithmetic using the extension principle method with the drastic product t-norm provides the fuzzy number with the smallest length of support in this case. The results of the simulation for the "Total Cost Rate" of the activity in a 30-day period were calculated using the *α*-cut method and using the extension principle method with the min, product, Lukasiewicz, and drastic product t-norms, as presented in Table 6.4.

Table 6.4. Simulation results and actual field data representing fuzzy number for total cost rate

Sim. Time	**Min** t-norm		**Product** t-norm		**Lukasiewicz** t-norm		**Drastic Product** t-norm		Actual Field Data
	Sim. Results *	Support Length	Sim. Results*	Support Length	Sim. Results*	Support Length	Sim. Results*	Support Length	
1	0.069	0.154	0.064	0.154	0.062	0.125	0.062	0.125	0.049
2	0.254	0.295	0.249	0.295	0.247	0.232	0.247	0.231	0.261
3	0.075	0.181	0.070	0.181	0.070	0.159	0.069	0.159	0.027
4	0.069	0.154	0.064	0.154	0.062	0.125	0.062	0.125	0.029
5	0.089	0.207	0.084	0.207	0.083	0.184	0.083	0.184	0.027
6	0.382	0.321	0.379	0.321	0.375	0.217	0.375	0.217	0.417
7	0.023	0.070	0.019	0.070	0.018	0.055	0.018	0.055	0.050
8	0.043	0.130	0.039	0.130	0.038	0.115	0.038	0.115	0.054
9	0.165	0.207	0.162	0.207	0.158	0.139	0.158	0.138	0.074
10	0.184	0.222	0.180	0.222	0.177	0.153	0.177	0.152	0.089
11	0.333	0.307	0.329	0.307	0.326	0.217	0.326	0.217	0.424
12	0.154	0.234	0.149	0.234	0.146	0.186	0.146	0.186	0.127
13	0.147	0.216	0.142	0.216	0.139	0.165	0.139	0.165	0.120
14	0.165	0.249	0.160	0.249	0.158	0.202	0.158	0.202	0.134
15	0.177	0.242	0.173	0.242	0.170	0.187	0.170	0.187	0.140
16	0.203	0.249	0.198	0.249	0.195	0.187	0.195	0.187	0.155
17	0.203	0.249	0.198	0.249	0.195	0.187	0.195	0.187	0.155
18	0.206	0.250	0.201	0.250	0.198	0.186	0.198	0.186	0.149
19	0.208	0.254	0.204	0.254	0.201	0.192	0.201	0.191	0.144
20	0.222	0.245	0.218	0.245	0.215	0.169	0.215	0.169	0.156
21	0.205	0.218	0.202	0.218	0.199	0.113	0.198	0.110	0.138
22	0.203	0.249	0.198	0.249	0.195	0.187	0.195	0.187	0.120
23	0.629	0.393	0.626	0.393	0.622	0.235	0.621	0.233	0.544
24	0.259	0.277	0.255	0.277	0.252	0.201	0.252	0.202	0.174
25	0.280	0.275	0.276	0.275	0.273	0.188	0.273	0.188	0.183
26	0.238	0.261	0.234	0.261	0.231	0.187	0.231	0.186	0.132
27	0.069	0.173	0.064	0.173	0.064	0.153	0.064	0.153	0.381
28	0.294	0.285	0.290	0.285	0.287	0.198	0.286	0.198	0.183
29	0.254	0.295	0.249	0.295	0.247	0.232	0.246	0.231	0.120
30	0.320	0.315	0.316	0.315	0.313	0.236	0.313	0.236	0.173
RMSE	**0.0915**		**0.0898**		**0.0884**		**0.0883**		**-**

The simulation results presented in Table 6.4 show the following: the implementation of fuzzy arithmetic operations using the α-cut method and using the extension principle method with the min t-norm always return the same results (Elbarkouky et al. 2016); using the *α*-cut method and the extension principle method with the min t-norm return the largest defuzzified values of the simulation results, followed by the extension principle method with the product t-norm, Lukasiewicz t-norm, and drastic product t-norm, respectively; and finally, using the extension principle method with the drastic product t-norm has the lowest RMSE, followed by the extension principle method with the Lukasiewicz t-norm, product t-norm, and min t-norm (and the *α*-cut method), respectively. In order to compare the uncertainty overestimation caused by the fuzzy arithmetic implementation methods, the length of the support of the fuzzy number for "Total Cost Rate" is presented in Table 6.4, and it is shown graphically in Fig. 6.4. The length of the support of the fuzzy number for "Total Cost Rate" represents the level of uncertainty overestimation.

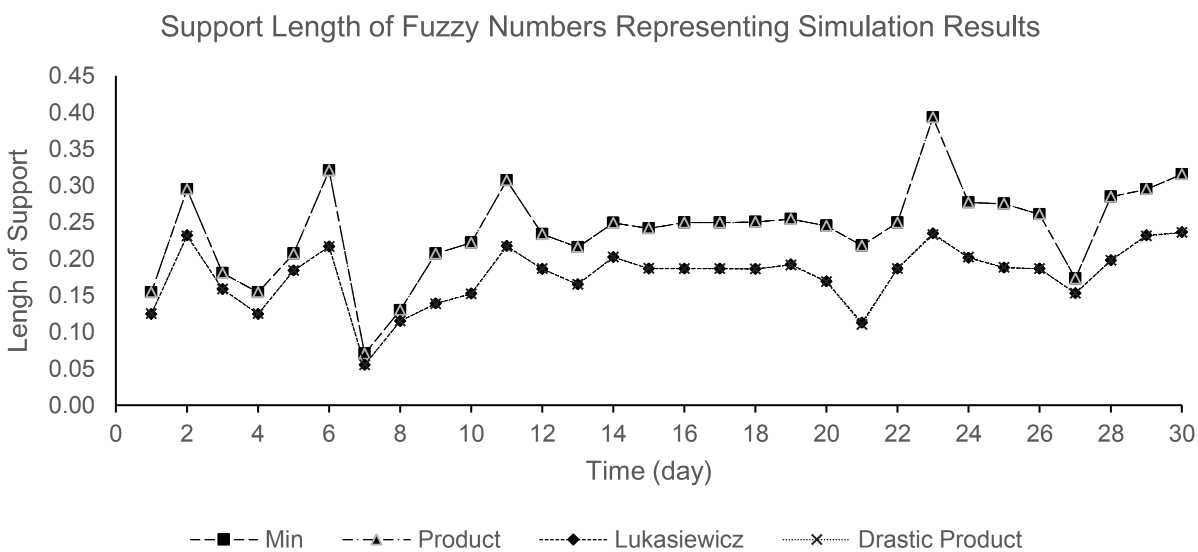

Figure 6.4. Length of support of fuzzy numbers for total cost rate

Referring to Table 6.4 and Fig. 6.4, a comparison of the length of the support of the fuzzy number for "Total Cost Rate" shows the following: the length of the support of the fuzzy number is always equal when using the *α*-cut method and when using the extension principle method with the min and product t-norms; and using the extension principle method with the drastic product t-norm returns a fuzzy number with the smallest length of the support, followed by the extension principle with the Lukasiewicz t-norm; and the other methods (i.e., using the *α*-cut method, using the extension principle method with the min and product t-norms) return a fuzzy number with the largest support length. Based on the fact that the extension principle method using the drastic product t-norm has both the lowest RMSE and the smallest uncertainty overestimation, this method was deemed to be the most appropriate method for fuzzy arithmetic implementation in the FSD model presented in this paper.

6.3.1. Discussion

The FSD model of construction productivity presented in this research can be used to predict the MFP of equipment-intensive activities for construction projects. Due to the fact that field data are used to develop the FSD model, the conditions of the project, from which field data are collected, needs to be considered for practical application of the model. The project conditions for the FSD model in this thesis are as follows: (1) field data are collected during the winter season in Alberta, Canada, (2) the average temperature during the data collection period was 1.29°C with the minimum of -24°C and the maximum of 11.5°C, (3) the soil type was mixed sand and clay cultivation soil, and (4) the soil moisture was rated as wetland "Marsh" class II according to Government of Alberta (2015). In practical application, the FSD model can facilitate the construction planning process by allowing users to predict the productivity of construction activities for different execution plans prior to the execution phase. In order to predict the productivity of an activity, the user provides the values of the independent system variables only; then the FSD model determines the values of the dependent system variables based on their relationships with the other system variables, and finally determines the MFP. The independent system variables are the variables that are not influenced by any other system variables in the FSD model (e.g., temperature). The FSD model of construction productivity presented in this research includes 12 independent system variables and 13 dependent system variables. Accordingly, the practical application of the FSD model for predicting MFP is more efficient and easier as compared to the static models of productivity (e.g., ANN model), where the static models require the value of all 25 system variables as input to predict the MFP. Users can change the system variables based on their execution plans (e.g., changing the crew size or number of equipment) and simulate the model to predict the productivity, and accordingly, they can select the most appropriate execution plan for the activity. The FSD model of productivity can predict the daily value of MFP, which provides more information about productivity, as compared to existing static productivity models, by allowing users to track changes in productivity over time.

The FSD model of construction productivity presented in this research helps construction practitioners to identify the most critical factors influencing productivity of equipment-intensive activities based on field data. Based on the results of feature selection (refer to Section 5.3), the top 25 critical factors that influence productivity of equipment-intensive activities are identified (refer to Table 5.1). This list can be used to analyze the effect of each critical factor on productivity and to develop strategies for improving productivity by optimizing the value of these factors, as discussed in this section. In order to analyze the effect of each system variable on productivity, the system variable that is being analyzed must first be changed in the desirable range, while the other system variables are kept unchanged; once this is accomplished, the FSD model can then be simulated. Accordingly, the results of simulation represent the effect of the system variables that were changed in step 1 on construction productivity; the results of the analysis help practitioners to identify the optimal value of each factor.

The FSD model of construction productivity presented in this paper is capable of capturing the probabilistic and non-probabilistic uncertainties of the system variables, as well as the deterministic values for the system variables. In order to capture these probabilistic uncertainties, the model allows users to represent variables with probabilistic distributions, such as the temperature in future projects. For capturing the non-probabilistic uncertainties of the system variables, the model allows users to represent variables with fuzzy membership functions, such as crew motivation. Due to the fact that the case study presented in this paper was extracted from a previously executed construction project, the system variables do not exhibit any probabilistic uncertainty; accordingly, in the case study presented in this paper, the system variables are represented by either deterministic values or by fuzzy membership functions.

In comparison to the SD models of productivity developed by Nasirzadeh and Nojedehi (2013) and Mawdesley and Al-Jiboury (2009), the FSD model of productivity presented in this paper can increase the accuracy of productivity predictions by capturing the effect of subjective variables (e.g., crew motivation) on productivity, as well as allowing practitioners to evaluate these variables using linguistic terms rather than precise numerical values. In contrast to the FSD model developed by Nojedehi and Nasirzadeh (2017), which is for labour-intensive activities and predicting CLP, the predictive model presented in this paper predicts MFP, which is the appropriate measure of productivity for equipment-intensive activities. Moreover, the predictive model presented in this paper provides construction practitioners with information regarding the cost of the three input resources of an activity (equipment cost, labour cost, and material cost), while the predictive models of CLP provide this information for one input resource only (i.e., labour). Finally, the comparison of the two fuzzy arithmetic implementation methods (i.e., the α-cut method and the extension principle method) shows that the implementation of fuzzy arithmetic operations by the extension principle using drastic product t-norm reduces the overestimation of uncertainty in comparison to the α-cut method, while increasing the accuracy of the simulation results, in contrast to previously developed FSD models (e.g., Nojedehi and Nasirzadeh 2017, Khanzadi et al. 2012), which only employ the α-cut method. Reducing the uncertainty overestimation of the simulation results increases the ability of construction practitioners to accurately predict the actual productivity of an activity based on the simulation results.

6.4. Summary

This chapter validates the predictive model of construction productivity using field data. A field data collection methodology was developed, and field data were collected on a case study in Alberta, Canada. Using the field data, the FSD model validation was implemented through the structural and behavioural validity tests, as discussed in this chapter. Finally, the contributions of the proposed model over the existing predictive models of productivity were discussed. The next chapter presents the conclusions and the academic and industrial contributions of this research. Moreover, the limitations of this research and proposed areas for extensions to this research are presented in the next chapter.

6.5. References

Bala, B. K., Arshad, F. M., & Noh, K. M. (2017). *Systems thinking: system dynamics.* Springer, Singapore.

Barlas, Y. (1985). *Validation of System Dynamics Models with a Sequential Procedure Involving Multiple Quantitative Methods* (Doctoral dissertation Georgia institute of Technology). Retrieved from http://hdl.handle.net/1853/25745.

Barlas, Y. (1994). "Model validation in system dynamics." *Proc., 1994 international system dynamics conference,* Sterling, Scotland, 1-10.

Barlas, Y. (1996). "Formal aspects of model validity and validation in system dynamics." *Syst. Dynam. Rev.,* 12(3), 183-210.

Elbarkouky, M. M., Fayek, A. Robinson, Siraj, N. B., and Sadeghi, N. (2016). "Fuzzy arithmetic risk analysis approach to determine construction project contingency." *J. Constr. Eng. Manage.*, 142(12), 04016070.

Government of Alberta (2015). “Alberta Wetland Classification System”. https://open.alberta.ca/dataset/2015-Alberta-Wetland-Classification-System-June-01-2015.pdf

Hyndman, R. J., & Koehler, A. B. (2006). Another look at measures of forecast accuracy. *International journal of forecasting*, 22(4), 679-688.

Khanzadi, M., Nasirzadeh, F., and Alipour, M. (2012). "Integrating system dynamics and fuzzy logic modeling to determine concession period in BOT projects." *Automat. Constr.,* 22 368-376.

Lucko, G., and Rojas, E. M. (2009). "Research validation: Challenges and opportunities in the construction domain." *J.Constr.Eng.Manage.*, 136(1), 127-135.

Mawdesley, M. J., and Al-Jibouri, S. (2009). "Modelling construction project productivity using systems dynamics approach." *International Journal of Productivity and Performance Management,* 59(1), 18-36.

Nasirzadeh, F., and Nojedehi, P. (2013). "Dynamic modeling of labor productivity in construction projects." *Int. J. Project Manage.,* 31(6), 903-911.

Nojedehi, P., and Nasirzadeh, F. (2017). “A hybrid simulation approach to model and improve construction labor productivity.” *KSCE Journal of Civil Engineering*, 21(5), 1516-1524.

Sargent, R. G. (1991). “Simulation model verification and validation.” *Proc. of the 23rd conference on Winter simulation*. IEEE Computer Society, Phoenix, AZ, 37-47.

Senge, P. M., and Forrester, J. W. (1980). "Tests for building confidence in system dynamics models." *System Dynamics, TIMS Studies in Management Sciences*, 14 209-228.

Shcherbakov, M.V., Brebels, A., Shcherbakova, N.L., Tyukov, A.P., Janovsky, T.A., and Kamaev, V.A., (2013) “A survey of Forecast error measures,” *World Applied Science Journal*, 24, 171-176.

Chapter 7. Conclusions and Recommendations

7.1. Introduction

This chapter presents the research summary and the academic and industrial contributions of this research. This chapter also discusses the limitations of this research and provides recommendations for future research.

7.2. Research Summary

Construction productivity has long been a major research interest in the construction engineering domain. Since construction is a labour-intensive industry, the majority of previous research on activity-level productivity has either focused on the identification of factors influencing construction labour productivity (CLP) or on the development of predictive models for CLP. However, with recent advancements in technology, equipment is now the driver of productivity for some construction activities, which are identified as equipment-intensive activities. Since the main drivers of productivity for equipment-intensive and labour-intensive activities are different, the factors that influence the productivity of these two activities are also different. Therefore, the predictive models that have been developed for labour-intensive activities cannot accurately predict the productivity of equipment-intensive activities. This research identified the factors influencing the productivity of equipment-intensive activities then developed a predictive model of productivity for these activities using the fuzzy system dynamics (FSD) modeling technique. This research also developed computational methods for the implementation of fuzzy arithmetic operations in FSD models. The objectives of this research were achieved in five stages, as discussed in this section.

7.2.1. The First Stage

An extensive literature review was conducted on the relevant topics and gaps in the research on each topic were identified. First, previous research on construction productivity was reviewed, and the three following gaps were identified: a failure to identify the factors influencing the productivity of equipment-intensive activities, a failure to determine the productivity of equipment-intensive activities with an appropriate productivity measure, and a failure to capture the dynamism of productivity and simultaneously address probabilistic and non-probabilistic uncertainties. Next, previous research on the FSD technique was reviewed and two gaps were identified. There is a gap in the research on the integration of the FSD technique with artificial intelligence methods to define the soft relationships of FSD models, and there is a gap in the research on the use of the FSD technique to reduce the overestimation of uncertainty in fuzzy numbers, which represent simulation results. Finally, previous research on the development of computational methods for implementing fuzzy arithmetic operations were reviewed. This review shows that there is a gap in the research on this topic, since there are no available computational methods for implementing fuzzy arithmetic operations using the extension principle approach with the two most common t-norms (i.e., product and Lukasiewicz).

7.2.2. The Second Stage

A comprehensive list of the factors that influence the productivity of equipment-intensive activities was developed. The relevant studies on construction productivity were reviewed using a literature review methodology, and a list of 221 micro- and macro-level factors were identified by reviewing 117 previous research works. Next, the most critical factors influencing the productivity of equipment-intensive activities were identified by expert knowledge, which was acquired from two groups of project staff (i.e., project management staff and project tradespeople staff). Two different interview surveys were designed: a project management survey, which included all micro- and macro-level factors, and a tradespeople survey, which included all crew- and activity-level factors as well as some project-level factors. In order to assess the level of influence of each factor on productivity, a framework was developed using the technique for order of preference by similarity to ideal solution (TOPSIS). Then the most critical factors influencing productivity were identified from two perspectives (i.e., project management survey respondents and tradespeople survey respondents). The perspectives of the two surveys' respondents on the common factors' impacts on productivity were compared. The comparison between the perspectives of the project management survey respondents and the tradespeople survey respondents was implemented through an analysis of the variance (ANOVA) F-test.

7.2.3. The Third Stage

A computational method was developed for implementing fuzzy arithmetic operations using the extension principle approach with product and Lukasiewicz t-norms. There are computational methods available in the literature for the implementation of fuzzy arithmetic operations using the extension principle approach with the min and drastic product t-norms. However, the extension principle approach with the min t-norm has been criticized for overestimating uncertainties in the fuzzy numbers resulting from the operation, and the extension principle approach with the drastic product t-norm has been criticized for producing fuzzy numbers that are highly sensitivity to changes in the input fuzzy numbers. To address these limitations, this research presented two computational methods for implementing fuzzy arithmetic operations using the extension principle approach with two common t-norms: product and Lukasiewicz t-norms. These computational methods are used for implementing fuzzy arithmetic operations in the FSD model of productivity and to select the most appropriate approach for reducing the overestimation of uncertainty in the fuzzy numbers that represent simulation results. In order to implement fuzzy arithmetic operations in the different applications of fuzzy numbers, the Fuzzy Calculator class was developed in the Python programming language. This class is capable of implementing fuzzy arithmetic operations on triangular fuzzy numbers using the α-cut approach and the extension principle approach with the min, product, Lukasiewicz, and drastic product t-norms.

7.2.4. The Fourth Stage

The predictive model of construction productivity was developed using the FSD technique through the following four steps: identification of the factors influencing productivity, feature selection, qualitative FSD modeling, and quantitative FSD modeling. Identification of the factors influencing productivity was accomplished in the second stage of research, as discussed in Section 7.2.2. Through the literature review, 72 crew-level and activity-level factors were identified and verified by expert knowledge to have either a negative or positive impact on construction productivity. Next, the number of these factors—hereafter referred as system variables—was reduced by feature selection. Feature selection was implemented using the following two approaches: correlation-based feature selection and the wrapper method with the genetic algorithm search method. As the result of feature selection, twenty-five system variables were selected for developing the predictive model of construction productivity.

Then the qualitative FSD model of productivity was developed by identifying the relationships between the system variables. This model includes two components: the stock and flow diagram and the cause and effect diagram. The stock and flow diagram measures the multifactor productivity (MFP) of the activity, the total cost rate, and the total activity direct cost. The cause and effect diagram uses system variables to predict the value of the three inputs of MFP (i.e., “labour direct cost”, “equipment direct cost”, and “material direct cost”), as well as the “production rate” of the activity. Finally, the quantitative FSD model was developed by identifying the system’s subjective variables and developing fuzzy membership functions for representing these variables, as well as defining the relationships between the system variables numerically. Hard relationships were defined by mathematical equations, and soft relationships were defined either by mathematical equations developed by statistical regression or data-driven FRBS developed by FCM clustering, which were selected based on their accuracy. Since they both contain subjective system variables represented by fuzzy numbers, fuzzy arithmetic was then used to solve the soft relationships defined using mathematical equations and the hard relationships.

7.2.5. The Fifth Stage

The predictive model of construction productivity was validated using a case study of earthmoving operations. In order to validate the predictive model of productivity, field data were collected for two equipment-intensive activities, excavation and backfilling. Next, the FSD model was validated using structural and behavioural validation tests. The structural validity of the FSD model was verified by the dimensional consistency test (for the hard relationships) and the structure verification test (for the soft relationships). The behavioural validity of the FSD model was verified by the behaviour reproduction test.

Next, the different approaches for implementing fuzzy arithmetic operations were compared and the extension principle approach with the drastic product t-norm was identified as the most appropriate method for implementing fuzzy arithmetic in the FSD model of productivity.

7.3. Research Contributions

7.3.1. Academic Contributions

The academic contributions of this research are as follows:

1) Development of a comprehensive list of the factors that influence the productivity of equipment-intensive activities. Previous research focused on the identification of the factors influencing the productivity of labour-intensive activities, while this list addresses a gap in the research on the productivity of equipment-intensive activities. This comprehensive list can be used for developing predictive models of productivity or for the assessment and identification of the most critical factors influencing the productivity of these activities.
2) Development of the first predictive model of construction productivity for determining the MFP of equipment-intensive activities. Existing predictive models of productivity for equipment-intensive activities do not determine an appropriate measure of productivity for these activities. They determine either the CLP of these activities, which does not provide any information about the resource that drives the productivity of equipment-intensive activities (i.e., equipment), or the production rate of these activities, which does not provide any information about the resource inputs of the activity. This thesis addresses the gap in the research by determining the MFP of equipment-intensive activities, and it provides information regarding the three input resources of these activities (labour, equipment, and material).
3) Development of the first FSD model of productivity for equipment-intensive activities, which captures the dynamism of construction productivity and the interactions between the factors influencing productivity while simultaneously processing the probabilistic and subjective uncertainty of these factors. Existing

models were either static or could not capture the subjective uncertainties of the factors influencing construction productivity. The FSD model of productivity addresses this gap, since the SD component captures the dynamism of construction projects and the relationships between the factors influencing construction productivity while the fuzzy logic component addresses the subjective uncertainty of these factors.

4) Integration of data-driven FRBS and FSD for defining the soft relationships between system variables. This integration fills the gap in the research on the FSD technique for increasing the accuracy of the methods that define the soft relationships of FSD models. Although soft relationships can be defined by any pattern recognition methods, previous research used only the statistical regression method. Integrating data-driven FRBS and the FSD technique increases the accuracy of the definition of soft relationships because the artificial intelligence methods for pattern recognition outperform the statistical regression method when data are limited (Paliwal and Kumar 2009).
5) Development of computational methods for the implementation of fuzzy arithmetic operations in different applications using the extension principle approach with product and Lukasiewicz t-norms. Existing computational methods for implementing fuzzy arithmetic operations are limited to the α-cut approach and the extension principle approach with the drastic product t-norm. The developed computational methods contribute to a more effective use of fuzzy numbers in different applications by addressing the limitation of the α-cut approach, which has been criticized for overestimation of uncertainties. The methods also address the limitation of the extension principle approach with the drastic product t-norm, which has been criticized for the high sensitivity of the resulting fuzzy numbers.
6) Evaluation of the different approaches for implementing fuzzy arithmetic operations in the FSD models and selection of the most appropriate approach based on the accuracy of simulation results and the amount of uncertainties in the simulation results. Previous applications of FSD models in construction have used only the α-cut approach to implement fuzzy arithmetic operations because of its simplicity. However, the α-cut approach causes an overestimation of uncertainty

in the resulting fuzzy numbers, and the ability of users to predict the actual system output accurately (e.g., actual productivity) based on the simulation results is reduced. This evaluation addresses this gap in the research and contributes to a more effective application of FSD models in construction.

7.3.2. Industrial Contributions

The industrial contributions of this research are as follows:

1) Assessment of the factors influencing the productivity of equipment-intensive activities in order to identify the most critical factors based on their level of influence on productivity. This assessment provides construction practitioners with information about the factors that have the highest level of influence on productivity and the factors that have the highest potential to improve productivity.
2) Identification of the differences between the perspectives of the project management staff and the tradespeople staff regarding the impact of different factors on productivity. This comparison enables construction managers to identify which factors produce the most significant disparities between the perspectives of the two groups. The identification of these factors can help project management staff and tradespeople staff reach a consensus for planning and improving the productivity of equipment-intensive activities.
3)
4) Prediction of the MFP of equipment-intensive activities to provide construction planners with more information about the resource inputs of these activities compared to predictive models of CLP. Predicting the MFP of construction activities provides practitioners with information about the three input resources of the activity (labour cost, equipment cost, and material cost). Existing models only provide this information about one of the activity's input resources (labour).
5) Developing an FSD simulation model of construction productivity that enables construction planners to track changes in productivity over time, evaluate potential productivity improvement strategies, analyze the effect of each factor on productivity in order to optimize these factors, and predict the productivity of different execution plans. The industrial application of the FSD model of

productivity makes the following improvements to existing models of productivity. First, compared to existing static productivity models, the FSD model of productivity provides more information about productivity by allowing users to track changes in productivity over time. Second, the FSD model of productivity can increase the accuracy of productivity predictions in practice by capturing the interrelationships between the factors influencing productivity, the factors' individual impact on productivity, and the effect of subjective variables (e.g., crew motivation) on productivity. Moreover, the FSD model of productivity enables practitioners to optimize project execution plans and productivity improvement strategies. It does this by allowing practitioners to predict productivity for different execution plans prior to execution or to predict the effectiveness of different productivity improvement strategies during execution. Finally, this model allows construction planners to analyze the effect of each factor on productivity by changing a given variable in the desirable range and simulating the model while the other variables are kept unchanged.

7.4. Research Limitations and Suggestions for Future Research

7.4.1. Identifying the Most Critical Factors Influencing Productivity

The identification of the most critical factors that influence the productivity of equipment-intensive activities as presented in this research has the following limitations, which can be addressed in future research.

- For the identification of the most critical factors influencing productivity, the interview surveys were only administered to one construction company that was active in the industrial construction sector. However, the problem of identifying the most critical factors influencing productivity is context-dependant, where the influence of the factors on productivity varies from one context to another. Thus the results of the interview surveys presented in this research cannot be generalized to all equipment-intensive activities in different contexts. In order to address this limitation, the interview surveys need to be administered to other construction companies to identify the most critical factors influencing productivity in other contexts.

- In this research, 15 project management surveys and 20 tradespeople surveys were collected. Considering the population of the respondents (i.e., 16 for the project management survey and 54 for the tradespeople survey), the response rates achieved in this research provided 99% confidence for the results of the project management survey and 90% confidence for the results of the tradespeople survey. In future research, the confidence level of the results of the tradespeople survey may be improved by increasing the number of survey respondents. By increasing the number of survey respondents, the confidence level of the comparison between the perspectives of the project management respondents and tradespeople respondents will also be increased.

7.4.2. Computational Methods for Implementing Fuzzy Arithmetic Operations

This research presented computational methods for the implementation of fuzzy arithmetic operations on triangular fuzzy numbers using the extension principle approach with product and Lukasiewicz t-norms. These computational methods have the following limitations, which can be addressed in future research.

- The computational methods presented in this research are only able to implement fuzzy arithmetic operations on triangular fuzzy numbers, which are common fuzzy numbers in engineering applications. In future research, these computational methods can be extended to implement fuzzy arithmetic operations on trapezoidal and Gaussian fuzzy numbers, which are the other two common forms of fuzzy numbers in engineering applications.
- The triangular fuzzy numbers are not closed under the fuzzy arithmetic operations using the extension principle approach with product and Lukasiewicz t-norms. In other words, the result of implementing fuzzy arithmetic operations on two triangular numbers using the extension principle approach with these two t-norms is not a triangular number. Therefore the computational methods presented in this research are not able to implement consecutive fuzzy arithmetic operations on triangular fuzzy numbers (i.e., implementing a fuzzy arithmetic operation on the

result of another fuzzy arithmetic operation). In order to address this limitation, the computational method presented in this research needs to be extended to implement fuzzy arithmetic operations using product and Lukasiewicz t-norms on any arbitrary-shaped fuzzy number defined by its α-cuts.

- Existing computational methods (including the computational methods presented in this research) are capable of implementing fuzzy arithmetic operations using the extension principle approach with the four common t-norms, the min, product, Lukasiewicz, and drastic product t-norms. Although these t-norms are the most common in engineering applications, parametric t-norms such as Yager t-norms are more flexible for the implementation of fuzzy arithmetic operations. Using parametric t-norms enables practitioners to change the amount of uncertainty included in the resulting fuzzy numbers and the sensitivity of the resulting fuzzy numbers to changes in the input fuzzy numbers by changing the parameters of the t-norm. Accordingly, developing computational methods for the implementation of fuzzy arithmetic operations using the extension principle approach with a parametric t-norm (e.g., a Yager t-norm) will contribute to a more effective use of fuzzy numbers in engineering applications.

7.4.3. Integration of the FSD Technique with Artificial Intelligence Methods

This research integrated the FSD technique with the FCM clustering method, which is an artificial intelligence method for pattern recognition. As presented in this research, the integration of the FSD technique and artificial intelligence methods has the following limitations, which can be addressed in future research.

- In this research, the FSD technique was integrated with the FCM clustering method for defining the soft relationships of FSD models with data-driven FRBSs. Although the FCM clustering method is a common approach to developing data-driven FRBSs, the accuracy of this method decreases as the number of its input variables increases. The FCM clustering method considers equal weights for the input and output variables for developing data-driven FRBS. However, research by Wang et al. (2004) shows that increasing the weights of the output variables (compared to the input variables) can increase the accuracy of FRBSs developed by this method. Further improvement to the FCM clustering method can increase the accuracy of the FRBSs that define soft relationships and can consequently increase the accuracy of the FSD models.

- In this research, the FCM clustering method was used to develop the data-driven FRBSs, and feature selection was implemented using the wrapper method with the genetic algorithm method. In addition to the input variables of the FRBS (i.e., the features), there are other parameters of the FCM clustering method that can be optimized to increase the accuracy of the FRBSs developed by this method. In future research, the number of fuzzy membership functions, the shape of fuzzy membership functions, the fuzzification coefficient, and the weights of the input and output variables in the FCM clustering method can be optimized to increase the accuracy of the FRBSs developed by this method.
- The integration of the FSD technique with the FCM clustering method in this research shows that the accuracy of FSD models can be increased by integrating the FSD technique with artificial intelligence methods for pattern recognition. However, this research did not evaluate the integration of the FSD technique with other artificial intelligence methods. In order to increase the accuracy of FSD models in future research, other artificial intelligence methods for pattern recognition, such neuro-fuzzy systems and artificial neural networks, can be integrated with the FSD technique to define the soft relationships of FSD models.
- In this research, the FCM clustering method was used to develop the data-driven FRBSs for defining the soft relationships between the system variables. Moreover, previous research proposed expert-driven FRBSs for defining the soft relationships between the system variables. The data-driven FRBSs are more accurate, as compared to the expert-driven FRBSs; while, the expert-driven FRBSs are more interpretable, as compared to the data-driven FRBSs (Guillaume and Magdalena, 2006). Accordingly, in future research, hybrid methods (i.e., using data and expert knowledge simultaneously) can be used for developing the FRBSs that define the soft relationships between the system variables. For developing FRBSs using hybrid methods, first a data-driven FRBS is developed; then the FRBS and the input and the output variables are verified using expert knowledge

(Guillaume and Charnomordic, 2012). The hybrid methods use expert knowledge to modify the fuzzy membership functions in order to represent the linguistic terms properly. These methods also use expert knowledge to modify the rule base if the sample data (i.e., which are used for developing the data-driven FRBS) is not a comprehensive representative of all the possible values of input and output variables (Guillaume and Charnomordic, 2012). Moreover, these hybrid methods allows the experts to include or exclude some of the input variables in the FRBS. Using hybrid methods for developing the FRBSs can increase the accuracy of the FRBSs, as well as verifying that the selection of the system variables and the definition of the relationships between these variables represent the real-world system.

7.4.4. Developing a Predictive Model of Construction Productivity

In this research, the predictive model of productivity was developed for equipment-intensive activities using the FSD technique. The predictive model of construction productivity as presented in this research has the following limitations, which can be addressed in future research.

- In this research, the predictive model of productivity was developed and validated by field data that were collected from a case study of earthmoving operations. However, predictive models of construction productivity are context-dependant; that is, the influence of factors on productivity varies from one context to another. In future research, the FSD model of productivity developed in this research can be adapted for other contexts using field data collected from construction activities in different contexts.
- In future research, the FSD model can be used for scenario analysis, by analyzing construction productivity for different project conditions. Scenario analysis allows construction practitioners to identify the most critical factors that affect construction productivity under different project conditions, as well as to identify the most appropriate project conditions that results in the optimal productivity for the activity.
- In this research, the behaviour validity of the FSD model has been investigated by the behaviour reproduction test. In order to build a higher level of confidence on

the results of the FSD model, behaviour validation of the model can be further investigated by the behaviour sensitivity test (Bala et al. 2017). The behaviour sensitivity test evaluates the sensitivity of the simulation results to changes in the values of the system variables and compares the behaviour sensitivity of the model to the real-world system.

- In order to assess how the factors with probabilistic uncertainties affect productivity, hybrid FSD-Monte Carlo simulation of productivity can be done using the FSD model presented in this research. For this purpose, the system variables that exhibit probabilistic uncertainty will be represented by probabilistic distributions, and the system variables that exhibit subjective uncertainty will be represented by fuzzy membership functions. Next, in each simulation run, the FSD model will randomly select a sample from the probabilistic distributions and evaluate the value of subjective variables as a fuzzy number; then the FSD model determines the value of productivity as a fuzzy number. Once, the simulation is run for a number of iterations (e.g., 100 or 1000 runs), at each time step of the simulation, all the fuzzy numbers that represent simulation results for each run are aggregated, and the value of productivity at each time step of the hybrid simulation will be represented as a fuzzy random variable. Fuzzy random variables can represent probabilistic and subjective uncertainties of the simulation results simultaneously (Sadeghi et al. 2010).
- The predictive model of productivity developed in this research determines the activity-level MFP of equipment-intensive activities. In future research, a predictive model can be developed to determine the activity-level MFP of labour-intensive activities using the FSD technique. The contributions of the FSD model of MFP for labour-intensive activities will be threefold: it will capture the dynamism of productivity, as compared to the static models of productivity; it will address the probabilistic and subjective uncertainties of the factors influencing productivity, as compared to the probabilistic models of productivity; and it will determine the MFP of labour-intensive activities, which is a more comprehensive measure of productivity than CLP models.

- In future research the predictive model of project-level MFP can be developed using the FSD technique as an integration of the two activity-level FSD models of MFP—equipment-intensive and labour-intensive—and can include the factors influencing construction productivity at the project level.

7.5. References

Bala, B. K., Arshad, F. M., & Noh, K. M. (2017). *Systems thinking: system dynamics.* Springer, Singapore.

Guillaume, S., & Magdalena, L. (2006). “Expert guided integration of induced knowledge into a fuzzy knowledge base.” *Soft Computing*, 10(9), 773-784.

Guillaume, S., & Charnomordic, B. (2012). “Fuzzy inference systems: An integrated modeling environment for collaboration between expert knowledge and data using FisPro.” *Expert Syst.Appl*, 39(10), 8744-8755.

Paliwal, M., and Kumar, U. A. (2009). "Neural networks and statistical techniques: A review of applications." *Expert Syst.Appl.,* 36(1), 2-17.

Sadeghi, N., Fayek, A. R., & Pedrycz, W. (2010). Fuzzy Monte Carlo simulation and risk assessment in construction. *Computer‐Aided Civil and Infrastructure Engineering*, 25(4), 238-252.

Wang, X., Wang, Y., & Wang, L. (2004). “Improving fuzzy c-means clustering based on feature-weight learning.” *Pattern recognition letters*, 25(10), 1123-1132.

Bibliography

Abebe, A., Guinot, V., & Solomatine, D. (2000). Fuzzy alpha-cut vs. Monte Carlo techniques in assessing uncertainty in model parameters. In Proceedings of the 4th International Conference on Hydroinformatics, Iowa.

Ahmad, S. S. S., and Pedrycz, W. (2011). "Feature and Instance selection via cooperative PSO." *Systems, Man, and Cybernetics (SMC), 2011 IEEE International Conference on,* IEEE, 2127-2132.

Alzraiee, H., Zayed, T., and Moselhi, O. (2015). "Dynamic planning of construction activities using hybrid simulation." *Automat. Constr.,* 49 176-192.

Bala, B. K., Arshad, F. M., & Noh, K. M. (2017). *Systems thinking: system dynamics.* Springer, Singapore.

Barlas, Y. (1985). *Validation of System Dynamics Models with a Sequential Procedure Involving Multiple Quantitative Methods* (Doctoral dissertation Georgia institute of Technology). Retrieved from http://hdl.handle.net/1853/25745.

Barlas, Y. (1994). "Model validation in system dynamics." *Proc., 1994 international system dynamics conference,* Sterling, Scotland, 1-10.

Barlas, Y. (1996). "Formal aspects of model validity and validation in system dynamics." *Syst. Dynam. Rev.,* 12(3), 183-210.

Bernold, L. E., and AbouRizk, S. M. (2010). *Managing performance in construction.* John Wiley & Sons.

Bezdek, J. (1981). “Pattern Recognition with Fuzzy Objective Function Algorithms.” Plenum Press, NY.

Bobko, P. (2001). *Correlation and regression: Applications for industrial organizational psychology and management*. Sage, London, UK.

Burns, A. C., and Bush, R. F. (2007). *Basic marketing research using Microsoft Excel data analysis*. Prentice Hall Press, Upper Saddle River, NJ.

Cabrerizo, F. J., Chiclana, F., Al-Hmouz, R., Morfeq, A., Balamash, A. S., & Herrera-Viedma, E. (2015). Fuzzy decision making and consensus: Challenges. Journal of Intelligent & Fuzzy Systems, 29(3), 1109-1118.

Carson, C., and Abbott, M. (2012). "A review of productivity analysis of the New Zealand construction industry." *Construction Economics and Building,* 12(3), 1-15.

Chang, P., & Hung, K. (2006). *α*-cut fuzzy arithmetic: Simplifying rules and a fuzzy function optimization with a decision variable. IEEE Transactions on Fuzzy Systems, 14(4), 496-510.

Chang, P., Pai, P., Lin, K., and Wu, M. (2006). "Applying fuzzy arithmetic to the system dynamics for the customer–producer–employment model." *Int. J. Syst. Sci.,* 37(10), 673-698.

Choi, J., and Ryu, H. (2015). "Statistical analysis of construction productivity for highway pavement operations." *KSCE J. of Civil Eng.,* 19(5), 1193-1202.

Construction Industry Institute (CII). (2006). *Workforce view of construction labor productivity (IR-252-2a).* Report, Construction Industry Institute, University of Texas at Austin, Austin, TX.

Coyle, G. (2000). "Qualitative and quantitative modelling in system dynamics: some research questions." *Sys. Dynam. Rev.,*16 (3), 225.

Dai, J. (2006). "A latent analysis and prototype system to manage jobsite factors impacting construction labor productivity." Doctoral dissertation, University of Kentucky, Lexington, KY.

Dai, J., Goodrum, P. M., and Maloney, W. F. (2009). "Construction craft workers' perceptions of the factors affecting their productivity." *J. Constr. Eng. Manage.,* 135(3), 217-226.

Delgado, M., Gómez-Skarmeta, A. F., and Martín, F. (1997). "A fuzzy clustering-based rapid prototyping for fuzzy rule-based modeling." *IEEE Trans. Fuzzy Syst.,* 5(2), 223-233.

Dong, W., & Wong, F. (1987). Fuzzy weighted averages and implementation of the extension principle. Fuzzy Sets and Systems, 21(2), 183-199.

Dubois, D., & Prade, H. (1978). Operations on fuzzy numbers. International Journal of Systems Science, 9(6), 613-626.

Dubois, D., & Prade, H. (1980). "Fuzzy sets and systems: Theory and applications." *Academic press*, Massachusetts.

Dunn, J. C. (1973). "A fuzzy relative of the ISODATA process and its use in detecting compact well-separated clusters." *Journal of Cybernetics,* 3(3), 32-57.

Eastman, C. M., and Sacks, R. (2008). "Relative productivity in the AEC industries in the United States for on-site and off-site activities." *J. Constr. Eng. Manage.,* 134(7), 517-526.

El Amine, M., Pailhes, J., and Perry, N. (2014). "Critical review of multi-criteria decision aid methods in conceptual design phases: Application to the development of a solar collector structure." *Procedia CIRP,* 21, 497-502.

Elbarkouky, M. M., Fayek, A. R., Siraj, N. B., & Sadeghi, N. (2016). Fuzzy arithmetic risk analysis approach to determine construction project contingency. Journal of Construction Engineering and Management, 142(12), 04016070.

Fellows, R. F., and Liu, A. M. (2015). *Research methods for construction*. John Wiley & Sons, Hoboken, NJ.

Ford, D. N. (1995). "The Dynamics of Project Management: An Investigation of the Impacts of Project Process and Coordination on Performance" (Doctoral dissertation Massachusetts Institute of Technology). Retrieved from http://hdl.handle.net/1721.1/11105.

Forrester, J. W. (1961). "Industry dynamics." *Cambridge, MA, USA*.

Gerami Seresht, N, and Fayek, A. Robinson. (2015). "Application of fuzzy logic integrated with system dynamics in construction modeling. *Proc., of the 5th International Construction Specialty Conference of the Canadian Society for Civil Engineering,* 050-01-050-10.

Gerek, I. H., Erdis, E., Mistikoglu, G., and Usmen, M. (2015). "Modelling masonry crew productivity using two artificial neural network techniques." *J. Civ. Eng. Manage.*, 21 (2), 231–238.

Ghoddousi, P., Poorafshar, O., Chileshe, N., and Hosseini, M. R. (2015). "Labour productivity in Iranian construction projects: Perceptions of chief executive officers." *Int. J. of Product. Perform. Manage.,* 64(6), 811-830.

Gkountis, I., and Zayed, T. (2015). "Subway infrastructure condition assessment." *J. Constr. Eng. Manage.,* 141(12), 04015042.

Goodrum, P. M., and Haas, C. T. (2004). "Long-term impact of equipment technology on labor productivity in the US construction industry at the activity level." *J. Constr. Eng. Manage.,* 130(1), 124-133.

Goodrum, P. M., Haas, C. T., Caldas, C., Zhai, D., Yeiser, J., and Homm, D. (2010). "Model to predict the impact of a technology on construction productivity." *J. Constr. Eng. Manage.,* 137(9), 678-688.

Government of Alberta (2015). "Alberta Wetland Classification System". https://open.alberta.ca/dataset/2015-Alberta-Wetland-Classification-System-June-01-2015.pdf

Grefenstette, J. J. (1986). "Optimization of control parameters for genetic algorithms." *IEEE Transactions on systems, man, and cybernetics*, *16*(1), 122-128.

Guillaume, S., & Charnomordic, B. (2012). "Fuzzy inference systems: An integrated modeling environment for collaboration between expert knowledge and data using FisPro." *Expert Syst.Appl*, 39(10), 8744-8755.

Guillaume, S., & Magdalena, L. (2006). "Expert guided integration of induced knowledge into a fuzzy knowledge base." *Soft Computing*, 10(9), 773-784.

Guo, J., White, J., Wang, G., Li, J., & Wang, Y. (2011). "A genetic algorithm for optimized feature selection with resource constraints in software product lines." *Journal of Systems and Software*, 84(12), 2208-2221.

Guyon, I., & Elisseeff, A. (2003). "An introduction to variable and feature selection." *Journal of machine learning research*, *3*(Mar), 1157-1182.

Guyon, I., Gunn, S., Nikravesh, M., & Zadeh, L. (2006). Feature extraction, foundations and applications. Springer, Berlin.

Hall, M. A. (1999). *Correlation-Based Feature Selection for Machine Learning* (Doctoral Dissertation University of Waikato). Retrieved from http://www.cs.waikato.ac.nz/~mhall/thesis.pdf.

Hanna, A., and Heale, D. G. (1994). "Factors affecting construction productivity: Newfoundland versus rest of Canada." *Can. J. of Civil Eng.*, 21(4), 663-673.

Hanss, M. (2002). The transformation method for the simulation and analysis of systems with uncertain parameters. Fuzzy Sets and Systems, 130(3), 277-289.

Heravi, G., and Eslamdoost, E. (2015). "Applying Artificial Neural Networks for Measuring and Predicting Construction-Labor Productivity." *J. Constr. Eng. Manage.,* 141(10), 04015032.

Heshmaty, B., & Kandel, A. (1985). Fuzzy linear regression and its applications to forecasting in uncertain environment. Fuzzy Sets and Systems, 15(2), 159-191.

Hong, D. H., & Do, H. Y. (1997). Fuzzy system reliability analysis by the use of Tω (the weakest t-norm) on fuzzy number arithmetic operations. Fuzzy Sets and Systems, 90(3), 307-316.

Hong, Y., Chan, D. W., Chan, A. P., and Yeung, J. F. (2011). "Critical analysis of partnering research trend in construction journals." *J. Manage. Eng.,* 28(2), 82-95.

Hwang, B. G., Zhu, L., and Ming, J. T. T. (2016). "Factors affecting productivity in green building construction projects: The case of Singapore." *J. Manage. Eng.,* 33(5), 04016052.

Hwang, C., and Yoon, K. (1981). "Methods for multiple attribute decision making." *Multiple attribute decision making,* Springer, Verlag, New York, NY, 58-191.

Hyndman, R. J., & Koehler, A. B. (2006). Another look at measures of forecast accuracy. *International journal of forecasting*, 22(4), 679-688.

Jabri, A., and Zayed, T. (2017). "Agent-based modeling and simulation of earthmoving operations." *Automat. Constr.,* 81 210-223.

Jarkas, A. M. (2010). "Critical investigation into the applicability of the learning curve theory to rebar fixing labor productivity." *J. Constr. Eng. Manage.,* 136(12), 1279-1288.

Jenei, S. (2002). A note on the ordinal sum theorem and its consequence for the construction of triangular norms. Fuzzy Sets and Systems, 126(2), 199-205.

Jenei, S. (2004). How to construct left-continuous triangular norms—state of the art. Fuzzy Sets and Systems, 143(1), 27-45.

Jiang, Z., Fang, D., and Zhang, M. (2014). "Understanding the causation of construction workers' unsafe behaviors based on system dynamics modeling." *J.Manage.Eng.,* 31(6), 04014099.

Kannan, G. (2011). "Field studies in construction equipment economics and productivity." *J. Constr. Eng. Manage.,* 137(10), 823-828.

Ke, Y., Wang, S., Chan, A. P., and Cheung, E. (2009). “Research trend of public-private partnership in construction journals.” *J. Constr. Eng. Manage.,* 135(10), 1076-1086.

Kechagias, P., & Papadopoulos, B. K. (2007). Computational method to evaluate fuzzy arithmetic operations. Applied Mathematics and Computation, 185(1), 169-177.

Khanzadi, M., Nasirzadeh, F., and Alipour, M. (2012). "Integrating system dynamics and fuzzy logic modeling to determine concession period in BOT projects." *Automat. Constr.,* 22 368-376.

Klement, E. P., & Navara, M. (1999). A survey on different triangular norm-based fuzzy logics. Fuzzy Sets and Systems, 101(2), 241-251.

Klir, G. J. (1997). Fuzzy arithmetic with requisite constraints. Fuzzy Sets and Systems, 91(2), 165-175.

Knight, K., and Fayek, A. Robinson. (2000). “A preliminary study of the factors affecting the cost escalation of construction projects.” *Can. J. of Civil Eng.,* 27(1), 73-83.

Kolesárová, A. (1995). Additive preserving the linearity of fuzzy intervals. Tatra Mountains Mathematical Publications, 6, 75-81.

Lee, C. (1990). Fuzzy logic in control systems: Fuzzy logic controller. I. IEEE Transactions on Systems, Man, and Cybernetics, 20(2), 404-418.

Lee, C. F., Lee, J. C., and Lee, A. C. (2013). *Statistics for business and financial economics (3rd Edition).* Springer, New York, NY.

Levary, R. R. (1990). "Systems dynamics with fuzzy logic." *Int.J.Syst.Sci.,* 21(8), 1701-1707.

Li, S., Wu, H., Wan, D., & Zhu, J. (2011). “An effective feature selection method for hyperspectral image classification based on genetic algorithm and support vector machine.” *Knowledge-Based Systems*, *24*(1), 40-48.

Li, Y., and Taylor, T. R. (2014). "Modeling the impact of design rework on transportation infrastructure construction project performance." *J.Constr.Eng.Manage.,* 140(9), 04014044.

Lin, K., Wen, W., Chou, C., Jen, C., & Hung, K. (2011). Applying fuzzy GERT with approximate fuzzy arithmetic based on the weakest t-norm operations to evaluate repairable reliability. Applied Mathematical Modelling, 35(11), 5314-5325.

Lorterapong, P., & Moselhi, O. (1996). Project-network analysis using fuzzy sets theory. Journal of Construction Engineering and Management, 122(4), 308-318.

Lucko, G., and Rojas, E. M. (2009). "Research validation: Challenges and opportunities in the construction domain." *J.Constr.Eng.Manage.*, 136(1), 127-135.

Mateo, José Ramón San Cristóbal. (2012). *Multi criteria analysis in the renewable energy industry.* Springer Science & Business Media, New York, NY.

Mawdesley, M. J., and Al-Jibouri, S. (2009). "Modelling construction project productivity using systems dynamics approach." *International Journal of Productivity and Performance Management,* 59(1), 18-36.

Mesiar, R. (1997). "Shape preserving additions of fuzzy intervals." *Fuzzy Sets and Systems*, 86(1), 73-78.

Mirahadi, F., and Zayed, T. (2016). "Simulation-based construction productivity forecast using neural-network-driven fuzzy reasoning." *Automat. Constr.,* 65 102-115.

Moore R. (1966). "Interval Analysis." *Prentice-Hall, Englewood Cliffs*, New Jersey.

Moore, R. E. (1979). "Methods and applications of interval analysis." *SIAM*, Philadelphia.

Moselhi, O., and Khan, Z. (2010). "Analysis of labour productivity of formwork operations in building construction." *Construction Innovation,* 10(3), 286-303.

Naoum, S. G. (2016). "Factors influencing labor productivity on construction sites: A state-of-the-art literature review and a survey." *Int. J. of Product. Perform. Manage.,* 65(3), 401-421.

Naoum, S. G., and Heap, J. (2016). "Factors influencing labor productivity on construction sites. A state-of-the-art literature review and a survey." *International Journal of Productivity and Performance Management,* 65(3).

Nasirzadeh, F., Afshar, A., Khanzadi, M., and Howick, S. (2008). "Integrating system dynamics and fuzzy logic modelling for construction risk management." *Constr. Manage. Econ.,* 26(11), 1197-1212.

Nasirzadeh, F., and Nojedehi, P. (2013). "Dynamic modeling of labor productivity in construction projects." *Int. J. Project Manage.,* 31(6), 903-911.

Nasirzadeh, F., Khanzadi, M., Afshar, A., and Howick, S. (2013). "Modeling quality management in construction projects." *International Journal of Civil Engineering*, 11(1), 14-22.

Nasirzadeh, F., Khanzadi, M., and Rezaie, M. (2014). "Dynamic modeling of the quantitative risk allocation in construction projects." *Int. J. Project Manage.,* 32(3), 442-451.

Nguyen, H. T. (1978). A note on the extension principle for fuzzy sets. Journal of Mathematical Analysis and Applications, 64(2), 369-380.

Nguyen, H. T., & Walker, E. A. (2005). A first course in fuzzy logic. CRC press, New York.

Nojedehi, P., & Nasirzadeh, F. (2017). “A hybrid simulation approach to model and improve construction labor productivity.” *KSCE Journal of Civil Engineering*, 21(5), 1516-1524.

Ok, S. C., and Sinha, S. K. (2006). "Construction equipment productivity estimation using artificial neural network model." *Constr. Manage. Econ.,* 24(10), 1029-1044.

Opricovic, S., and Tzeng, G. (2004). “Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS.” *Eur. J. Oper. Res.,* 156(2), 445-455.

Organization for Economic Co-operation and Development. (2015). “Growth in GDP per capita, productivity and ULC: Multifactor productivity”. http://stats.oecd.org/Index.aspx?DataSetCode=PDB_GR (July 3, 2017).

Paliwal, M., and Kumar, U. A. (2009). "Neural networks and statistical techniques: A review of applications." *Expert Syst.Appl.,* 36(1), 2-17.

Park, M. (2005). "Model-based dynamic resource management for construction projects." *Autom.Constr.,* 14(5), 585-598.

Pedrycz, A., Reformat,M. (2006). “Hierarchical FCM in a stepwise discovery of structure in data.” *Soft Comput.* 10, 244–256.

Pedrycz, W. (2013). Granular computing: analysis and design of intelligent systems. CRC press, Boca Raton, FL, USA.

Pedrycz, W., and Gomide, F. (2007). *Fuzzy systems engineering: toward human-centric computing.* John Wiley & Sons.

Portas, J., and AbouRizk, S. (1997). “Neural network model for estimating construction productivity.” *J. Constr. Eng. Manage.*, 123(4), 399-410.

Rakhra, A. (1991). "Construction productivity: concept, measurement and trends, organisation and management in construction." *Proc., of the 4th Yugoslavian Symposium on Construction Management, Dubrovnik,* 487-497.

Riley, M., and Clare-Brown, D. (2001). "Comparison of cultures in construction and manufacturing industries." *J. Manage. Eng.,* 17(3), 149-158.

Roeva, O., Fidanova, S., & Paprzycki, M. (2013). "Influence of the population size on the genetic algorithm performance in case of cultivation process modelling." In *Computer Science and Information Systems (FedCSIS), 2013 Federated Conference on* (pp. 371-376). IEEE.

Ross, T. J. (2009). "Fuzzy logic with engineering applications." *John Wiley & Sons*, West Sussex.

Sadeghi, N. (2015). "A Hybrid Fuzzy Discrete Event Simulation Framework for Analysis of Stochastic and Subjective Uncertainties in Construction Projects" (Doctoral dissertation university of Alberta). Retrieved from https://doi.org/10.7939/R34084.

Sadeghi, N., Fayek, A. R., & Pedrycz, W. (2010). Fuzzy Monte Carlo simulation and risk assessment in construction. *Computer‐Aided Civil and Infrastructure Engineering*, 25(4), 238-252.

Sargent, R. G. (1991). "Simulation model verification and validation." *Proc. of the 23rd conference on Winter simulation*. IEEE Computer Society, Phoenix, AZ, 37-47.

Senge, P. M., and Forrester, J. W. (1980). "Tests for building confidence in system dynamics models." *System Dynamics, TIMS Studies in Management Sciences*, 14 209-228.

Shcherbakov, M.V., Brebels, A., Shcherbakova, N.L., Tyukov, A.P., Janovsky, T.A., and Kamaev, V.A., (2013) "A survey of Forecast error measures," *World Applied Science Journal*, 24, 171-176.

Statistics Canada, (2017). "Gross domestic product at basic prices, by industry, 2012-2016." http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/manuf10-eng.htm (September 15, 2017).

Sterman, J. D. (2000). *Business dynamics: systems thinking and modeling for a complex world.* Irwin/McGraw-Hill Boston, USA.

Sweetser, A. (1999). "A comparison of system dynamics (SD) and discrete event simulation (DES)." *17th International Conference of the System Dynamics Society*, Wellington, New Zealand, 20-23.

Talhouni, B. T. (1990). Measurement and Analysis of Construction Labour Productivity (Doctoral dissertation university of Dundee).

Tessem, B., and Davidsen, P. I. (1994). "Fuzzy system dynamics: an approach to vague and qualitative variables in simulation." *System Dynamics Review,* 10(1), 49-62.

Thomas, H. R., Maloney, W. F., Horner, R. M. W., Smith, G. R., Handa, V. K., and Sanders, S. R. (1990). "Modeling construction labor productivity." *J. Constr. Eng. Manage.,* 116(4), 705-726.

Tsai, C., and Wen, M. L. (2005). “Research and trends in science education from 1998 to 2002: A content analysis of publication in selected journals.” *Int. J. Sci. Educ.,* 27(1), 3-14.

Tsehayae, A. A. (2015). “Developing and optimizing context-specific and universal construction labour productivity models.” Doctoral dissertation, University of Alberta, Edmonton, Canada.

Tsehayae, A. A., and Fayek, A. Robinson (2014). "Identification and comparative analysis of key parameters influencing construction labour productivity in building and industrial projects." *Can. J. Civil Eng.,* 41(10), 878-891.

Tsehayae, A. A., and Fayek, A. Robinson (2016a). "Developing and Optimizing Context-Specific Fuzzy Inference System-Based Construction Labor Productivity Models." *J. Constr. Eng. Manage.,* 142(7), 04016017.

Tsehayae, A. A., and Fayek, A. Robinson (2016b). "Developing and Optimizing Context-Specific Fuzzy Inference System-Based Construction Labor Productivity Models." *J. Constr. Eng. Manage.,* 142(7), 04016017.

Urbański, M. K., & Wasowski, J. (2005). Fuzzy arithmetic based on boundary weak t-norms. International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 13(01), 27-37.

Wang, X., Wang, Y., & Wang, L. (2004). “Improving fuzzy c-means clustering based on feature-weight learning.” *Pattern recognition letters*, 25(10), 1123-1132.

Whitley, D. (1994). “A genetic algorithm tutorial.” *Statistics and computing*, *4*(2), 65-85.

Wing, C. K. (1997). “The ranking of construction management journals.” *Constr. Manage. Econ.,* 15(4), 387-398.

Wolstenholme, E. F. (1999). "Qualitative vs quantitative modelling: the evolving balance." *J. Oper. Res. Soc.,* 422-428.

Yi, W., and Chan, A. (2014). "Critical review of labor productivity research in construction journals." *J. Manage. Eng.,* 30(2), 214–225.

Yi, W., and Chan, A. P. (2013). “Critical review of labor productivity research in construction journals.” *J. Manage. Eng.,* 30(2), 214-225.

Zadeh, L. A. (1965). "Fuzzy sets." *Information and Control,* 8(3), 338-353.

Zadeh, L. A. (1975). “The concept of a linguistic variable and its application to approximate reasoning.” *Information Sciences*, 8(3), 199-249.

Zakeri, M., Olomolaiye, P. O., Holt, G. D., & Harris, F. C. (1996). “A survey of constraints on Iranian construction operatives’ productivity.” *Constr. Manage. Econ.*, *14*(5), 417-426.

Zayed, T. M., and Halpin, D. W. (2005). "Productivity and cost regression models for pile construction." *J. Constr. Eng. Manage.,* 131(7), 779-789.

Appendix A. Factors Influencing Construction Productivity Identified from Literature

A.1. Factors Influencing Construction Productivity

Table A.1. Factors influencing construction productivity and sources

No.	Authors	Country	Category	Factor
1	Zakeri et al. (1996)	Iran	Equipment Operatives	Lack of materials, weather and site conditions, equipment breakdowns, drawing/spec./change orders, lack of proper tools and equipment, inspection delay, absenteeism, safety, improper plan of work, repeating work, changing crew size/turnover, interference at work, poor communication and miscommunication
2	Choi & Ryu (2015)	USA	Management	Problems with predecessor activities, out of sequence work, work conflict, work area, material shortage, equipment breakdown
			Weather	Precipitation, temperature
			Work Contents	Complexity
3	Kannan (2011)	USA	Organization	Capital and budget-related decision making, analysis of fleet performance (age, cost, reliability), ownership period and economic decisions (repair, replace, rebuild, retire), standard equipment specification, equipment procurement and disposal, financing method, equipment hire operations, guidelines for workshop operations, outsourcing maintenance, asset monitoring, equipment/fleet inspection and appraisal reports, developing standards for equipment safety and operation, analysis and implementation of training needs
			Repair Policy	Repair policy (operate to fail, fixed time-based maintenance, condition based maintenance)
			Equipment Policy	Make and model (specification), ownership period, warranty, ownership (owned, lease, rental, subcontracted), repair vs. service contract
			Job Site Optimization	Machine configuration, site configuration, fleet selection, production, total cost of ownership, unit cost of operation

No.	Authors	Country	Category	Factor
4	Ok & Sinha (2006)	USA	Forecast Factors	Hauling distance, earth conditions, age of equipment, encountered resistances, work space restrictions, the system of work involved
			Unanticipated Factors	Weather conditions, downtime, site management efficiency
			Dozer Selection	Type of use, duration of use, site spaciousness, soil property
5	Zayd & Halpin (2005)	USA	Piling Process Productivity Factors	Soil type, drill type and height of drilling tool, method of spoils removal, size of hauling units, space consideration at the construction site, pile axis adjustment, equipment operator efficiency, weather conditions, concrete pouring method and efficiency, waiting time for other operations, job and management conditions, cycle time, pile size and pile depth.
			Piling Process Cost Factors	Subsurface soil conditions, site conditions, geometry of pile, specifications, expected weather conditions, location of the project, governmental environmental regulations, availability of proper equipment, contractor experience and economic conditions, contract requirements
6	Goodrum & Haas (2004)	USA	Equipment Production Factors	Amplification of human energy, level of control, functional range, ergonomics, information processing
7	Goodrum et al., (2010)	USA	Economic Analysis	Budget analysis, potential benefits associated with adoption of technology
			Technology Feasibility	Technology maturity, technology risks, technology performance
			Technology Usage Issues	Technology acceptance, technology synergy and protocol, technology logistics functions
			Technology Impacts	Equipment technology, material technology, automation and integration potential
8	Naoum (2016)	UK	Pre-Construction Activity	Ineffective project planning, delay caused by design error and variation orders, communication system, design and buildability-related issues, procurement method, specification, clarity of client brief and project objectives, site managers involvement at contract stage, poor scheduling of project activities, sub-contractor involvement, poor selection of project personnel,
			Motivational and Social	Work environment, constraints on a worker's performance, team/group integration during construction, job security, mismatch of beliefs among personnel on site,

No.	Authors	Country	Category	Factor
				resentment of company policy, delegation of responsibilities, response to employee grievances, salary and incentives, reappraisal of site managers and promotion, opportunities to exercise skill
			During Construction	Lack of integration of the management information system for the project, management of material on site, control system on site, group co-ordination/overcrowding on site, ineffective site planning leading to program disruption, supervision of subordinate, delay/rework, site safety, clarity of tasks, accuracy of tech. information, co-ordination of sub-contractors, direct v sub-contract labor, interference on workmanship, lack of consultation in the decision-making process, attitude of site personnel, management of equipment/use of inappropriate tools/equipment for operations, knowledge of techniques, inefficient site layout
			Managerial Factor	Management/leadership style, project structure/authority and influence on site
			Organizational	Experience and training, construction technology and methods, availability of skilled workers, contract administration skill
9	Ghodoosi et al. (2015)	Iran	Motivational factors	Amount of remuneration , work satisfaction , promotion opportunities, solving individual problems, incentive payments, job security, giving responsibility, job permanence, good relationship with colleagues, safe working condition, competition with colleagues, healthy working condition
			Project nature and working environment	Procurement, weather conditions, new project techniques, quality inspections, overcrowding on the site, project complexity, geography of site, reworks
			Management policies and leadership strategies	Timeliness of remuneration, ethical behaviour of manager, skilled workers, welfare conditions on site, training, relation-oriented style leadership, task-oriented style leadership, competent site manager, penalty clause, worker participation in decision – making, communication, periodical report
10	Jarkas & Bitar (2011)	Kuwait	Technological	Clarity of technical specifications, the extent of variation/change orders during execution, coordination level among design disciplines, design complexity level, stringent inspection by the engineer, delay in responding to requests for information (RFI), compatibility and consistency among contract documents, rework, site restricted access, confinement of working space, site layout, inspection delay by the engineer
			Human/Labour	Motivation of labour, skill of labour, physical fatigue, shortage of experienced labour
			Management	Lack of labour supervision, proportion of work subcontracted, lack of incentive scheme, construction manager’s lack of leadership, unsuitability of storage location, working overtime, crew size and composition, unrealistic scheduling and expectation of labour performance, labour interference and congestion, shortage of materials, construction method, payment delay ,communication problems between site

No.	Authors	Country	Category	Factor
				management and labour, accidents as a result of poor site safety program, late arrival, early quit, and frequent unscheduled breaks, unavailability of suitable tools ,lack of training offered to operatives, inspection delay by site management, sequencing problems, lack of recognition program, lack of periodical meetings with crew leaders, owner's representative intervention with site management and operatives, lack of suitable rest area offered to labour on site, lack of providing labour with transportation
			External	High/low temperature, high humidity, sandstorms, high winds, rain
11	El-Gohari & Aziz (2013)	Egypt	Management	Incentive programs, availability of materials and their ease of handling, leadership and competency of construction management, competency of labor supervision, planning, work flow, and site congestion, clarity of instructions and information exchange, surrounding events (revolutions), services offered to laborers (social insurance, medical care), construction management type (individuals, firms), management of subcontractors
			Labour/Human	Laborer experience and skill, labor operating system (daily wage, lump sum), laborer age, effect of labor availability—work capacity (shortage), overtime (up to 4 h after 8 h=day), effect of labor availability—work capacity (excess), degree of laborer education, rest time(s) during the workday, overtime (more than 4 h after 8 h=day)
			Industry	Construction technology (construction method and material), constructability (integrated design and construction), weather effect (temperature, humidity), distance between site and cities, project specifications, project scale, available quantity of daily work (workload), work interruptions (design changes), work at heights, total project duration (total work hours), type of project (industrial, residential)
12	Mahamid (2013)	Saudi Arabia	Labour	Lack of labor experience, labor disloyalty, craft turnover, lack of cooperation and communication between labours, over-manning, lack of competition, lack of labors in the market, labor absenteeism
			Managerial	Rework, lack of cooperation and communication between construction parties, misuse of time schedule, out of sequence work, poor site management by contractor, lack of superintendents experience, lack of cooperation and communication between labors and management team, lack of labor surveillance, lack of site safety resources, improper construction method
			Environmental	Working within a confined space, poor access to the project, availability of alternative opportunities, weather changes
			Material and Equipment	Lack of materials, lack of equipment, old and inefficient equipment, unsuitability of material storage location, poor material quality

No.	Authors	Country	Category	Factor
			Financial Group	Financial status of the owner, financial status of the contractor, low wages, lack of financial motivation system
13	Jarkas & Rodosavljevic (2013)	Kuwait	Motivational Factors	Rework, design complexity level, quality level of drawings, clarity of technical specifications, inspection delay, delay in responding to requests for information, extent of change orders during execution, stringent inspection by the engineer, incompetent supervisors, communication problems between supervisors and master craftsmen, unrealistic scheduling and performance expectation, operatives interface and congestion, working overtime, lack of providing master craftsmen with transportation, shortage of materials on site, unavailability of suitable tools, financial stability of employer, payment delay, lack of financial incentive scheme, lack of recognition, lack of suitable rest area offered to master craftsmen on site, accidents on site, inclement weather
14	Rivas et al. (2011)	Chili	Schedule Acceleration	Overcrowding and/or over-manning, peak craft level and single craft population, scheduled overtime
			Poor Coordination	Stacking of trades, concurrent operations
			Changes	Reassignment of manpower, deterioration of learning curves, ripple effect, engineering errors and omissions
			Resources and Site management	Site conditions and organization, materials and tools availability, material handling space, site access, interference, poor lighting and housekeeping, the size and dispersion of tasks, methods and equipment, size of a crew
			Management Characteristics	Management control or project team, dilution of supervision
			Project Characteristics	Project size, work types, beneficial occupancy, joint occupancy, fast track, subcontract
			Labour and Morale	Quality of craftsmanship, quality control and quality assurance practices, absenteeism, craft turnover, fatigue, morale, wages
			Project Location and External Conditions	Economic activity or availability of skilled labor, commuting time, support community size, weather, population differences
15	Dai et al. (2007)	USA	Supervisor Direction	Inadequate instruction provided by supervisors, not receiving directions due to size of the project, not receiving compliments for doing a good job, not being notified of mistakes when they occur, lack of goals for craft workers
			Communication	Different languages spoken on a project, disregard of crafts' productivity improvement suggestion, lack of 'big picture' view on behalf of the crafts, craft worker importance, lack of communication among site management
			Safety	Shortage of personal protective equipment, lack of site safety resources

No.	Authors	Country	Category	Factor
			Tools and Consumables	Availability of consumables, restrictive project policy on consumables, availability of hand tools, availability of power tools, lack of power source for tools, lack of extension cords, inexperienced tool room attendants, misplaced tools, poor power tool quality
			Materials	Availability of material, poor material quality, availability of bulk commodities, errors in prefabricated material, difficulty in tracking material
			Engineering Drawing Management	Drawing errors, availability of drawings, slow response to questions with drawings, drawing legibility, needed information not on drawings
			Labour	Availability of skill training, jobsite orientation program, availability of health and safety training, unqualified craft workers, lack of pride in their work, lack of incentive to attend training, demotivated craft workers, less pay than the projects in a geographic area, craft workers' distrust in supervisors
			Foreman	Lack of people skill on behalf of foremen, unqualified foremen, unfair performance reviews, foremen not allowing crafts to work autonomously, lack of construction knowledge on behalf of foremen, lack of authority to discipline craft workers, lack of proper resource allocation, lack of managerial and administrative support, excessive paperwork
			Superintendent	Lack of people skill on behalf of superintendents, qualified superintendents, lack of experience on behalf of superintendents, disrespect for craft workers, micro-management on behalf of superintendent, political/performance competitions within company, inconsistent safety policies established by different superintendents, different work rules by superintendents
			Project Management	Delay in work permits, out of sequence work assignments, absenteeism, unreasonable project goals and milestones, disrespect for craft workers and foremen, layoff qualified craft workers,
			Construction Equipment	Unawareness of on-site activities and project progress, pulling people off a task before it is done, jobsite congestion, different pay scales for the same job on a project, different per diem rate, lack of incentive for good performance, material storage area too far from workface, insufficient size of material storage area, shortage of temporary facilities,
16	Rojas & Aramvareekul (2003)	USA	Management and Strategies	Lack of coordination between the trades, slow decisions, incorrect crew size, inappropriate vehicle traffic routes, lack of weather protection
			Industry and Environment	Availability of crane or forklift, availability of man-lift, waiting for people and/or equipment to move material, poor equipment maintenance, slow equipment repairs, improperly maintenance of power tools

No.	Authors	Country	Category	Factor
			Manpower	Management skills, scheduling, material and equipment management, quality control.
			External Conditions	Adverse weather, uniqueness, working conditions, subcontractors integration
17	Portas & AbouRizk (1997)	USA	Activity Performance	Experience, activity training, education, motivation, seniority
			Activity Staff	Scope changes, economy, research and development, information technology
			Activity Crew	Work complexity, degree of difficulty
			Activity Design	Superintendent skill, district performance
			Activity Dimensions	Crew skill, crew size, union/non-union
			Activity Repetition	Cost code, formwork duty, tie type, tie spacing, accuracy of design
			Activity Working Conditions	Quantity, height, thickness
			Project Complexity	Degree of repetition, number of reuses, panel area
			Project Structure	Crane time, continuity of cycle, shift duration
			Project Size	Project staffing, project superintendent skill, project district performance
			Project Location	Gross building area, no. of floors above grade, no. of floors below grade
			Project Site	Original company estimate, original total contract
18	Heravi & Eslamdoost (2015)	Iran	Supervision	District, climate (not temperature)
			Proper coordination	Site congestion, site access, site conditions
			Effective communication	Sufficient labor supervision, supervisor’s competence, supervisor’s positive characteristic and behavior,
			Proper planning	Fair/just performance reviews by supervisor
			Proper HSE program	Coordination between the trades, prevent interference and congestion
			Technical excellence	Constructive communication between site management and labor, interaction of technical office and executive committee
			Suitable site layout	Proper and realistic scheduling, proper crew size and composition, proper resource allocation, consider proper sequence of work assignments

No.	Authors	Country	Category	Factor
			Labor competence	Site safety program and performance for prevention of accidents, site health program and performance for prevention of labor injuries, safety and health training
			Sufficient facilities and accommodation	Designs, drawings and technical specifications (in terms of availability, errorless, clarity, and legibility), proper construction method and technology
			Motivation of labor	General layout of construction site
			Poor decision making	Skill of labor, experience of labor, skill training of labor
			Schedule compression	Sanitary/welfare rooms and buildings, providing labor with ample transportation
			Frequent change order	Respect for worker, craftsmen's incentive scheme, avoid delay in payments
			Materials, tools and equipment deficiency	Decisions on the basis of flawed logic emotionalism or incomplete information, delay in work permit, delay in responding to requests for change orders
			Unfavorable external condition	Working overtime, shift work, over-manning, extra work
19	Hanna & Heale (1993)	Canada	Site Management	Change of design, change of plans, change of scheduling, change of sequence of works
			Contract Environment	Material damage and defect, deficiency of tools and equipment, lack of repairman for tools and equipment, equipment poor maintenance
			Planning	Bad weather conditions (e.g., high/low temperature, rain, and snow), environmental factors (noise, dust, poor lighting, and ventilation), political, social, cultural and poor economic conditions
			Working Conditions	Change orders , availability and clarity of working drawings , site layout , task sequencing , materials management , on-site storage , government and regulatory inspections
			Motivation	Effect of contract type, constructability, inspection regime
20	Mawdesley & Al-jibouri (2009)	Netherlands	-	Absenteeism, disruptions, level of skilled labour, use of equipment, over time, length of work day, number of foreman on site, crew size, motivation, learning curves, communications, design & build-ability, interference by owner, restricted access, change orders, acceleration of performance, differing site conditions, safety, work inspection by engineer, material management, control of the project, planning, modern management systems, crew interference
21	Tsehayae & Fayek (2014)	Canada	Labour and Crew	Absenteeism, worker turnover, accidents, safety, hot weather, cold weather, height of work site above ground, site irritants - pollution, noise, worker fatigue,

No.	Authors	Country	Category	Factor
				unavailability of tools, equipment breakdown, unavailability of construction equipment, inappropriate uses of tools and equipment
			Materials and Consumables	Incentive caused by benefits, foreman supervision, teamwork, crew size, and makeup, employee motivation, end of project effect, communication, reward (money, recognition), job reworking
			Equipment and Tools	Absenteeism, disruptions, level of skilled labour, use of equipment, over time, length of work day, number of foreman on site, crew size, motivation, learning curves, communications, design & build-ability, interference by owner, restricted access, change orders, acceleration of performance, differing site conditions, safety, work inspection by engineer, material management, control of the project, planning, modern management systems, crew interference
			Task Property	Crew size, crew experience and competence, crew balance between journeymen and apprentices, work assignment to different crews, crowding, crew team spirit, cooperation between craftsmen, cooperation between the different crews, crew turnover, craftsmen treatment by foreman, number of consecutive days on job, craftsmen positive attitude towards the task, craftsmen physical fitness, craftsmen learning speed, craftsmen boredom and fatigue, craftsmen flexibility in accommodating task changes, job site orientation program, craftsmen trust in the skills and judgment of their supervisors, craftsmen participation in decision making process, level of job security, absenteeism of craftsmen, craftsmen's labour union status, craftsmen's skill utilization, feedback on performance to craftsmen, provision of clear goals, remunerations (salary, benefits)
			Location Property	Materials delivery to task location, material quality, shortage of consumables, correction work on prefabricated products, temporary material storage location, unloading of materials, vertical movement materials, horizontal material movement, material order tracking system
			Foreman	Transportation equipment (cranes, forklifts), electrical power connection during operation, waiting time for man-lifts, adequacy of hand tools, adequacy of power tools, quality of work tools, efficiency of tool crib attendant, misplacement of tools
			Engineering and Instructions	Tasks repetitiveness, tasks nature (challenging and interesting), total work volume, rework sources (vendor or contractor), rework frequency, change orders frequency, interruption and disruption frequency, most of the tasks in this project have repetitive nature, change orders frequency
			Project Delivery and Contract	Weather (temperature, wind, humidity, precipitation), location of work scope (distance and elevation), work area congestion, cleanness of work area, temporary electrical service provision, work conditions (noise, dust, and fumes), work area protection from weather effect, washrooms location, adequacy and location of

No.	Authors	Country	Category	Factor
				lunchrooms, adequacy of camp facilities (residences, recreation, and shops), site access
			HSE	Foreman experience, foreman training for leadership, foreman's management style, frequency of change of foremen, span of control, fairness in performance reviews of craft workers, foreman skill in proper resource allocation, clear goals provision by project managers, feedback on performance, uniformity of work rules
			Project Management and Practices	Availability of drawings and specifications, readability of drawings and specifications, drawings and specification's frequency of updates, response time for drawing questions, adequacy of job instructions
			Project best practices	Delivery system (design bid build, design build, boot), contract type (lump sum, unit rate, cost plus)
			Project Owner Nature	Health and safety training, daily project briefing and debriefing practice, daily job hazard assessment system practice, tailgate safety meetings, stringency of project site safety rules, accidents and injury frequency, efficiency of safety incident investigations, planning of safety inspections and audits, sorting of waste materials practice, frequency of corrective actions to meet environmental requirements, planning of environmental inspections and audits
			Organizational	Integration, scope, cost (identification and documentation of the estimation stages), cost (monitoring status of project to update project budget and manage changes), cost (reporting system for the identification of cost overruns), quality (identifying quality requirements and (or) standards), quality (process for monitoring and recording results of quality activities, qc), human resource (trainings, workshops, seminars), human resource (overall participation of HR in the formulation and realization of competitive strategies), procurement (project procurement plan), procurement (evaluation criterion to select bidders), procurement (documentation of procurement process and follow up), risk (use of risk assessment tool), risk (process for tracking, monitoring, and mitigation of risks), change (documentation process), change (monitoring and controlling changes), communication (availability of procedures), communication (documentation and tracking systems), business development (development of a time scaled business plan)
			Provincial	Detailed front end planning, alignment in front end planning stage, constructability reviews, formal team building process, material management practices (planning and controlling of materials), zero accident techniques implementation, use of automation and integration technologies, planning for startup, productivity measurement and improvement practices, efficiency of work permit process
			National	Owner's primary driver (schedule, cost, quality, safety), the project site is transferred timely to the contractor, owner team competence and knowledge, owner team

No.	Authors	Country	Category	Factor
				decision provision, owner's project team adoption of project risk management practices, frequency of change requests, suspension of projects (frequency)
			Global	Diversity of organization's principal construction project type (industrial, commercial, infrastructure), successful years in industry, number of divisions, number of employees, annual turnover in dollars, organizational structure system (matrix, project based, mixed), number of projects awarded per year, annual turnover of employees, execution of work approach (subcontracting, self-performing, both)

A.2. References

Choi, J., and Ryu, H. (2015). “Statistical analysis of construction productivity for highway pavement operations.” *KSCE J. of Civil Eng.,* 19(5), 1193-1202.

Dai, J., Goodrum, P. M., & Maloney, W. F. (2007). “Analysis of craft workers' and foremen's perceptions of the factors affecting construction labour productivity.” Constr. Manage. Econ., 25(11), 1139-1152.

El-Gohary, K. M., & Aziz, R. F. (2013). “Factors influencing construction labor productivity in Egypt.” Journal of Management in Engineering, 30(1), 1-9.

Ghoddousi, P., Poorafshar, O., Chileshe, N., and Hosseini, M. R. (2015). “Labour productivity in Iranian construction projects: Perceptions of chief executive officers.” Int. J. of Product. Perform. Manage., 64(6), 811-830.

Goodrum, P. M., and Haas, C. T. (2004). “Long-term impact of equipment technology on labor productivity in the US construction industry at the activity level.” *J. Constr. Eng. Manage.,* 130(1), 124-133.

Goodrum, P. M., Haas, C. T., Caldas, C., Zhai, D., Yeiser, J., and Homm, D. (2010). “Model to predict the impact of a technology on construction productivity.” *J. Constr. Eng. Manage.,* 137(9), 678-688.

Hanna, A., and Heale, D. G. (1994). “Factors affecting construction productivity: Newfoundland versus rest of Canada.” Can. J. of Civil Eng., 21(4), 663-673.

Heravi, G., & Eslamdoost, E. (2015). “Applying artificial neural networks for measuring and predicting construction-labor productivity.” J. Constr. Eng. Manage., 141(10), 04015032.

Jarkas, A. M., & Bitar, C. G. (2011). “Factors affecting construction labor productivity in Kuwait.” J. Constr. Eng. Manage., 138(7), 811-820.

Jarkas, A. M., & Radosavljevic, M. (2012). “Motivational factors impacting the productivity of construction master craftsmen in Kuwait.” J. of Man. in Eng., 29(4), 446-454.

Kannan, G. (2011). “Field studies in construction equipment economics and productivity.” *J. Constr. Eng. Manage.,* 137(10), 823-828.

Mahamid, I. (2013). “Contractors perspective toward factors affecting labor productivity in building construction.” Engineering, Construction and Architectural Management, 20(5), 446-460.

Mawdesley, M. J., & Al-Jibouri, S. (2009). “Modelling construction project productivity using systems dynamics approach.” International Journal of Productivity and Performance Management, 59(1), 18-36.

Naoum, S. G. (2016). “Factors influencing labor productivity on construction sites: A state-of-the-art literature review and a survey.” Int. J. of Product. Perform. Manage., 65(3), 401-421.

Ok, S. C., and Sinha, S. K. (2006). “Construction equipment productivity estimation using artificial neural network model.” *Constr. Manage. Econ.,* 24(10), 1029-1044.

Portas, J., & AbouRizk, S. (1997). “Neural network model for estimating construction productivity.” J. Constr. Eng. Manage., 123(4), 399-410.

Rivas, R. A., Borcherding, J. D., González, V., & Alarcón, L. F. (2010). “Analysis of factors influencing productivity using craftsmen questionnaires: Case study in a Chilean construction company.” J. Constr. Eng. Manage., 137(4), 312-320.

Rojas, E. M., & Aramvareekul, P. (2003). “Labor productivity drivers and opportunities in the construction industry.” J. of Man. in Eng., 19(2), 78-82.

Tsehayae, A. A., and Fayek, A. Robinson. (2014). “Identification and comparative analysis of key parameters influencing construction labour productivity in building and industrial projects.” Can. J. of Civil Eng., 41(10), 878-891.

Zakeri, M., Olomolaiye, P. O., Holt, G. D., & Harris, F. C. (1996). “A survey of constraints on Iranian construction operatives’ productivity.” *Constr. Manage. Econ.*, *14*(5), 417-426.

Zayed, T. M., and Halpin, D. W. (2005). “Productivity and cost regression models for pile construction.” *J. Constr. Eng. Manage.,* 131(7), 779-789.

Appendix B. Field Data Collection Details

B.1. Field Data Collection Details for Factors Influencing Productivity

B.1.1. Field Data Collection Details for Activity-Level Factors

Table B.1. Field data collection details for activity-level factors

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
1.1. Labour and Crew					
1.1.1	Crew Size	The total size of the crew performing the actual task will have an effect on the production rate of the construction operations.	Integer number (crew size)	Daily	Foreman
1.1.2	Adequacy of Crew Size	The adequacy of crew size may affect the productivity of the crew and consequently the production rate of the construction activities. Limitations imposed to the selection of crew size may be due to different reasons (e.g., project site restriction).	1-5 Predetermined rating	Daily	Foreman
	1- Crew size is VERY POOR fit for the activity's volume of work. 2- Crew size is POOR fit for the activity's volume of work.3- Crew size is FAIR fit for the activity's volume of work. 4- Crew size is GOOD fit for the activity's volume of work. 5- Crew size is VERY GOOD fit for the activity's volume of work.				
1.1.3	Crew Composition	Refers to the number of journeymen and apprentices of the crew. The composition of the crew may affect the production rate of the construction operations.	Integer numbers (no. journeymen, no. apprentices)	Daily	Foreman
	Note: labourer refers to the unregistered apprentices.				
1.1.4	Crew Experience	Refers to the average years of experience of the crew members which can affect the production rate of the construction operations.	Integer number (years of experience)	Daily	Foreman
1.1.5	Crew Makeup Changes	Refers to the change of crew members made by the foreman (supervisor) by moving member(s) of one crew to another. Keeping the crew makeup unchanged may	Percentage (occurrence of crew member changes	Weekly	Foreman

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
		cause a better communication between the members and increased the production rate.	divided by weekly average crew size)		
1.1.6	Crew Turnover Rate	Refers to separation of crew members from the job. This factor should be should be measured as the ratio of total separations from the job to the weekly average crew size.	Percentage (no. of separated crew members divided by weekly average crew size)	Weekly	Foreman
1.1.7	Number of Languages Spoken in the Crew	It defines the ability of the crew for communication specially communication between labours and equipment operators which is needed for the coordination of equipment and labour.	Integer number	Once, Crew Change	Foreman
1.1.8	Crew Motivation	The motivation of the crew can affect the productivity of the crew and consequently the production rate of the construction operations.			
1.1.8.1	Intensity of effort	Self-explanatory measure of the intensity of crew effort toward achieving the assigned goals.	1-5 Predetermined rating	Daily	Foreman
	1- VERY LOW effort intensity to perform the task. 2- LOW intensity of effort to perform the task. 3- AVERAGE intensity of effort to perform the task. 4- HIGH intensity of effort to perform the task. 5- VERY HIGH intensity of effort to perform the task				
1.1.8.2	Persistence of effort	Self-explanatory measure of the persistence of crew effort toward achieving the assigned goals.	1-5 Predetermined rating	Daily	Foreman
	1- VERY LOW persistency of effort to perform the task. 2- LOW persistency of effort to perform the task. 3- AVERAGE persistency of effort to perform the task. 4- HIGH persistency of effort to perform the task. 5- VERY HIGH persistency of effort to perform the task				
1.1.8.3	Direction of effort	Self-explanatory measure of how the crew effort is consistent with the assigned goals.	1-5 Predetermined rating	Daily	Foreman
	1- VERY LOW consistency between direction of effort and the assigned goals. 2- LOW consistency between direction of effort and the assigned goals. 3- AVERAGE consistency between direction of effort and the assigned goals. 4- HIGH consistency between direction of effort and the assigned goals. 5- VERY HIGH consistency between direction of effort and the assigned goals				
1.1.9	Level of Interruptions and Disruptions	Refers to the number of delay events caused due to several reasons during the working hours, which may disrupt the crew from performing the assigned tasks.	Real number (total time lost due to interruptions, min)	Daily	Foreman

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
1.1.10	Number of Consecutive Working Days	Number of days crew spend on the job-site in each working cycle may cause physical and mental fatigue and consequently affect the production rate of construction operation.	Integer number (no. of consecutive days, day)	Once, Project Start	Project Manager
1.1.11	Total Daily Overtime Work	Working long overtime hours cause physical and mental fatigue and consequently affect the production rate of construction operation.	Integer number (overtime Work, hr)	Daily	Foreman
1.1.12	Crew Skill Level	Refers to the crew skills which are needed for accomplishing their responsibilities.	1-5 Predetermined rating	Once, Crew Change	Foreman
	1- Skill level of the crew is VERY LOW for execution of the activity. 2- Skill level of the crew is LOW for execution of the activity. 3- Skill level of the crew is FAIR for execution of the activity. 4- Skill level of the crew is HIGH for execution of the activity. 5- Skill level of the crew is VERY HIGH for execution of the activity.				
1.1.13	Unscheduled Breaks	Refers to the unscheduled break times during the working hours which may happen due to the different reasons (e.g., smoking, extra coffee time in cold days and etc.)	Real number (total time lost due to unscheduled breaks, min)	Daily	Foreman
1.1.14	Late Arrival / Early Quit	Refers to the total time lost by late arrival or early quit of the crew members. This factor should be measured for each crew including the total time lost by the crew members individually.	Real number (total time lost due to late arrival or early quit, min)	Daily	Foreman
1.1.15	Level of Absenteeism	Absenteeism is known as an effective factor on the crew makeup, morale of workers, and labour productivity and consequently production rate of construction operations.	Percentage (average no. of absent crew members to weekly average crew size)	Weekly	Foreman
1.2. Material and Consumables					
1.2.1	Material Availability	Refers to whether the required material for execution of the activity is available in the material storage.	Categorical	Daily	Foreman
	Yes, No				
1.2.2	Waiting Time for Material	Refers to the total time spent to provide the required material for execution of the task at the working area.	Real number (total time lost due to	Daily	Foreman

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
		The time may be lost due to the different reasons (e.g., delivery of material from the storage to working area).	waiting for materials, min)		
1.2.3	Material Quality	The quality of the material may affect the production rate of the construction operations by causing delays due to the defected material or adjustment to the materials (e.g., concrete does not meet the design specifications such as slump test).	Real number (total time lost due to material quality problems, min)	Daily	Foreman
1.2.4	Material Storage Practice	The material storage practice in the construction site may affect the production rate of the operation by causing unreasonable delays for delivering the material from the storage to the working area.	1-5 Predetermined rating	Weekly	Foreman
	1- VERY POOR material storage practice, VERY FREQUENT time loss for delivering material from the storage, VERY POOR arrangement of material in the storage. 2- POOR material storage practice, FREQUENT time loss for delivering material from the storage, POOR arrangement of material in the storage. 3- FAIR material storage practice, INFREQUENT time loss for delivering material from the storage, FAIR arrangement of material in the storage. 4- GOOD material storage practice, RARE time loss for delivering material from the storage, GOOD arrangement of material in the storage. 5- VERY GOOD material storage practice, VERY RARE time loss for delivering material from the storage, VERY GOOD arrangement of material in the storage				
1.2.5	Pre-installation Requirements	The pre-installation refers to the tests performed prior to the use of material for execution of the activity such as; the concrete slump test prior to placing the concrete. The pre-installation requirements of material can affect the production rate of construction operations since it can cause time delays for performing the tests and receiving approvals for starting the activities.	Real number (total waiting time, hr)	Once, Activity Finish	Project Manager
1.3. Equipment and Tools					
1.3.1	Number and Type of Active Equipment on the Task	The total number and the type of equipment available at the working area for execution of the activity affects the production rate of the construction operation.	Integer number (no. equipment), Categorical (Equipment type)	Daily	Researcher
1.3.2	Equipment Breakdown Frequency	Refers to the total number of equipment breakdown occurrences per week of work which affect the	Integer number (no. of breakdowns per week)	Weekly	Foreman

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
		production rate of construction operations by causing delays and suspensions.			
1.3.3	Equipment Breakdown Downtime	Refers to the total delay caused by the breakdown of the equipment which might be spent for repairs or substitution of the broken equipment by other piece of equipment.	Real number (total time lost due to equipment breakdown, min)	Daily	Foreman
1.3.4	Equipment Maintenance Frequency	Refers to the frequency of the maintenance services (i.e., minor and major) performed for each piece of equipment. The maintenance services may affect the production rate of the construction activities	Integer number (no. of breakdowns per week)	Weekly	Foreman
1.3.4	Equipment Maintenance Downtime	The total time (during the working hours) spent for maintenance of the equipment including; major and minor services and inspections which affect the production rate of the construction operations.	Real number (total time lost due to equipment maintenance, min)	Daily	Foreman
1.3.5	Work Equipment Availability	Availability of the appropriate equipment for execution of an activity can affect the production rate of the operation.			
1.3.5.1	Equipment Delivery to Working Area	Refers to the total time spent to deliver the equipment to the working area (e.g., delivery from the fleet or shelter) before the start of the activity.	Real number (total time lost due to delivery of equipment, min)	Daily	Foreman
1.3.5.2	Waiting Time for Equipment	Refers to the time spent to provide the appropriate piece of equipment at the working area to perform the task. The waiting time may be spent for start-up of the equipment, refueling, change of operator or other reasons.	Real number (total time lost due to waiting for equipment, min)	Daily	Foreman
1.3.5.3	Appropriateness of Equipment	Refers to the appropriateness of the equipment for execution of the activity (e.g., proper blade shape, material, proper volume).	1-5 Predetermined rating	Daily	Superintendent
	1- Equipment Size is a VERY POOR fit for the activity, equipment setting is a VERY POOR fit for the activity or equipment Power is a VERY POOR fit for the activity. 2- Equipment Size is a POOR fit for the activity, equipment setting is a POOR fit for the activity or equipment Power is a POOR fit for the activity. 3- Equipment Size is a FAIR fit for the activity, equipment setting is a FAIR fit for the activity or equipment Power is a FAIR fit for the activity. 4- Equipment Size is a GOOD fit for the activity, equipment setting is a				

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
	GOOD fit for the activity or equipment Power is a GOOD fit for the activity. 5-Equipment Size is a VERY GOOD fit for the activity, equipment setting is a VERY GOOD fit for the activity or equipment Power is a VERY GOOD fit for the activity.				
1.3.6	Equipment Ownership	Refers to the ownership of the equipment pieces which are used for execution of the activity under study.	Categorical	Once, Equipment Change	Project Manager
	Own, Lease, Rental				
1.3.7	Equipment Production Capacity	The maximum production capacity of the equipment has a direct effect on the production rate of the construction activity. This factor measures the maximum production rate in ideal situation as it is mentioned in equipment specifications.	Real number (total power generated, hp-hour) Real number (context dependant, [e.g., m^3/hr for excavator])	Once, Equipment Change	Project Manager
1.3.8	Equipment Age	The age of equipment is an important factor for maintenance of the equipment and may affect the production rate of the construction operations.	Real number (age of equipment, hr)	Once, Equipment Change	Project Manager
1.3.9	Equipment Operator Experience	Experience of the equipment operator working on the construction equipment is an important factor affecting the production rate of the construction operations. This factor measures the experience of the operator for operating the same type of equipment which she/he operates for execution of the activity under study.	Integer number (years of experience)	Once, Operator Change	Project Manager
1.3.10	Equipment Operator Education	The education of the equipment operator may affect the production of construction operations considering the IT options and settings of the modern equipment.	Categorical	Once, Operator Change	Equipment Operator
	Below Secondary, Secondary School, Technical or Apprentice, College, University				
1.3.11	Equipment Operator Skill Level	Refers to the skills of the operators which they needed for execution of the activity.	1-5 Predetermined rating	Once, Operator Change	Foreman
	1- Skill level of the operator is VERY LOW for execution of the activity. 2- Skill level of the operator is LOW for execution of the activity. 3- Skill level of the operator is FAIR for execution of the activity. 4- Skill level of the operator is HIGH for execution of the activity. 5- Skill level of the operator is VERY HIGH for execution of the activity.				

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
1.3.12	Amplification of Human Energy	Refers to the driving energy provided by the equipment to contribute the human energy for execution of the activity. Providing driving energy varies from no driving energy like hand tools to providing all the driving energy needed for execution of the operation such as TBM.	1-5 Predetermined rating	Once, Equipment Change	Foreman
	1- Equipment supplies no driving energy. 2- Equipment supplies some driving energy. 3- Equipment supplies measurably more energy but not all. 4- Equipment supplies all driving energy. 5- Equipment supplies all driving energy plus more than the earlier generations of this type of equipment.				
1.3.13	Level of Control[2,3]	Refers to the controllability on the equipment which can defer from the manual hand tools (e.g., electric hammers) to the GPS controlled equipment (e.g., TBM)	1-5 Predetermined rating	Once, Equipment Change	Foreman
	1- Manual hand tools. 2- Manually controlled devices. 3- Assisted controlled devices. 4- Tele-controlled devices. 5- Preprogrammed devices.				
1.3.14	Functional Range[2,3]	Refers to the enhancement of human capabilities by the equipment. This factor evaluates if the functionality of the equipment could be substituted by human resources (e.g., excavators) or cannot be substituted by human resources at all (e.g., trenchless drilling machines).	1-3 Predetermined rating	Once, Equipment Change	Foreman
	1- Equipment provides no enhancement to human resources' capabilities. 2- Equipment expands human resources' capabilities. 3- Equipment expands human resources' capabilities more than the previous generations of the equipment.				
1.3.15	Equipment Ergonomic Design[2,3]	Refers to the ergonomics of the equipment which may provide relief from the physical stresses for the operator or not. Not providing relief from physical stresses can cause fatigue for the operator and consequently affect the production rate of the operation.	1-3 Predetermined rating	Once, Equipment Change	Equipment Operator
	1- Equipment provides no relief from physical stresses. 2- Equipment provides relief from physical stresses. 3- Equipment provides relief from physical stresses as well as recovery from the existing physical fatigue (e.g., heated and ventilated seats).				
1.3.16	Information Feedback Provision[2,3]	The capabilities of high tech equipment for information processing can affect the production rate of construction activities. The information processing refers to the capability of processing the information which are collected by the different sensors or any other source of information from the different part of equipment (e.g.,	1-5 Predetermined rating	Once, Equipment Change	Foreman

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
		time for maintenance) or from the surrounding environment (e.g., pressure sensor on drilling equipment)			
	1- Equipment provides no level of information feedback to the operator. 2- Equipment provides basic level of information feedback to the operator regarding internal operating factors. 3- Equipment provides internal information to the operator and is able to respond to its own information. 4- Equipment provides information regarding external and internal factors to the operator. 5- Equipment provides information to the operator regarding internal and external factors and responds to both.				
1.3.17	Moving Technology	The moving technology of equipment affects their top speed, traction, maximum permissible slope for operation, service costs, operation costs and etc. Therefore, the moving technology of the equipment can affect the production rate of construction activities.	Categorical	Once, Equipment Change	Researcher
	Crawling, Wheels				
1.3.18	Equipment Warranty	Equipment warranty is an important factor affecting the cost of the equipment operation and consequently the production rate of the equipment measured as the total cost per unit of output.	Categorical	Once, Equipment Change	Project Manager
	Yes, No				
1.3.19	Equipment Specification	The equipment specification can affect the production rate of the construction operations.	Nominal value	Once, Equipment Change	Project Manager
1.4. Task Characteristics					
1.4.1	Task Complexity	Refers to the complexity of the task in terms of known alternatives to doing it and the number of subtasks required.	1-5 Predetermined rating	Daily	Foreman
	1- Working area Spaciousness is VERY LOW and STRICTLY affect the selection of Equipment and the Crew Size. 2- Working area Spaciousness is LOW and STRICTLY affect the selection of Equipment and MODERATELY affect the selection of Crew Size. 3- Working area Spaciousness is AVERAGE and MODERATELY affect the selection of Equipment and the Crew Size. 4- Working area Spaciousness is HIGH and SLIGHTLY affect the selection of Equipment and the Crew Size. 5- Working area Spaciousness is VERY HIGH and DOES NOT affect the selection of Equipment and the Crew Size.				

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
1.4.2	Total Volume of Work	Refers to the total quantity approved for construction for the activity under study.	Real number (approved quantity for construction)	Once	Foreman
1.4.3	Task Repetitiveness	Refer to how much of the work volume is repetitive in terms of having identical materials, equipment and construction methods.	Percentage (identical work qty divided by the total work qty)	Weekly	Foreman
1.4.4	Out of Sequence Work	Refers to the situation in which the construction crew has to wait or slow down the operation because the ongoing prerequisite task has slowed down or stopped.	Real number (total time lost due to ongoing prerequisite task, min)	Weekly	Foreman
1.4.5	Problems with Predecessors	Refers to the deficiency from the previous work which should be modified or redone and consequently the execution of the activity under study should be stopped.	Real number (total time lost for correction of predecessor, min)	Weekly	Foreman
1.4.6	Construction Method	Refers to the method of construction (which is selected due to the different considerations) used to execute the task which can affect the production rate of the construction activity (e.g., trenchless pipe drilling and open cut method for pipe installation)	Categorical (context dependant)	Once	Foreman
	Spoil removal method, Drilling method[6]				
1.4.7	Task Waste Disposal	The time spent for disposal of the waste material considering the regulations can affect the production rate of the construction operations.	Real number (total time lost for waste material disposal, min)	Weekly	Superintendent
1.4.8	Level of Rework (Contractor Initiated)	Refers to redoing the work because of not meeting project requirements which are initiated due to the deficiency of the contractor's work on the activity under study.	Percentage (activity weekly volume of rework to total activity work volume [including rework])	Weekly	Superintendent

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
1.4.9	Frequency of Rework (Contractor Initiated)	Referring to the number reworks occurrences per week which are initiated due to the deficiency of contractor's work on the activity under study.	Integer number (number of reworks incidents weekly)	Weekly	Superintendent
1.4.10	Rework Cost (Contractor Initiated)	The total cost of rework usually exceeds the direct cost of rework. This factor measures the total cost of rework (i.e., direct costs and indirect costs) divided by the total cost of the activity considering the reworks which are initiated due to the deficiency of contractor's work.	Percentage (activity total weekly cost of rework divided by total activity cost [including rework])	Weekly	Superintendent
1.4.11	Balance between Labour and Equipment	Refers to the appropriateness of the balance between the labour forces and the equipment working on the activity considering the capacity of the equipment and capabilities of the labour. This factor measures the number of equipment and their capacity and the number of labour directly working on the activity excluding the equipment operators.	Integer numbers (no. equipment, no. of labour)	Daily	Foreman
1.5. Location Properties					
1.5.1	Spaciousness of Working Area	Refers to the total area provided in the construction site for execution of the activity under study. Space limitation can affect the selection of the equipment and crew size and consequently production rate of the construction operations (e.g., crew size selection for slipping formwork concrete placing, equipment selection for road side construction).	1-5 Predetermined rating	Once, Working Area Change	Superintendent
	1- Working area Spaciousness is VERY LOW and STRICTLY affect the selection of Equipment and the Crew Size. 2- Working area Spaciousness is LOW and STRICTLY affect the selection of Equipment and MODERATELY affect the selection of Crew Size. 3- Working area Spaciousness is AVERAGE and MODERATELY affect the selection of Equipment and the Crew Size. 4- Working area Spaciousness is HIGH and SLIGHTLY affect the selection of Equipment and the Crew Size. 5- Working area Spaciousness is VERY HIGH and DOES NOT affect the selection of Equipment and the Crew Size.				
1.5.2	Site Restrictions	Refers to the restrictions and regulations at the project site which govern the construction equipment operations (e.g., time restrictions for use of earthmoving equipment). The total time loss caused by the	Real number (total time lost due to project site	Daily	Superintendent

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
		regulations and the restrictions affect the production rate of the construction operations.	restrictions for use of equipment, min)		
1.5.3	Soil Conditions (Dependency)	Dependency of the activity under study on the soil conditions may affect the production rate of the construction operations. Highly dependant activities (e.g., excavation, drilling) are more vulnerable than the lower dependant activities (e.g., paving)	1-5 Predetermined rating	Once, Activity Start	Foreman
	1- Activity execution IS NOT dependant to the soil conditions, VERY HIGH tolerance to the properties. 2- Activity execution is RARELY dependant to the soil conditions, HIGH tolerance to the soil properties. 3- Activity execution is MODERATELY dependant to the soil conditions, MODERATE tolerance to the soil properties. 4- Activity execution is HIGHLY dependant to the soil conditions, LOW tolerance to the soil properties. 5- Activity execution is EXTREMELY dependant to the soil conditions, VERY LOW tolerance to the soil properties.				
1.5.4	Soil Properties (Type, Moisture and etc.)	The soil properties can highly affect the production rate of the construction equipment if the activity is dependant to the soil conditions.			
1.5.4.1	Soil Type	Refers to the type of the soil on which the construction operations is taking place.	Categorical	Once, Activity Start	Project Manager
	Gumbo Clay Loam, Silty Clay Loam, Silty Loam, Sandy Loam, Sandy/Coarse				
1.4.5.2	Soil Moisture	Refers to the moisture content of the soil on which the construction operations is taking place.	Percentage (weight of water content of soil divided by total weight of soil)	Once, Activity Start	Project Manager
1.5.5	Unseen Subsurface Conditions	The unseen subsurface conditions such as the groundwater level and existence of underground urban facilities can affect the production rate of the construction operations.			
1.5.5.1	Groundwater Level	Refers to the groundwater level at the construction site.	Real number (groundwater level, m)	Once, Activity Start	Project Manager
1.5.5.2	Underground Facilities	Refers to the existence of any underground urban facilities which can affect the construction process by regulations.	Categorical	Once, Activity Start	Project Manager

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
	Yes, no				
1.5.6	Hauling/Delivery Elevation Difference	The elevation difference between the working area and the dump/quarry site can affect the production rate of construction operations.	Real number (elevation difference, m)	Once, Activity Start	Project Manager
1.5.7	Hauling/Delivery Distance	The distance between the working area and the dump/quarry site can affect the production rate of construction operations.	Real number (distance, km)	Once, Activity Start	Project Manager
1.6. Foreman (Supervisor)					
1.6.1	Foreman (Supervisor) Experience	Refers to the foreman (supervisor) experience in terms of year in industry after reaching to the current career stage.	Integer number (years of experience)	Once, Change of Foreman (Supervisor)	Superintendent
1.6.2	Change of Foreman (Supervisor)	Refers to the number of changes of the foreman (supervisor) who is responsible for the activity under study.	Integer number (no. changes of foreman [supervisor] per month)	Monthly	Project Manager
1.6.3	Work Planning Skills	Refers to the planning skills of the foreman (supervisor) in terms of identifying and verifying that tools, equipment and materials are available and identifying the needs and deficiencies in the plan/schedule and communicating these to appropriate persons; translating general work requirements into a prioritized plan for individual tasks and assignments.	1-5 Predetermined rating	Weekly	Superintendent
	1- VERY POOR in Identifying and verifying that tools and materials are available and complete; VERY POOR in Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; VERY POOR in Translating general work requirements into a prioritized plan for individual tasks and assignments. 2- POOR in Identifying and verifying that tools and materials are available and complete; POOR in Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; POOR in Translating general work requirements into a prioritized plan for individual tasks and assignments. 3- FAIR in Identifying and verifying that tools and materials are available and complete; FAIR in Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; FAIR in Translating general work requirements into a prioritized plan for individual tasks and assignments. 4- GOOD in Identifying and verifying that tools and materials are available and complete; GOOD in Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; GOOD in				

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
	Translating general work requirements into a prioritized plan for individual tasks and assignments. 5- VERY GOOD in Identifying and verifying that tools and materials are available and complete; VERY GOOD in Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; VERY GOOD in Translating general work requirements into a prioritized plan for individual tasks and assignments.				
1.6.4	Leadership and Supervisory Skills	Refers to the skill of the foreman (supervisor) for leading and supervising the crew(s) to consistently apply the project's policies at the work.	1-5 Predetermined rating	Weekly	Superintendent
	1. INADEQUATE Orientation of crew members; VERY POOR in Assigning individual and crew tasks; VERY POOR in Communicating the job to and with the crew; VERY POOR in Controlling and maintaining work standards. 2. INADEQUATE Orientation of crew members; POOR in Assigning individual and crew tasks; POOR in Communicating the job to and with the crew; POOR in Setting and maintaining work standards. 3. ADEQUATE Orientation of crew members; FAIR in Assigning individual and crew tasks; FAIR in Communicating the job to and with the crew; FAIR in Setting and maintaining work standards. 4. ADEQUATE Orientation of crew members; GOOD in Assigning individual and crew tasks; GOOD in Communicating the job to and with the crew; GOOD in Setting and maintaining work standards. 5. ADEQUATE Orientation of crew members; VERY GOOD in Assigning individual and crew tasks; VERY GOOD in Communicating the job to and with the crew; VERY GOOD in Setting and maintaining work standards				
1.6.5	Coordination Between Labour and Equipment Operators	Refers to the coordination between the equipment operators and the labour which may be achieved by a signalman, or other means specified by the foreman.	Real number (total time lost due to lack of coordination, min)	Daily	Foreman
1.7. Engineering and Instructions					
1.7.1	Availability of Drawings	Refers to whether required work drawings are available on site.	1-5 Predetermined rating	Monthly	Superintendent
	1- Always Not Available. 2- Sometimes Not Available. 3- Sometimes Available. 4- Mostly Available. 5- Always Available				
1.7.2	Quality of Drawings	Refers to the quality of the drawings in terms of completeness, readability, reusability, clarity of information, and frequency of updates.	1-5 Predetermined rating	Monthly	Superintendent
	1- Incomplete, VERY POOR Readability, VERY LOW Reusability, TOO MANY Unclear information, NOT Updated. 2- Incomplete, POOR Readability, LOW Reusability, SOME Unclear information, NOT Updated. 3- Incomplete, AVERGAE Readability, AVERAGE Reusability, FEW Unclear information, NOT Updated. 4- Complete, GOOD Readability, HIGH Reusability, FEW Unclear information, Updated. 5- Complete, VERY GOOD Readability, HIGH Reusability, VERY FEW Unclear information, Updated.				

Factor ID	Factor	Description	Scale of Measure	Data Collection Cycle	Data Source
1.7.3	Number of Revisions on Drawings	Refers to the number of drawing revisions submitted to foreman (supervisor) throughout the project execution.	Integer number (number of the drawing revisions per week)	Weekly	Superintendent
1.7.4	Design Changes	Refers to the design changes submitted to the foreman (supervisor) throughout the project execution.	Integer number (number of the design changes per week)	Weekly	Superintendent
1.7.5	Quality of Specifications	Refers to the quality of the specifications in terms of completeness, and clarity of information.	1-5 Predetermined rating	Once, Activity Start	Superintendent
	1- VERY POOR Clarity, VERY Incomplete. 2- POOR Clarity, Incomplete. 3- FAIR Clarity, FAIRLY Complete. 4- GOOD Clarity, Complete. 5- VERY GOOD Clarity, VERY Complete				
1.7.6	Time to Respond RFIs	Refers to the response time to the requests for information (RFI) from the contractor to the owner and/or engineer.	Real number (average response time, hr)	Weekly	Superintendent
1.7.7	Frequency of Rework (Design Initiated)	Referring to the number reworks occurrences per week which are initiated due to the deficiency of the engineering design or specification on the activity under study.	Integer Number (Number of reworks incidents weekly)	Weekly	Superintendent
1.7.8	Level of Rework (Design Initiated)	Refers to a work redone for not meeting project requirements which are initiated due to the deficiency of the engineering design or specification on the activity under study.	Percentage (activity total volume of rework divided by total activity work volume)	Weekly	Superintendent
1.7.9	Rework Cost (Design Initiated)	The total cost of rework usually exceeds the direct cost of rework. This factor measures the total cost of rework (i.e., direct costs and indirect costs) divided by the total cost of the activity considering the reworks which are initiated due to the deficiency of the engineering design or specification on the activity under study.	Percentage (activity total weekly cost of rework divided by total activity cost [including rework])	Weekly	Superintendent
1.7.10	Time to Do Inspections	Refers to the time before the engineering team/owner does the inspection after completion of the activity and receiving the notice from the contractor.	Real number (time lost due to waiting for inspection, min)	Weekly	Superintendent

B.1.2. Field Data Collection Details for Project-Level Factors

Table B.2. Field data collection details for project-level factors

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.1. Project Delivery and Contract					
2.1.1	Level of Sub-Contracting	Refer to the level of subcontracting on the project site			
2.1.1.1	Subcontracted Amount	Refers to the portion of the construction works which are transferred to subcontractors.	Percentage ($ value subcontracts divided by total $ value of contract)	Once, Project Start	Project Manager
2.1.1.2	Number of Subcontractors	Total number of subcontractor companies on site.	Real number (Total number of subcontractors per project)	Once, Project Start	Project Manager
2.1.2	Delivery System	Refers to the arrangement between the owner and contractor on the means to design, execute, and operate the project.	Categorical	Once, Project Start	Project Manager
	Design Bid Build (DBB), Design Build (DB), Build Operate Transfer (BOT), Private Public Partnership (PPP)				
2.1.3	Contract Type	Refers to the contract arrangement made for the project between the owner and contractor or general contractor and subcontractor.	Categorical	Once, Project Start	Project Manager
	Lump Sum, Unit Rate, Cost Reimbursable				
2.1.4	Level of Fast Tracking	Refers to whether the project construction begun before the completion of the design process.	Percentage (% Overlap between design and construction schedule)	Once, Project Start	Project Manager
2.1.5	Contract Conditions for Changes	Number of revisions on contract conditions submitted at the project level for all activities.	Real Number (No. of contract conditions changes	Monthly	Project Manager

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
			divided by total number of contract clauses)		
2.1.6	Lack of Information	Refers to the lack of information associated with the design and execution of the project and will be measured in terms of the number of RFI's per month.	Integer Number (No. RFIs per month)	Monthly	Project Manager
2.1.7	Change in Specifications	Refers to the changes in the project specifications which represent the project design quality and may affect the productivity of the project.	Percentage (no. of changed specifications to total no. of specification clauses on specific scope)	Monthly	Superintendent
2.1.8	Change in Design Drawings	Refers to the changes in the drawings represents the project design quality and may affect the productivity of the project.	Percentage (no. of changed drawings to total no. of specification clauses on specific scope)	Monthly	Superintendent
2.1.9	Lack of Information	Lack of information represents the quality of the project design documents and may affect the productivity of the construction project.	Real number (no. of RFI's per month per discipline)	Monthly	Project Manager
2.2. Project Best Practices					
2.2.1	Use of Automation and Information Technology	Refers to the use of IT for the planning, monitoring and control of the project (e.g., 4D project planning, building information modeling [BIM])	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- NO Use of IT in planning of project, NO Use of IT for project monitoring and controlling. 2- POOR Use of IT in planning of project, POOR Use of IT for project monitoring and controlling. 3- FAIR Use of IT in planning of project, FAIR Use of IT for project monitoring and controlling. 4- GOOD Use of IT in planning of project, GOOD Use of IT for project monitoring and controlling. 5- VERY GOOD Use of IT in planning of project, VERY GOOD Use of IT for project monitoring and controlling				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.2.2	Constructability Review	Refers to the constructability reviews implemented prior to execution phase of the project to improve the time, cost and quality performance of the project.			
2.2.2.1	Constructability Review Participants	Refers to the participants of the constructability review meetings. The meetings may include designer/engineering team, owner team, contractor team, subcontractors and possibly project manager and superintendent.	Categorical	Once, Project Start	Project Manager
	Owner, Engineering, Contractor, Sub-contractor, Project manager, Superintendent				
2.2.2.2	Constructability Review Implementation	Refers to the modifications and updates made on the project plan and/or design by the constructability reviews to improve the project performance in terms of achieving the project objectives.	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- Objectives of Constructability Reviews are VERY POORLY defined, and VERY POORLY match the Project Objectives, VERY LOW improvement on project performance are made. 2- Objectives of Constructability Reviews are POORLY defined and POORLY match the Project Objectives, LOW improvement on project performance are made. 3- Objectives of Constructability Reviews are FAIRLY defined, and FAIRLY match the Project Objectives, FAIR improvement on project performance are made. 4- Objectives of Constructability Reviews are WELL defined, and WELL match the Project Objectives, HIGH improvement on project performance are made. 5- Objectives of Constructability Reviews are VERY WELL defined, and VERY WELL match the Project Objectives, VERY HIGH improvement on project performance are made.				
2.2.3	Start-up Planning	Project start-up planning can decrease the project life cycle costs and improve the cost performance of the project. Start-up planning as a major element of front end planning may increase the production rate of construction projects.	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- NO Use of technological methods, ONLY FEW Alternative evaluated, NO Risk analysis. 2- NO Use of technological methods, FEW Alternative evaluated, NO Risk analysis. 3- NO Use of technological methods, SOME Alternatives evaluated, SOME form of Risk analysis. 4- SOME Use of technological methods, SOME Alternatives evaluated, SOME form of Risk analysis. 5- DETAILED Use of technological methods, MANY Alternatives evaluated, DETAILED Risk analysis.				
2.2.4	Productivity Measurement Practice	Refers to the productivity measurement practice used by the company to evaluate the performance of the project execution and project control purposes.	1-5 Predetermined rating	Once, Project Start	Project Manager

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
	1- NO Use of Standard systems to measure the outputs and inputs, Frequency of data collection NOT properly established, VERY POOR Productivity evaluation and forecasting. 2- NO Use of Standard systems to measure the outputs and inputs, Frequency of data collection NOT properly established, POOR Productivity evaluation and forecasting. 3- Use of SOME Standard systems to measure the outputs and inputs, Frequency of data collection SOMEWHAT established, FAIR Productivity evaluation and forecasting. 4- Use of SOME Standard systems to measure the outputs and inputs, Frequency of data collection PROPERLY established, GOOD Productivity evaluation and forecasting. 5- Use of PROPER Standard systems to measure the outputs and inputs, Frequency of data collection PROPERLY established, VERY GOOD Productivity evaluation and forecasting.				
2.2.5	Use of Workface Planning	Refers to decomposing the construction work packages into more manageable installation work packages. Workface planning gives a better understanding of the work to the foreman and make the material management possible at work package level. Use of workface planning may increase the productivity of construction projects.	1-5 Predetermined rating	Once, Project Start	Project Manager
	1-VERY POOR Implementation of workforce planning in the project. 2- POOR Implementation of workforce planning in the project. 3- FAIR Implementation of workforce planning in the project. 4- GOOD Implementation of workforce planning in the project. 5- VERY GOOD Implementation of workforce planning in the project				
2.3. Project's Owner Nature					
2.3.1	Owner's Supervision	Refers to the supervision of the owner or their representative on the project site in the construction phase.	1-5 Predetermined rating	Weekly	Superintendent
	1- VERY LOW Supervision. 2- LOW Supervision. 3- SOME Supervision. 4- HIGH Supervision. 5- VERY HIGH Supervision				
2.3.2	Owner's Intervention	Refer to the intervention of the owner or its representative during the construction phase which caused any delays in project execution. This factor measures the total time lost due to the direct request or action of the owner.	Real number (total time lost due to owner intervention, hr)	Weekly	Superintendent
2.3.3	Owner's Primary Driver	The owner's primary driver affects the execution plan and the different managerial aspects of the project and can affect the project productivity measured as the units of project output per dollars.	Categorical	Once, Project Start	Project Manager
	Time, Cost, Quality				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.3.4	Clarity of Owner's Objectives	The higher clarity of the owner's objectives in their communication with the engineering and contractor teams can affect the productivity of the construction process.	1-5 Predetermined rating	Weekly	Superintendent
	1- VERY POOR clarity of the owner's objectives. 2- POOR clarity of the owner's objectives. 3- FAIR clarity of the owner's objectives. 4- GOOD clarity of the owner's objectives. 5- VERY GOOD clarity of the owner's objectives.				
2.3.5	Delivery of Site to Contractor	Refers to the total time between the delivery date stated in the contract and the actual delivery date of the project site to the contractor.	Real number (total delay to handover the project site to contractor, days)	Once, Project Start	Project Manager
2.3.6	Owner's Staff On-Site	Refers to the weekly average number of the owner's staff available on the project site.	Integer number (weekly average no. of owner's staff on site)	Weekly	Superintendent
2.3.7	Suspension of Work (Owner's Reasons)	Refers to the suspensions of work occurred during the construction phase which are caused by the project owner.			
2.3.7.1	Frequency of Suspensions	This factor measures the number of work suspensions occurs monthly.	Integer number (number of suspension occurrences per week)	Weekly	Project Manager
2.3.7.2	Length of Suspensions	Self-explanatory	Real number (total days lost due to work suspensions)	Weekly	Project Manager
2.4. Project Conditions					
2.4.1	Camp Conditions	Refers to the conditions of the camp (if available) which is provided for workers.	1-5 Predetermined rating	Once, Project Start	Superintendent
	1- VERY POOR Room condition, POOR Food service, NO Facilities. 2- POOR Room condition, POOR Food service, NO Facilities. 3- FAIR Room condition, FAIR Food service, SOME Facilities. 4- GOOD Room condition, GOOD Food service, SOME Facilities. 5- VERY GOOD Room condition, VERY GOOD Food service, MANY Facilities				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.4.2	Total Project-Site Area	The total area of the project site affect different aspects of the project such as; total duration workers spend travelling in the project site, number of transportation equipment. Therefore, the productivity of the project may be affected as well.	Real number (total project site area, m²)	Once, Project Start	Project Manager
2.4.3	Site Facilities Conditions	The project site facilities provided for the workers may affect the productivity of the construction projects.			
2.4.3.1	Project Site Lunchroom for Workers	Refers to the total area and number of the seats available for the workers in the lunchroom of the project site.	Real number (total area, m²) Integer number (no. of seats)	Once, Project Start	Project Manager
2.4.3.2	Project Site Washroom for Workers	Refers to the total number of the washrooms provided at the project site for the workers.	Integer number (no. washrooms)	Once, Project Start	Project Manager
2.4.4	Project Working Time	Refers to the regular daily working time of the project.	Time (start time and finish time)	Once, Project Start	Project Manager
2.4.5	Project Working Cycle	Refers to the general working cycle of the project team which may affect the productivity of the project.	Integer numbers (no. consecutive working days, no. of consecutive off days)	Once, Project Start	Project Manager
2.4.6	Site Layout	The layout of the project site affects the productivity of the construction projects.			
2.4.6.1	Temporary Facilities	Refers to the identification of the required temporary facilities and their size and placement at the project site. The temporary facilities include; the material laydown area, project site storage, fabrication shops, and batch plant.	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY POOR Identification, POOR Placement, VERY LARGE Size requirement. 2- POOR Identification, POOR Placement, LARGE Size requirement. 3- GOOD Identification, POOR Placement, LARGE Size requirement. 4- GOOD Identification, GOOD Placement, AVERAGE Size requirement. 5- VERY GOOD Identification, VERY GOOD Placement, SMALL Size requirement.				
2.4.6.2	Equipment Storage Location	Refers to the space provided for the construction equipment at the project site. The equipment may	1-5 Predetermined rating	Once, Project Start	Project Manager

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
		work at the working space provided (e.g., crane) or parked in the space for non-working hours (e.g., dozers).			
	1- The shelter for moving equipment is TOO FAR from the workspace, VERY LIMITED space for operation of steady equipment. 2- The shelter for moving equipment is FAR from the workspace, LIMITED space for operation of steady equipment. 3- The shelter for moving equipment is in FAIR DISTANCE from the workspace, FAIR space for operation of steady equipment. 4- The shelter for moving equipment is CLOSE to the workspace, ENOUGH space for operation of steady equipment. 5- The shelter for moving equipment is VERY CLOSE to the workspace, MORE THAN ENOUGH space for operation of steady equipment.				
2.4.6.3	Access Roads and On-Site Paths	Availability of access roads (i.e., roads with pavement) and on-site paths (i.e., temporary unpaved paths for equipment) affect the moving speed of the construction equipment and consequently may affect the productivity of the construction projects. This factor measures the number of the access roads and the on-site paths per square meter of the project site area.	Real number (no. access roads and on-site paths divided by project site area)	Once, Project Start	Project Manager
2.4.6.4	Workspace and Site Objects	Refers to the layout design of the project workspace where the construction is taking place and the site objects which are un-movable objects at the project site (e.g., trees) which can affect the project layout design.	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- Project workspace is VERY POORLY designed, VERY FREQUENT conflict between the workspace and the site objects happens. 2- Project workspace is POORLY designed, FREQUENT conflict between the workspace and the site objects happens. 3- Project workspace is FAIRLY designed, NOT FREQUENT conflict between the workspace and the site objects happens. 4- Project workspace is WELL designed, RARE conflict between the workspace and the site objects happens. 5- Project workspace is VERY WELL designed, VERY RARE conflict between the workspace and the site objects happens.				
2.4.7	Restrictions for Project Site Access	Refers to the restrictions which may affect productivity of the project by limiting the access of employees to the project site.	1-5 Predetermined rating	Weekly	Superintendent
	1- TOO MANY Restrictions for project site access, VERY COMMON Time loss due to the restrictions. 2- MANY Restrictions for project site access, COMMON Time loss due to the restrictions. 3-SOME Restrictions for project site access, NOT COMMON Time loss due to the restrictions. 4- FEW Restrictions for project site access, RARE Time loss due to the restrictions. 5- VERY FEW Restrictions for project site access, VERY RARE Time loss due to the restrictions.				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.4.8	Construction Method	Refers to the methodology selected for execution of the construction project.	Categorical (context dependant)	Once, Project Start	Project Manager
2.4.9	Distance between Project Site and City	The distance between the project site and the closest city can affect the construction team selection, flight arrangement for the crew and consequently may affect construction productivity.	Real number (distance to the nearest city, km)	Once, Project Start	Project Manager
2.4.10	Project Size	Refers to the total value of the project contract.	Real number (Project contract value, $ Million)	Once, Project Start	Project Manager
2.4.11	Project Type (Industry Sector)	The industry sector of the project under study may affect the productivity of the project.	Categorical	Once, Project Start	Project Manager
	Industrial, Residential, Commercial and Institutional, Civil				
2.4.12	Government and Regulatory Inspections	Refers to the inspections which are made by the government or regulatory agencies such as building inspections (e.g., sewer and water permit inspection). These inspections and their approvals are required for project progress.			
2.4.12.1	Frequency of Inspections	This factor measures the number of inspection occurrences monthly.	Integer number (number of inspections per month)	Monthly	Project Manager
2.4.12.2	Total Time for Inspections	This factor measures the total duration of the inspections monthly.	Real number (total duration of inspections, hr)	Monthly	Project Manager
2.4.13	Suspension of project	Refers to the suspensions of work occurred during the construction phase which are caused due to the project conditions (e.g., damages to urban facilities)			
2.4.13.1	Frequency of Suspensions	This factor measures the number of work suspensions occurs monthly.	Integer number (number of suspension occurrences monthly)	Monthly	Project Manager

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.4.13.2	Length of Suspensions	Self-explanatory	Real number (total time lost due to work suspensions, day)	Monthly	Project Manager
2.4.14	Project Complexity	Refers to the complexity of the project which needs to be evaluated by the project manager based on the sub-factors.			
2.4.14.1	Use of Unproven Technology	Refers to the use of technologies which are not tested to be executable in the construction phase in previous projects.	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY LOW use of unproven technologies in the project. 2- LOW use of unproven technologies in the project. 3- AVERAGE use of unproven technologies in the project. 4- HIGH use of unproven technologies in the project. 5- VERY HIGH use of unproven technologies in the project.				
2.4.14.2	Facility Size and Process Capacity	Refers to the project deliverable size which should be measure in the relevant units (e.g., total built floor space in m² for commercial building construction)	Real number (context dependant)	Once, Project Start	Project Manager
2.4.14.3	Past Experience with the Configurations and Geometry	This factor measures the number of the similar projects executed by the owner or contractor team which affect the familiarity of the team with this project and consequently may affect the productivity of the project.	Integer number (no. of similar project completed)	Once, Project Start	Project Manager
2.4.14.4	Familiarity with Construction Methods	This factor measures the familiarity of the contractor team with the construction methods and techniques which may be an effective factor on the productivity of the project.	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY POOR Experience with methods and technology, LACK of proper procedure. 2- POOR Experience with methods and technology, LACK of proper procedure. 3- FAIR Experience with methods and technology, WITH proper procedure. 4- GOOD Experience with methods and technology, WITH proper procedure. 5- VERY GOOD Experience with methods and technology , WITH proper procedure				
2.4.15	Year of Construction	Self-explanatory	Date (project construction start date)	Once, Project Start	

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.4.16	Level of Modularization	Refers to the level of modularization of the project. The amount of off-site work and installation at the project site may be an effective factor on construction productivity.	Percentage (off-site construction cost divided by the total project cost)	Once, Project Start	Project Manager
2.4.17	Site Congestion	Refers to the total free space area in the construction site which is available to the project team for different temporary use during the construction such as; equipment maneuver. The information can be extracted from the project site layout design.	Percentage (free site space area divided by total site area)	Once, Project Start	Project Manager
2.5. Project Scope Management					
2.5.1	Project scope definition	Refers to the process of developing a detailed description of the project and its product.	1 - 5 Predetermined rating	Once	Project Manager
	1- Defined project scope IS NOT properly used to define project WBS, VERY POOR Experience in work decomposition, Developed WBS DOES NOT cover the project scope. 2- Defined project scope IS NOT properly used to define project WBS, POOR Experience in work decomposition, Developed WBS covers the project scope POORLY. 3- Defined project scope IS USED properly to define project WBS, FAIR Experience in work decomposition, Developed WBS covers the project scope FAIRLY. 4- Defined project scope IS USED properly to define project WBS, GOOD Experience in work decomposition, Developed WBS covers the project scope SOMEHOW. 5- Defined project scope IS USED properly to define project WBS, VERY GOOD Experience in work decomposition, Developed WBS covers the project scope COMPREHENSIVELY				
2.5.2	Project scope verification	Refers to the process of formalizing acceptance of the completed project deliverables.	1 - 3 Predetermined rating	Once	Project Manager
	1- Project scope verification IS NOT conducted. 2- Project scope verification IS SOMEWHAT conducted. 3- Project scope verification IS PROPERLY conducted.				
2.5.3	Project scope change control	Refers to the process of monitoring the status of the project and product scope and managing changes to the scope baseline.	1 - 5 Predetermined rating	Once	Project Manager
	1- LACK of project change documents, NO procedure for change management tracking and approval, VERY POOR performance measurement system, VERY POOR Integration with other control processes. 2- LACK of project change documents, NO procedure for change management tracking and approval, POOR performance measurement system, POOR Integration with other control processes. 3- PRESENCE of project change documents, NO procedure for change management tracking and approval, FAIR				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
	performance measurement system, FAIR Integration with other control processes. 4- PRESENCE of project change documents, EXISTING procedure for change management tracking and approval, GOOD performance measurement system, GOOD Integration with other control processes. 5- PRESENCE of project change documents, EXISTING procedure for change management tracking and approval, VERY GOOD performance measurement system, VERY GOOD Integration with other control processes				
2.6. Project Time Management					
2.6.1	Project Activity Definition	The process of identifying and documenting the specific actions to be performed to produce the project deliverables.	1 - 5 Predetermined rating	Once	Project Manager
	1- VERY POOR Use of project information (WBS, Scope statement), assumptions ARE NOT Documented, VERY POOR decomposition of activities from WBS, NOT Using concurrent engineering ideas. 2- POOR Use of project information (WBS, Scope statement), assumptions ARE NOT Documented properly, POOR decomposition of activities from WBS, NOT Using concurrent engineering ideas. 3- AVERAGE Use of project information (WBS, Scope statement), assumptions ARE NOT Documented properly, FAIR decomposition of activities from WBS, NOT Using concurrent engineering ideas. 4- GOOD Use of project information (WBS, Scope statement), assumptions ARE Documented properly, GOOD decomposition of activities from WBS, Using SOME concurrent engineering ideas. 5- VERY GOOD Use of project information (WBS, Scope statement), assumptions ARE Documented properly, VERY GOOD decomposition of activities from WBS, Using many concurrent engineering ideas.				
2.6.2	Project Activity Sequencing	The process of identifying and documenting relationships among the project activities.	1 - 5 Predetermined rating	Once	Project Manager
	1- VERY POOR Understanding of technical and resource dependencies between activities, NOT Using activity sequencing tools. 2- POOR Understanding of technical and resource dependencies between activities, NOT Using activity sequencing tools. 3- FAIR Understanding of technical and resource dependencies between activities, FAIR Use of activity sequencing tools. 4- GOOD Understanding of technical and resource dependencies between activities, GOOD Use of activity sequencing tools. 5- VERY GOOD Understanding of technical and resource dependencies between activities, VERY GOOD Use of activity sequencing tools				
2.6.3	Project Activity Duration	The process of estimating the number of work periods needed to complete individual activities with estimated resources.			
2.6.3.1	Project Activity Duration Estimation	Self-explanatory	1 - 5 Predetermined rating	Weekly	Superintendent
	1- Resource requirements and resource capabilities ARE NOT PROPERLY documented, NO Use of historical information, VERY POOR Experience of estimator. 2- Resource requirements and resource capabilities ARE NOT PROPERLY documented, NO Use of				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
	historical information, POOR Experience of estimator. 3- Resource requirements and resource capabilities ARE SOMEWHAT documented, SOME Use of historical information (past project files, commercial databases like RS Means), Experience of estimator FAIR. 4- Resource requirements and resource capabilities ARE WELL documented, AVERAGE Use of historical information, GOOD Experience of estimator. 5- Resource requirements and resource capabilities ARE VERY WELL documented, EXCELLENT Use of historical information, VERY GOOD Experience of estimator.				
2.6.3.2	Activity Duration Prediction Accuracy	Self-explanatory	1 - 5 Predetermined rating	Weekly	Superintendent
	1- VERY Unrealistic. 2- Unrealistic. 3- Common industry average. 4- Realistic. 5- VERY Realistic				
2.6.4	Project Schedule Development	The process of analyzing activity sequences, durations, resource requirements, and schedule constraints to create the project schedule model.	1 - 5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY POOR Understanding of constraints, project calendar, resource plans, VERY POORLY Developed activity attributes, NOT Using scheduling techniques, NO Use of resource leveling and Project management software. 2- POOR Understanding of constraints, project calendar, resource plans, POORLY Developed activity attributes, NOT Using scheduling techniques, NO Use of resource leveling and Project management software. 3- FAIR Understanding of constraints, project calendar, resource plans, FAIRLY Developed activity attributes, FAIR Use of scheduling techniques, FAIR Use of resource leveling and Project management software. 4- GOOD Understanding of constraints, project calendar, resource plans, WELL Developed activity attributes, GOOD Use scheduling techniques, GOOD Use of resource leveling and Project management software. 5- VERY GOOD Understanding of constraints, project calendar, resource plans, WELL Developed activity attributes, VERY GOOD Use scheduling tools, VERY GOOD Use of resource leveling and Project management software				
2.6.5	Project Duration Accuracy	Self-explanatory	1 - 5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY Unrealistic. 2- Unrealistic. 3- Common industry average. 4- Realistic. 5- VERY Realistic				
2.6.6	Project Schedule Criticality Index	The criticality index of the project's schedule is an important factor affecting the project's time management and consequently may affect the productivity of project.	Percentage (no. of critical activities divided by the total no. of activities)	Once, Project Start	Project Manager
2.6.7	Project Schedule Control	The process of monitoring the status of project activities to update project progress and manage changes to the schedule baseline to achieve the plan.	1 - 5 Predetermined rating	Once, Project Start	Project Manager

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
	1- LACK of proper change request documents, VERY POOR Use of Performance reports, NO Schedule Updates schedule, NOT taking corrective actions. 2- LACK of proper change request documents, POOR Use of Performance reports, NO Schedule updates, NOT taking corrective actions. 3- Use of proper change request documents, FAIR Use of Performance reports, PROPER Schedule updates, NOT taking corrective actions. 4- Use of proper change request documents, GOOD Use of Performance reports, PROPER Schedule updates, Taking UNTIMELY corrective actions. 5- Use of proper change request documents, VERY GOOD Use of Performance reports, PROPER Schedule updates, Taking TIMELY corrective actions				
2.6.8	Schedule Compression	Schedule compression is an alternative for expediting the final delivery of the project which may affect the productivity of construction projects.	Percentage (total crashed duration divided by original duration)	Monthly	Project Manager
2.6.9	Project Activity Weights Definition	Involves evaluating activities characteristics and attributes in order to assess the contribution of each particular project activity to the overall project progress in a given phase or preparation of the project deliverable.	1 - 5 Predetermined rating	Once	Project Manager
	1- Defining activity attributes in terms of durations, costs, labour hours, quantities NOT DONE, NO Use of expert judgment, NO Use of percentage calculation. 2- Defining activity attributes in terms of durations, costs, labour hours, quantities SOMEWHAT, NO Use of expert judgment, NO Use of percentage calculation. 3- Defining activity attributes in terms of durations, costs, labour hours, quantities PARTIALLY DONE, NO Use of expert judgment, YES to Use of percentage calculation. 4- Defining activity attributes in terms of durations, costs, labour hours, quantities MOSTLY DONE, YES Use of expert judgment, YES Use of percentage calculation. 5- Defining activity attributes in terms of durations, costs, labour hours, quantities FULLY DONE, YES Use of expert judgment, YES Use of percentage calculation				
2.6.10	Project progress curves development and Progress monitoring	Project progress curves are an alternative for project time monitoring. Developing the progress curves can affect the project time management and consequently affect the project productivity.	1 - 5 Predetermined rating	Once	Project Manager
	1- NO Use of project schedules, activity weights, Standard Performance curves ARE NOT developed, Project management software IS NOT USED. 2- POOR Use of project schedules, activity weights, Standard Performance curves ARE NOT developed, Project management software IS NOT USED. 3- FAIR Use of project schedules, activity weights, Standard Performance curves ARE POORLY developed, Project management software IS NOT USED. 4- GOOD Use of project schedules, activity weights, Standard Performance curves ARE WELL developed, Project management software IS USED. 5- VERY GOOD Use of project schedules, activity weights, Standard Performance curves ARE VERY WELL developed, Project management software IS USED.				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.7. Project Cost Management					
2.7.1	Project Resource Planning	Refers to the process of analyzing the required resources to produce the project deliverables as specified in the project scope.	1 - 5 Predetermined rating	Once	Project Manager
	1- VERY POOR Use of project information, NO Use of Project management software, INADEQUATELY Developed resource plan. 2- POOR Use of project information, NO Use of Project management software, INADEQUATELY Developed resource plan. 3- FAIR Use of project information, NO Use of Project management software, INADEQUATELY Developed resource plan. 4- GOOD Use of project information, Use of Project management software, ADEQUATELY Developed resource plan. 5- VERY GOOD Use of project information, ADVANCED Use of Project management software, ADEQUATELY Developed resource plan.				
2.7.2	Project Cost Estimate	The process of developing an approximation of the monetary resources needed to complete project activities.			
2.7.2.1	Development of Material, Equipment Requirement List	Self-explanatory	1 - 5 Predetermined rating	Once	Project Manager
	1- VERY POOR Material and Equipment requirement list is developed. 2- POOR Material and Equipment requirement list is developed. 3- FAIR Material and Equipment requirement list is developed. 4- GOOD Material and Equipment requirement list is developed. 5- VERY GOOD Material and Equipment requirement list is developed				
2.7.2.2	Project Cost Estimator Experience	Self-explanatory	Real number (average years of experience of estimation team)	Once	Project Manager
2.7.2.3	Time Allowed for Cost Estimate	Self-explanatory	Real number (total time spent for estimation, days)	Once	Project Manager
2.7.2.4	Bidding Process Conditions	Refers to the conditions of the bidding process for the project under study, evaluating the different aspects of the bidding process such as; the bid documents, competitiveness.	1 - 5 Predetermined rating	Once	Project Manager
	1- VERY HIGH Uncertainty in future, VERY POOR Quality of bid document, VERY HIGH Competition level, UNFAVOURABLE Type of project. 2- HIGH Uncertainty in future, POOR Quality of bid document, HIGH Competition level, UNFAVOURABLE Type of project. 3-				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
	FAIR Uncertainty in future, AVERAGE Quality of bid document, MEDIUM Competition level, FAVOURABLE Type of project. 4- FAIR Uncertainty in future, GOOD Quality of bid document, LOW Competition level, FAVOURABLE Type of project. 5- LOW Uncertainty in future, VERY GOOD Quality of bid document, VERY LOW Competition level, FAVOURABLE Type of project				
2.7.2.5	Labour Force Conditions	Self-explanatory	1 - 5 Predetermined rating	Once	Project Manager
	1- VERY LOW Availability of labour, VERY POOR Quality of labour, NO Agreement with Unions. 2- LOW Availability of labour, POOR Quality of labour, NO Agreement with Unions. 3- FAIR Availability of labour, FAIR Quality of labour, YES Agreement with Unions. 4- HIGH Availability of labour, GOOD Quality of labour, YES Agreement with Unions. 5- VERY HIGH Availability of labour, VERY GOOD Quality of labour, YES Agreement with Unions				
2.7.3	Project Cost Budgeting	The process of aggregating the estimated costs of individual activities or work packages to establish an authorized cost baseline.	1 - 5 Predetermined rating	Once	Project Manager
	1- VERY POOR Use of project information, NO Use of computerized tools, INADEQUATE Cost baseline is developed. 2- POOR Use of project information, NO Use of computerized tools, INADEQUATE Cost baseline is developed. 3- FAIR Use of project information, SOME Use of computerized tools, INADEQUATE Cost baseline is developed. 4- GOOD Use of project information, Use of computerized tools, ADEQUATE Cost baseline is developed. 5- VERY GOOD Use of project information, ADVANCED Use of computerized tools, ADEQUATE Cost baseline is developed.				
2.7.4	Project Cost Control	The process of monitoring the status of the project to update the project costs and managing changes to the cost baseline.	1 - 5 Predetermined rating	Monthly	Project Manager
	1- VERY POOR Use of project information, NO Use of Cost control tools and techniques, VERY POOR Update of project financial documents. 2- POOR Use of project information, NO Use of Cost control tools and techniques, POOR Update of project financial documents. 3- FAIR Use of project information, SOME Use of Cost control tools and techniques, FAIR Update of project financial documents. 4- GOOD Use of project information, Use of Cost control tools and techniques, GOOD Update of project financial documents. 5- VERY GOOD Use of project information, ADVANCED Use of Cost control tools and techniques, VERY GOOD Update of project financial documents				
2.7.5	Use of Earned Value Methods	Self-explanatory	1 - 3 Predetermined rating	Monthly	Project Manager
	1- Earned value methods NOT employed. 2- Earned value methods SOMEWHAT Employed but NOT fully (in terms of forecasting application). 3- Earned value methods PROERLY employed				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.8. Project Quality Management					
2.8.1	Project Quality Planning	The process of identifying quality requirements and/or standards for the project and its deliverables and documenting how the project will demonstrate compliance with quality requirements.	1 - 5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY POOR Understanding of project specification and design requirements, VERY VAGUE project quality policy. 2- POOR Understanding of project specification and design requirements, VAGUE project quality policy. 3- FAIR Understanding of project specification and design requirements, UNCLEAR project quality policy. 4- GOOD Understanding of project specification and design requirements, CLEAR project quality policy. 5- VERY GOOD Understanding of project specification and design requirements, VERY CLEAR project quality policy				
2.8.2	Demand for Over Quality Work	Refers for the demand from the owner for exceeding the quality levels set in specifications and drawing	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY LOW Demand for exceeding the quality levels of drawings. 2- LOW Demand for exceeding the quality levels of drawings. 3- MODERATE Demand for exceeding the quality levels of drawings. 4- HIGH Demand for exceeding the quality levels of drawings. 5- VERY HIGH Demand for exceeding the quality levels of drawings				
2.8.3	Project Quality Assurance	The process of auditing the quality requirements and the results from quality control measurements to ensure that appropriate quality standards and operational definitions are used.	1 - 5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY INFREQUENT Quality audits, VERY POOR Quality improvement Implementation. 2- INFREQUENT Quality audits, POOR Quality improvement Implementation. 3- INFREQUENT Quality audits, FAIR Quality improvement Implementation. 4- FREQUENT Quality audits, GOOD Quality improvement Implementation. 5- VERY FREQUENT Quality audits, VERY GOOD Quality improvement Implementation				
2.8.4	Quality Audits	Refers to the project quality audits performed by the quality insurer company.	Real number (no. of quality audits per month)	Monthly	Project Manager
2.8.5	Project Quality Control	The process of monitoring and recording results of executing the quality activities to assess performance and recommend necessary changes.			
2.8.5.1	Inspection Delay	Self-explanatory	Real number (average delay for inspection, min)	Weekly	Superintendent

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.8.5.2	Interference	Interference due to inspections of other trades, safety evaluations, management site visits. On average per week.	Real number (total time lost due to interruptions, hr)	Weekly	Superintendent
2.8.5.3	Out of Sequence Inspection or Survey Work	Self-explanatory	Real number (no. of occurrence per week)	Weekly	Superintendent
2.9. Project Procurement Management					
2.9.1	Procurement Planning	The process of documenting project procurement decisions, specifying the approach, and identifying potential sellers.	1 - 5 Predetermined rating	Once, Project Start	Project Manager
	1- NO make-or-buy analysis, Developing and selecting alternatives is VERY POORLY done, VERY POOR solicitation and administration plan. 2- IMPRECISE make-or-buy analysis, Developing and selecting alternatives is POORLY done, POOR solicitation and administration plan. 3- FAIR make-or-buy analysis, Developing and selecting alternatives is FAIRLY done, FAIR solicitation and administration plan. 4- DETAILED make-or-buy analysis, Developing and selecting alternatives is WELL done, GOOD solicitation and administration plan. 5- DETAILED make-or-buy analysis, Developing and selecting alternatives is VERY WELL done, VERY GOOD solicitation and administration plan				
2.9.2	Procurement Solicitation Planning	The process of identifying the best sellers for providing the procurement based on a set of criteria and preparing the bid/contract documents.	1 - 5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY POOR Procurement documents for bids, VERY POOR Decisions on contract types, NO Detailed evaluation criteria. 2- POOR Procurement documents for bids, POOR Decisions on contract types, NO Detailed evaluation criteria. 3- FAIR Procurement documents for bids, FAIR Decisions on contract types, SOME Detail evaluation criteria. 4- GOOD Procurement documents for bids, GOOD Decisions on contract types, PROVIDED Detailed evaluation criteria. 5- VERY GOOD procurement documents for bids, VERY GOOD Decisions on contract types, Detailed evaluation criteria				
2.9.3	Procurement Solicitation Execution	The process of awarding the contract to the project's procurement provider.	1 - 5 Predetermined rating	Once, Project Start	Project Manager
	1- NO Use of prequalification process, NO PROPER Advertisement, VERY POOR Practice in evaluation of proposals, NO PROPER Award of contract. 2- NO Use of prequalification process, SOME Advertisement, POOR Practice in evaluation of proposals, NO PROPER Award of contract. 3- SOME Use of prequalification process, SOME Advertisement, FAIR Practice in evaluation of proposals, PROPER Award of contract. 4- DETAILED prequalification process, PROPER Advertisement, GOOD Practice in evaluation				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
	of proposals, PROPER Award of contract. 5- DETAILED prequalification process, PROPER Advertisement, VERY GOOD Practice in evaluation of proposals, PROPER Award of contract.				
2.9.4	Procurement Administration	Refers to the procurement process for the required material, equipment and tools at the project site.	1 - 5 Predetermined rating	Once, Project Start	Project Manager
	1- INADEQUATE Contact Process, UNORGANIZED Placement of Orders, VERY POOR Follow-up. 2- INADEQUATE Contact Process, UNORGANIZED Placement of Orders, POOR Follow-up. 3- ADEQUATE Contact Process, FAIRLY ORGANIZED Placement of Orders, FAIR Follow-up. 4- ADEQUATE Contact Process, ORGANIZED Placement of Orders, GOOD Follow-up. 5- ADEQUATE Contact Process, WELL ORGANIZED Placement of Orders, VERY GOOD Follow-up				
2.10. Project Safety Management					
2.10.1	Project Safety Planning	Development of the approach to manage the various hazards to safety inherent in the project.	1 - 5 Predetermined rating	Once	Project Manager
	1- INADEQUATE Understanding of regulatory laws and contract requirements, VERY POOR project hazard assessment, INADEQUATE Project Safety plan, VERY POOR Budget and time development. 2- INADEQUATE Understanding of regulatory laws and contract requirements, POOR project hazard assessment, INADEQUATE Project Safety plan, POOR Budget and time development. 3- ADEQUATE Understanding of regulatory laws and contract requirements, FAIR project hazard assessment, ADEQUATE Project Safety plan, FAIR Budget and time development. 4- ADEQUATE Understanding of regulatory laws and contract requirements, ADEQUATE project hazard assessment, ADEQUATE Project Safety plan, GOOD Budget and time development. 5- ADEQUATE Understanding of regulatory laws and contract requirements, VERY GOOD project hazard assessment, ADEQUATE Project Safety plan, VERY GOOD Budget and time development.				
2.10.2	Use of Site Safety Officer	Self-explanatory	Categorical	Once	Project Manager
	Yes, No				
2.10.3	Project Safety Plan Execution	Refers to carrying out the safety plan by performing the activities included there in.			
2.10.3.1	Daily Job Hazard Assessment Forms	Refers to the use of daily job hazard assessment forms at the project site.	Categorical	Once	Superintendent
	Yes, No				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.10.3.2	Personnel Protective Equipment	Refers to the availability of the appropriate personnel protective equipment which suits to the project conditions.	Categorical	Once, Project Start	Superintendent
	Yes, No				
2.10.3.3	Site Safety Communication	Refers to the communications between the projects personnel regarding the project safety. The communication may include project safety barriers, signs, daily kickoff and debriefing meetings.	1 - 5 Predetermined rating	Monthly	Superintendent
	1- Safety Meetings NOT conducted. 2- Safety Meetings conducted BUT NOT regularly, Effectiveness of meetings is POOR. 3- Safety Meetings conducted REGULARLY, Effectiveness of meetings is FAIR. 4- Safety Meetings conducted REGULARLY, Effectiveness of meetings is GOOD. 5- Safety Meetings conducted REGULARLY, Effectiveness of meetings is VERY GOOD.				
2.10.3.4	Project Safety Equipment	Refers to the availability of the appropriate project safety equipment which are required through the construction phase to minimize the risk of incidents. The safety equipment may include; wall trench bracing, fire protection equipment and safety warning devices.	Categorical	Once, Project Start	Superintendent
	Yes, No				
2.10.3.5	Drug testing	Self-explanatory	Categorical	Once	Superintendent
2.10.3.6	Safety training	Refers to the total hours of safety training provided for the project crew to minimize the safety incidents at the project site.	Real number (no. trainings attended x duration of Training, hrs)	Once, Crew Change	Foreman
2.10.3.7	Safety Inspections	Self-explanatory	Integer number (no. of inspections per month)	Monthly	Project Manager
2.10.3.8	Safety Audits	Self-explanatory	Integer number no. of audits per month)	Monthly	Project Manager
2.14.4	Safety Incidents	Self-explanatory			
2.10.4.1	Near Miss	Near Miss - An undesired event that, under slightly different circumstances, could have resulted in	Integer number (no. of reported near	Monthly	Superintendent

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
		personal harm, loss of process, property and/or environmental.	miss incidents per month)		
2.10.4.2	First Aid	A first aid is when immediate treatment is rendered by a qualified person and worker immediately returns to work.	Integer number (no. of reported first aid per month)	Monthly	Superintendent
2.10.4.3	Medical Aid	An injury which requires treatment by a physician beyond simple first aid care but does not result in time lost from work beyond the day of the injury.	Integer (Number of reported medical aid per month)	Monthly	Superintendent
2.10.4.4	Modified Work Incidents	Refers to the incidents which cause modifying the work duties to accommodate an injured personnel who cannot perform their regular work duties.	Integer number (no. of reported modified work incident per month)	Monthly	Superintendent
2.10.4.5	Number of Modified Work Days	Refers to the total number of days spent performing the modified work duties by all the project personnel.	Integer number (no. of reported modified work days per month)	Monthly	Superintendent
2.10.4.6	Lost Time Incident	Refers to an accident where a physician directs the injured worker to remain away from work longer that day of the accident	Integer number (no. of reported lost time incident per month)	Monthly	Superintendent
2.10.4.8	Fatality Incident	Refers to the number of fatal incidents at the project site.	Integer number (no. of reported personnel fatality per month)	Monthly	Superintendent
2.10.4.9	Equipment/Property Damage	Refers to the accident causing damage to equipment and/or property on site	Integer number (no. of reported equipment/property damage incident per month)	Monthly	Superintendent
2.10.5	Safety Incident Investigation				
2.10.5.1	Personnel Involved in Investigation	Self-explanatory	Integer number (no. of personnel	Monthly	Superintendent

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
			involved in investigation)		
2.10.5.2	Process Time	Refers to the average process time for each incident investigation at the project site.	Real number (average time lost due to investigation, hr)	Monthly	Superintendent
2.10.6	Uniformity of Safety Procedures	Self-explanatory	1 - 5 Predetermined rating	Once	Superintendent
	1- HIGHLY VARIABLE among crews and HIGHLY VARIABLE in daily work times and work days. 2- VARIABLE among crews and VARIABLE in daily work times and work days. 3- UNIFORM among crews and VARIABLE in daily work times and work days. 4- ALMOST UNIFORM among crews, ALMOST UNIFORM in daily work times and work days. 5- UNIFORM among crews, UNIFORM in daily work times and work days.				
2.10.7	Project Safety Administration and Reporting	Refers to the administration of the hazard assessment forms and documents.	1 - 5 Predetermined rating	Weekly	Superintendent
	1- VERY POOR Record keeping, NO Use of visual aids. 2- POOR Record keeping, NO Use of visual aids. 3- FAIR Record keeping, Use of visual aids. 4- GOOD Record keeping, GOOD Use of visual aids. 5- VERY GOOD Record keeping, VERY GOOD Use of visual aids.				
2.11. Project Risk Management					
2.11.1	Risk Identification and Planning	The process of determining which risks may affect the project and documenting their characteristics and defining how the risk management activities should take place through the project life cycle.	1 - 5 Predetermined rating	Once, Project Start	Project Manager
	1- NO Proper risk identification, VERY POOR Overall risk management plan with risk response planning. 2- NO Proper risk identification, POOR Overall risk management plan with risk response planning. 3- SOME Risk identification, FAIR Overall risk management plan with risk response planning. 4- SOME Risk identification, GOOD Overall risk management plan with risk response planning. 5- DETAILED Risk identification, VERY GOOD Overall risk management plan with risk response planning.				
2.11.2	Use of Risk Assessment Tool	Self-explanatory	1 - 3 Predetermined rating	Once, Project Start	Project Manager

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
	1- Risk assessment ARE NOT used. 2- Qualitative risk assessment ARE used, Quantitative risk assessment ARE NOT used. 3- Qualitative risk assessment ARE used, Quantitative risk assessment ARE used				
2.11.3	Risk Monitoring and Control	The process of monitoring the project risks and controlling the project risk plan.	1 - 5 Predetermined rating	Monthly	Project Manager
	1- NOT Keeping track of identified risks, VERY POOR Monitoring of residual risks and identifying new risks, VERY POOR in Ensuring the execution of risk plans, NO Evaluation on their effectiveness in reducing risk. 2- NOT Keeping track of identified risks, POOR Monitoring of residual risks and identifying new risks, POOR in Ensuring the execution of risk plans, NO Evaluation on their effectiveness in reducing risk. 3- Keeping SOME track of identified risks, FAIR Monitoring of residual risks and identifying new risks, FAIR in Ensuring the execution of risk plans, SOME Evaluation on their effectiveness in reducing risk. 4- Keeping DETAIL track of identified risks, GOOD Monitoring of residual risks and identifying new risks, GOOD in Ensuring the execution of risk plans, DETAILED Evaluation on their effectiveness in reducing risk. 5- Keeping DETAIL track of identified risks, VERY GOOD Monitoring of residual risks and identifying new risks, VERY GOOD in Ensuring the execution of risk plans, DETAILED Evaluation on their effectiveness in reducing risk.				
2.11.4	Crisis Management	The crisis management process refers to identification of the potential crises through the project life cycle and defining a strategy for management of the project in terms of crises happening.	1 - 5 Predetermined rating	Monthly	Project Manager
	1- VERY POOR Understanding possible crises and stakeholders, REACTIVE Response to the crises, NO Prevention system from crises. 2- POOR Understanding possible crises and stakeholders, REACTIVE Response to the crises, NO Prevention system from crises. 3- FAIR Understanding possible crises and stakeholders, REACTIVE Response to the crises, SOME Prevention system from crises. 4- GOOD Understanding possible crises and stakeholders, PROACTIVE Response to the crises, PROVIDED Prevention system from crises. 5- VERY GOOD Understanding possible crises and stakeholders, PROACTIVE Response to the crises, PROVIDED Prevention system from crises.				
2.12. Project Communication Management					
2.12.1	Project Communication Plan and Implementation	The process of developing an appropriate approach and plan for project communications based on stakeholder's information needs and requirements, and available organizational assets.	1 - 5 Predetermined rating	Once, Project Start	Superintendent
	1- VERY POOR Communication plan, NO Clear roles and responsibilities, NO Identification of stakeholders, VERY POOR Distribution of information. 2- POOR Communication plan, NO Clear roles and responsibilities, NO Identification of stakeholders, POOR Distribution of information. 3- GOOD Communication plan, PROPER Clear roles and responsibilities, PROPER Identification of stakeholders, POOR Distribution of information. 4- GOOD Communication plan, PROPER Clear roles and responsibilities, PROPER				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
	Identification of stakeholders, GOOD Distribution of information. 5- VERY GOOD Communication plan, PROPER Clear roles and responsibilities, PROPER Identification of stakeholders, VERY GOOD Distribution of information.				
2.12.2	Communication between Trades	Refers to the communication between the different trades at the project site which may affect the productivity of the project.	1 - 5 Predetermined rating	Weekly	Superintendent
	1- VERY POOR Communication. 2- POOR Communication. 3- FAIR Communication. 4- GOOD Communication. 5- VERY GOOD Communication.				
2.12.3	Communication Devices	Refers to the total number of communication devices provided at the project site for the supervisory and management personnel of the project measure as a ratio to the total number of project personnel.	Real number (no. communication devices divided by no. of crews)	Once, Project Start	Superintendent
2.13. Project Human Resource Management					
2.13.1	Project Interface Development	Refers to the definition of a systematic way for communication between the project team members considering the different roles in the project such as the reporting system from foremen to superintendent and from superintendent to the project manager.	1 - 5 Predetermined rating	Once	Project Manager
	1- Interfaces between project team INADEQUATELY developed, NO Clearly established reporting system. 2- Interfaces between project team INADEQUATELY developed, POORLY established reporting system. 3- Interfaces between project team ADEQUATELY developed, FAIRLY established reporting system. 4- Interfaces between project team ADEQUATELY developed, WELL Established reporting system. 5- Interfaces between project team ADEQUATELY developed, VERY WELL Established reporting system.				
2.13.2	Project Staff Hiring Practice	The process of confirming human resource availability and obtaining the team necessary to complete project activities.	1 - 5 Predetermined rating	Monthly	Project Manager
	1- VERY POOR Advertisement, NO Detailed job description, VERY UNFAIR Screening, interview and selection process, VERY UNREASONABLE Job requirements. 2- POOR Advertisement, NO Detailed job description, UNFAIR Screening, interview and selection process, UNREASONABLE job requirements. 3- FAIR Advertisement, SOME Detailed job description, FAIR Screening, interview and selection process, ALMOST REASONABLE job requirements. 4- GOOD Advertisement, SOME Detailed job description, FAIR Screening, interview and selection process, REASONBLE job requirements. 5- VERY GOOD Advertisement, Detailed job description, VERY FAIR screening, interview and selection process, REASONABLE job requirements.				
2.13.3	Project Team Development				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.13.3.1	Team Building Activities	Refers to the activities which are planned to develop the team spirit between the project personnel. The activities may include, outdoor activities or sport contests.	Integer number (no. team building events planned per month)	Monthly	Project Manager
2.13.3.2	Reward and Recognition System	Refers to the number of reward and recognition occurrences for excellence in safety and productivity per year.	Integer number (no. recognition and reward occurrences per year)	Once, Project Start	Superintendent
2.13.3.3	Work Culture	The work culture of the project team may be an effective factor on the productivity of the project.	1 - 5 Predetermined rating	Once	Project Manager
	1- VERY HIGH Fragmentation, Antagonism, Mistrust, POOR communication, COMMON Short-term mentality, VERY FREQUENT Blames, VERY COMMON Approach to recruitment. 2- HIGH Fragmentation, Antagonism, Mistrust, POOR communication, COMMON Short-term mentality, FREQUENT Blames, COMMON Approach to recruitment. 3- NORMAL Fragmentation, Antagonism, Mistrust, FAIR communication, COMMON Short-term mentality, INFREQUENT Blames, UNCOMMON Approach to recruitment. 4- LOW Fragmentation, Antagonism, Mistrust, GOOD communication, UNCOMMON Short-term mentality, RARE Blames, UNCOMMON Approach to recruitment. 5- VERY LOW Fragmentation, Antagonism, Mistrust, VERY GOOD communication, UNCOMMON Short-term mentality, VERY RARE Blames, VERY UNCOMMON Approach to recruitment.				
2.13.4	Project Team Closeout	Refers to the process of project team closeout after project completion.			
2.13.4.1	Use of Personal Exit Interviews	Self-explanatory	1 - 3 Predetermined rating	Once, Project Start	Superintendent
	1- Exit interview NOT conducted. 2- Exit interview SOMEWHAT conducted. 3- Exit interview PROPERLY conducted				
2.13.4.2	Layoff Practices	Self-explanatory	1 - 5 Predetermined rating	Monthly	Project Manager
	1- VERY POOR in informing rules to employees, UNFAIRNESS among workers, LACK of Consistency and Follow through, UNREASONABLE Rules. 2- POOR in informing rules to employees, UNFAIRNESS among workers, LACK of Consistency and Follow through, UNREASONABLE Rules. 3- FAIR in informing rules to employees, UNFAIRNESS among workers, GOOD Consistency and Follow through, UNREASONABLE Rules. 4- GOOD in informing rules to employees, FAIRNESS among workers, GOOD Consistency and Follow through, REASONABLE Rules. 5- VERY GOOD in informing rules to employees, FAIRNESS among workers, VERY GOOD Consistency and Follow through, REASONABLE Rules.				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.13.4.3	Personnel Record Development	Refers to development of a database for the project employees' information including the different information of the project staff (e.g., salaries).	Categorical	Once, Project Start	Superintendent
	Yes, No				
2.14. Project Environmental Management					
2.14.1	Environmental Rating of Project	Self-explanatory	Categorical	Once	Project Manager
	LEED (Certified, Silver, Gold, Platinum), BREEAM, BOMA BESt				
2.14.2	Project Environmental Planning	Refers to the process of identifying what are the characteristics of the environment surrounding the construction site and which environmental standards are relevant to the project, and determining what impact the project will bring to the environment and how to satisfy the identified environmental standards.	1 - 5 Predetermined rating	Once	Project Manager
	1- VERY POOR Understanding of contract provisions, VERY POOR Site and neighborhood condition analysis, INADEQUATE Environmental management plan, VERY POOR Use of checklists. 2- POOR Understanding of contract provisions, POOR Site and neighborhood condition analysis, INADEQUATE Environmental management plan, POOR Use of checklists. 3- FAIR Understanding of contract provisions, FAIR Site and neighborhood condition analysis, INADEQUATE Environmental management plan, FAIR Use of checklists. 4- GOOD Understanding of contract provisions, GOOD Site and neighborhood condition analysis, ADEQUATE Environmental management plan, GOOD Use of checklists. 5- VERY GOOD Understanding of contract provisions, VERY GOOD Site and neighborhood condition analysis, ADEQUATE Environmental management plan, VERY GOOD Use of checklists.				
2.14.3	Project Environmental Assurance	Refers to the process of evaluating the results of environmental management on a regular basis to provide confidence that the project will satisfy the relevant environmental standards.	1 - 5 Predetermined rating	Monthly	Project Manager
	1- VERY POOR Recycling practice, Waste material sorting IS NOT done, No Awareness trainings. 2- POOR Recycling practice, Waste material sorting IS NOT done, NO awareness trainings. 3- FAIR Recycling practice, Waste material sorting IS DONE SOMEHOW done, AWARENESS trainings are provided. 4- GOOD Recycling practice, Waste material sorting is STRICTLY done, Awareness trainings provided. 5- VERY GOOD Recycling practice, Waste material sorting IS VERY STRICTLY done, Awareness trainings provided.				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.14.4	Environmental Audits	Self-explanatory	Integer number (no. of audits per month)	Monthly	Project Manager
2.14.5	Project Environmental Control	Monitoring specific project results to determine if they comply with relevant environmental standards and identifying ways to eliminate causes of unsatisfactory performance.	1 - 5 Predetermined rating	Monthly	Project Manager
	1- NO Use of checklist, NO Rework/remedial action. 2- POOR Use of checklist, NO Rework/remedial action. 3- FAIR Use of checklist, NO Rework/remedial action. 4- GOOD Use of checklist, Rework/remedial action taken when needed. 5- VER GOOD Use of checklist, Rework/remedial action taken when needed.				
2.14.4.1	Rework/Remedial Action	Self-explanatory	1 - 3 Predetermined rating	Monthly	Project Manager
	1- Corrective action NOT done. 2- Corrective action SOMEWHAT done. 3- Corrective action PROPERLY done.				
2.14.4.2	Environmental Inspections	Self-explanatory	Integer number (no. of inspections per month)	Monthly	Project Manager
2.15. Project Claim Management					
2.15.1	Project Claim Identification	The process of comparing the project scope and project execution to identify any potential adjustment to the project contract.	1 - 5 Predetermined rating	Monthly	Project Manager
	1- VERY INADEQUATE. 2- INADEQUATE. 3- FAIRLY ADEQUATE. 4- ADEQUATE. 5- VERY ADEQUATE.				
2.15.2	Project Claim Team Characteristics	Refers to the characteristics of the project claim team. Due to the importance of the claim management in construction projects, the claim team may affect project process and consequently the productivity of project.			
2.15.2.1	Experience of Claim Reviewer	Self-explanatory	Real number (no. of years working as claim expert)	Monthly	Project Manager

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.15.2.2	Claim Review Process Time	Self-explanatory	Real number (average time taken to finalize a review, days)	Monthly	Project Manager
2.15.3	Project Claim Resolution	Refers to the resolution process for any disagreements between the project parties which are raised as the project claims.			
2.15.3.1	Resolution Method	Self-explanatory	Categorical	Monthly	Project Manager
	Negotiation, mediation, arbitration, mini-trials or litigation				
2.15.3.2	Resolution process	Self-explanatory	Real number (average time taken to resolve claim, month)	Once	Project Manager
2.16. Miscellaneous Factors					
2.16.1	Job Security	Refers to the level of job security a project worker has in terms of availability of work over a year period.	Real number (Yearly average length of unemployment, month)	Once, Project Start	Superintendent
2.16.2	Weather Conditions	Weather conditions may affect the construction productivity. Precipitation cold weather or hot weather may affect productivity of the different types of construction operations.			
2.16.2.1	Temperature	Self-explanatory	Real number (daily average temperature, Celsius)	Daily	Researcher
2.16.2.2	Humidity	Self-explanatory	Percentage (daily average humidity)	Daily	Researcher

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.16.2.3	Precipitation	Self-explanatory	Real number (daily total precipitation, mm)	Daily	Researcher
2.16.2.4	Wind Speed	Self-explanatory	Real number (wind speed, km/hr)	Daily	Researcher
2.16.2.5	Solar Radiation	Self-explanatory	Real number (daily average radiation, Hz)	Daily	Researcher
2.16.3	Contractor Financial Status	Poor financial conditions of the project contractor may affect the project productivity by unreasonable construction delays due to the contractor financial crisis.	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- Project contractor has VERY POOR Financial conditions. 2- Project contractor has POOR Financial conditions. 3- Project contractor has FAIR Financial conditions. 4- Project contractor has VERY POOR Financial conditions. 5- Project contractor has VERY GOOD Financial conditions.				
2.16.4	Research and Development	This factor measures whether research and development efforts made by the contractor or the owner team. The R&D efforts may affect the construction productivity.	Categorical	Once, Project Start	Project Manager
	Yes, No				
2.16.5	Coordination between Trades	Refers to the coordination between the different trades at the project site which should be made by the superintendent or the project manager.	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY POOR Coordination, VERY FREQUENT Conflicts between the trades, VERY FREQUENT Time loss due to the conflicts. 2- POOR Coordination, FREQUENT Conflicts between the trades, FREQUENT Time loss due to the conflicts. 3- FAIR Coordination, NOT FREQUENT Conflicts between the trades, NOT FREQUENT Time loss due to the conflicts. 4- GOOD Coordination, RARE Conflicts between the trades, RARE Time loss due to the conflicts. 5- VERY GOOD Coordination, VERY RARE Conflicts between the trades, VERY RARE Time loss due to the conflicts.				
2.16.6	Project Completion Percentage	The productivity of construction projects may be different at different stages of the project. This factor measures the completion percentage monthly.	Percentage (total value of completed works divided by total project value)	Monthly	Project Manager

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.16.7	Superintendent Management Style	Self-explanatory	1-5 Predetermined rating	Monthly	Project Manager
	1- ALWAYS Disrespectful to project team, Insincere, NO Counselling. 2- OFTEN Disrespectful to project team, Insincere, NO Counselling. 3- SOMETIMES Respectful to project team, Sincere, Counselling. 4- OFTEN Respectful to project team, Sincere, Counselling. 5- ALWAYS Respectful to project team, Sincere, Counselling.				
2.16.8	Superintendent Trainings	Refers to the trainings sessions attended by the superintendent for developing their qualities for management of the project site.	Integer number (no. of trainings attended) Real number (total hours of training, hr)	Once, Superintendent Change	Superintendent
2.16.9	Superintendent Education	Refers to the highest level of education of the superintendent.	Categorical	Once, Superintendent Change	Superintendent
	Below Secondary, Secondary School, Technical or Apprentice, College, University				
2.16.10	Uniformity of Work Rules by Superintendent	Refers to the uniformity of the rules defined by the superintendent which may affect the perception of the workers toward the project and their motivation and consequently affect the construction productivity.	1-5 Predetermined rating	Once, Superintendent Change	Project Manager
	1- VERY Irregular among crews and HIGHLY Variable in daily work times and work days. 2- Irregular among crews and Variable in daily work times and work days. 3- Uniform among crews and Variable in daily work times and work days. 4- Uniform among crews, Always the same in daily work times and work days. 5- VERY Uniform among crews, Always the same in daily work times and work days.				
2.16.11	Project Management Team Experience	Refers to the average experience of the project management team which may affect the construction productivity of the project.	Real number (average years of experience, yr)	Once, Project Start	Project Manager
2.16.12	Project Manager Trainings	Refers to the trainings sessions attended by the project manager for developing the qualities for management of the project.	Integer number (no. of trainings attended) Real number (total hours of training, hr)	Once, Project Manager Change	Project Manager

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.16.13	Project Manager Education	Refers to the highest level of education of the project manager.	Categorical	Once, Project Manager Change	Project Manager
	Below Secondary, Secondary School, Technical or Apprentice, College, University				
2.16.14	Level of Paperwork	Refers to the total number of documents exchanged between the contractor and the owner (or representative) to receive the work approvals.	Integer number (total number of docs per month)	Monthly	Project Manager
2.16.15	Permits	Refers to the total time lost for receiving the required permits (e.g., approval for building permit) to execute the project which should be measured monthly.	Real number (total time lost due to permits approvals, hr)	Monthly	Project Manager
2.16.16	Availability of Labour	This factor measures the availability of craftspeople for completing the project team at the project start or substitution for the project team turnovers.	1-5 Predetermined rating	Once, Project Start	Project Manager
	1- VERY LOW labour availability for the project, VERY LONG Time loss for completion of the project team. 2- LOW labour availability for the project, LONG Time loss for completion of the project team. 3- AVERAGE labour availability for the project, AVERAGE Time loss for completion of the project team. 4- HIGH labour availability for the project, SHORT Time loss for completion of the project team. 5- VERY HIGH labour availability for the project, VERY SHORT Time loss for completion of the project team.				
2.16.17	Contractor experience	Refers to the experience of the contractor company in construction industry.	Integer number (no. of years of experience)	Once, Contractor Change	Project Manager
2.16.18	Project Level Rework	Refers to the overall level of rework in the project measure by	Real number (project overall CFRI)	Monthly	Project Manager
2.16.19	Parking Facilities	This factor measures the availability of parking spots for the workers of the project. This factor affect the choice of transportation for the project workers and may affect the construction productivity as well.	Real number (no. of project workers divided by the no. parking spots)	Once, Project Start	Project Manager
2.16.20	Project Financial Management (Payments, Salary)				

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
2.16.20.1	Project Team Salary	This factor measures the average income of each position of the project team including the annual salaries or hourly payments.			
2.16.20.1.1	Craftsperson Income	Self-explanatory	Real numbers (average annual salaries or hourly payment, $)	Once, Project Start	Human Resources
2.16.20.1.2	Journeyman Income	Self-explanatory	Real numbers (average annual salaries or hourly payment, $)	Once, Project Start	Human Resources
2.16.20.1.3	Foreman Income	Self-explanatory	Real numbers (average annual salaries or hourly payment, $)	Once, Project Start	Human Resources
2.16.20.1.4	Superintendent Income	Self-explanatory	Real numbers (average annual salaries or hourly payment, $)	Once, Project Start	Human Resources
2.16.20.1.5	Project Manager Income	Self-explanatory	Real numbers (average annual salaries or hourly payment, $)	Once, Project Start	Human Resources
2.16.20.2	Project Team Payments	Refers to the timely manner of the payments to the project team.	1-5 Predetermined rating	Once	Human Resources
	1- VERY FREQUENT Delays for payments, VERY LONG Delays for payments. 2- FREQUENT Delays for payments, LONG Delays for payments. 3- NOT FREQUENT Delays for payments, AVERAGE Delays for payments. 4- RARE Delays for payments, SHORT Delays for payments. 5- VERY RARE Delays for payments, VERY SHORT Delays for payments.				
2.16.21	Labour Disputes	Refers to the dispute cases occurred in the project per month.	Integer number (no. of disputes)	Monthly	Project Manager

B.1.3. Field Data Collection Details for Macro-Level Factors

Table B.3. Field data collection details for macro-level factors

Factor ID	Sub - Factors	Description	Scale of Measure	Data Collection Cycle	Data Source
3.1. Organizational Properties					
3.1.1	Organization's Principal Project Type	Refers to the most common project type which is executed by the organization can develop the organization expertise for execution of the project type. As the result this factor may affect the construction productivity.	Categorical	Once, Project Start	Project Manager
	Industrial, Commercial, Infrastructure, Institutional, Other				
3.1.2	Organization Experience	Refers to the number of years the organization is in the industry.	Integer number (experience in industry, yr)	Once, Project Start	Project Manager
3.1.3	Organization Annual Turnover	Refers to the total annual turnover of the organization in terms of dollar value of turnover per year.	Real number (annual turnover, $)	Once, Project Start	Project Manager
3.1.4	Annual Employee Turnover	Refers to the total number the employees who separated from the organization per year.	Integer number (annual turnover)	Once, Project Start	Project Manager
3.1.5	Number of Active Projects	Refers to the number of the active projects the organization has in hand in time of execution of the project under study.	Integer number (no. of active projects)	Once, Project Start	Project Manager
3.1.6	Organizational Structure	Self-explanatory	Categorical	Once, Project Start	Project Manager
	Matrix, Project based, Mixed				
3.1.7	Organization Level of Subcontracting	Refers to the subcontracting culture of the organization which may differ from awarding all the project components to different subcontractors to executing the whole project as the general contractor.	Percentage (average value of subcontracted work divided by total projects' values of organization, $/$)	Once, Project Start	Project Manager

3.1.8	Organization Construction Equipment Fleet	Refers to the equipment fleet of the organization which may be recorded as the number of pieces of equipment for each type of construction equipment.	Integer number (no. of equipment) Nominal (equipment type)	Once, Project Start	Project Manager
3.1.9	Organization Equipment Maintenance Policy	Refers to the policy of the organization for maintenance of the equipment which are owned by the company (i.e., active at project sites or inactive in the fleet)	Categorical	Once, Project Start	Project Manager
	Operate to fail, Condition based maintenance, Fixed time-based maintenance				
3.1.10	Equipment Fleet Inspections and Analysis	Refers to the organization culture for inspecting and analyzing the performance of the equipment fleet. The analysis should include age, cost and reliability analysis of the equipment in the fleet.	Real number (no. of inspections done per year)	Once, Project Start	Project Manager
3.1.11	Equipment Operator Trainings	Refers to the trainings provided for the equipment operators which are held by the organization to increase the efficiency the construction equipment.	Real number (no. of hours of training per year)	Once, Project Start	Project Manager
3.1.12	Organization Policy for Equipment Ownership	Refers to the high level policy of the organization for the ownership of the construction equipment.	Categorical	Once, Project Start	Project Manager
	Own, Lease, Rent				
3.1.13	Organization Equipment Warranty Policy	Refers to the high level policy of the organization for having warranties for the equipment of the fleet or operating the equipment on their own risk.	Categorical	Once, Project Start	Project Manager
	Yes, No				
3.1.14	Ownership Period and Economic Analysis	Refers to the analysis of the organization for the ownership period of the equipment and the economic decisions regarding the equipment available in the fleet.	Categorical	Once, Project Start	Project Manager
3.2. Provincial					
3.2.1	Provincial Economy	Provincial economy may be an effective factor on construction productivity. The Gross Domestic Product (GDP) is the economic measure for representing the economic status in large scale (i.e., country, province).	Real number (Provincial GDP, Billion $)	Once, Project Start	Researcher

3.2.2	Number of Provincial Construction Projects	Refers to the number of construction projects executed in the province per year.	Integer (Number of projects under construction per year)	Once, Project Start	Researcher
3.2.3	Provincial Codes and Regulations	Refers to the provincial codes and regulations which are applied to the construction projects which may include environmental codes, safety codes and engineering codes.	1 - 5 Predetermined rating	Once, Project Start	Researcher
	1- VERY STRICT regulations. 2- STRICT regulations. 3- NORMAL regulations. 4- FLEXIBLE regulations. 5- VERY FLEXIBLE regulations.				
3.2.4	Unemployment Rate of Construction Workers	Self-explanatory	Percentage (annual unemployment rate)	Once, Project Start	Researcher
3.2.5	Labour Strikes	Self-explanatory	Integer number (no. of annual recorded labour strike in construction workforce)	Once, Project Start	Researcher
3.2.6	Available Supervisor Pool in Province	Self-explanatory	Integer number (no. of qualified supervisors in province, annual)	Once, Project Start	Researcher
3.2.7	Tax	Self-explanatory		Once, Project Start	Researcher
3.2.7.1	Income tax	Self-explanatory	Percentage (average income tax)	Once, Project Start	Researcher
3.2.7.2	GST	Self-explanatory	Percentage (GST)	Once, Project Start	Researcher
3.2.8	Construction Material Price Fluctuation	Refers to the construction material price fluctuations in the province.	Percentage (Industrial product price index change)	Once, Project Start	Researcher
3.2.9	Availability of Labour in Province	Self-explanatory	Real number (annual unemployment rate	Once, Project Start	Researcher

			of construction labours)		
3.2.10	Expenditure Level towards Projects	Refers to the total construction budget spent in the major types of construction projects in the province annually.			
3.2.10.1	Residential	Self-explanatory	Real number (annual invested amount, Billion $)	Once, Project Start	Researcher
3.2.10.2	Non-residential	Self-explanatory	Real number (annual invested amount, Billion $)	Once, Project Start	Researcher
3.2.10.3	Energy	Self-explanatory	Real number (annual invested amount, Billion $)	Once, Project Start	Researcher
3.2.11	Cost of Project (index)	Refers to the average cost for the same type of project as the project under study.	Real number (Average cost of project per index)	Once, Project Start	Researcher
3.3. National					
3.3.1	Political System	Refers to the political system of the country which may affect the construction productivity of the infrastructure projects which are operated by the government. The political stability index released by The Global Economy institute can represent the stability of the political system of the country.	1 - 4 Predetermined rating	Once	Researcher
	1- VERY LOW Stability. 2- LOW Stability. 3- AVERAGE Stability. 4- HIGH Stability. 5- VERY HIGH Stability				
3.3.2	Competing Project Across Nation	The number of competing projects across the nation may affect the productivity of the project.	Real number (no. of projects in per province)	Once	Researcher
3.3.3	Availability of labour in Nation	Availability of the labour in the nation can affect the construction industry in different aspects such as; turnover rate of employees in the construction industry and consequently affect the productivity of construction projects.	Percentage (annual unemployment rate of construction labours)	Once	Researcher
3.3.4	Foreign Construction	The foreign construction workers recruitment process affects the total number of available construction	Percentage (total number of foreign	Once	Researcher

	Workers Recruitment	workforce at national level and consequently affect the construction productivity. BuildForce® Canada reports the total number of foreign construction workers and total construction workers.	construction workers divided by total construction workers)		
3.3.5	Canada Population				
3.3.5.1	Size of population	Self-explanatory	Real number (population)	Once	Researcher
3.3.5.2	Growth of population	Self-explanatory	Percentage (annual growth rate)	Once	Researcher
3.3.5.3	Aging of population	Self-explanatory	Real number (median age of Canada's population)	Once	Researcher
3.3.6	Interest Rates	Refers to the national annual interest rate which is specified by the Bank of Canada. The annual interest rate affects the Minimum Acceptable Rate of Return (MARR) and consequently affect the productivity of construction projects.	Real number (annual interest rate)	Once	Researcher
3.3.7	Inflation Rate	Refers to the Consumer Price Index (CPI).	Real number (Change of CPI)	Once	Researcher
3.3.8	Construction Price Index	Refers to the construction price index reported by Statistics Canada annually representing the inflation of the construction prices.	Real number (Construction Price Index)	Once	Researcher
3.4.1	Global Economic Outlook	Refers to the growth of the global economy which should be measure as the growth of GDP of Canada. The information regarding the GDPs of the different countries need to be extracted from the semi annual report of The World Bank[4].	Percentage (GDP growth)	Once, Project Start	Researcher
3.4.2	Global Energy Supply and Demand	Self-explanatory			
3.4.2.1	Global Energy Demand	Self-explanatory	Real number (energy demand, quadrillion BTUs)	Once, Project Start	Researcher

3.4.2.2	Global Energy Supply		Real number (energy supply, quadrillion BTUs)	Once, Project Start	Researcher
3.4.3	Oil Price and Price Fluctuation	Self-explanatory		Daily	Researcher
3.4.3.1	Oil Price	Self-explanatory	Real number (dollar / barrel)	Daily	Researcher
3.4.3.2	Price Fluctuation	Self-explanatory	Percentage (weekly price change)	Weekly	Researcher
3.4.4	Natural Gas Price and Price Fluctuation	Self-explanatory			
3.4.4.1	Natural Gas Price	Self-explanatory	Real number (dollar / GJ)	Daily	Researcher
3.4.4.2	Natural Gas Fluctuation	Self-explanatory	Percentage (weekly price change)	Weekly	Researcher

B.2. Field Data Collection Forms

Daily Field Factor Form

Project Code: **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub factors/Categorie	Predetermined Ratings (1 - 5)/ Note	Input Value
1.1 Labour and Crew	1.1.1	Crew Size	Integer number (crew size)	Foreman			
	1.1.2	Adequacy of Crew Size	1-5 Predetermined rating	Foreman		1- Crew size is VERY POOR fit for the activity's volume of work. 2- Crew size is POOR fit for the activity's volume of work. 3- Crew size is FAIR fit for the activity's volume of work. 4- Crew size is GOOD fit for the activity's volume of work. 5- Crew size is VERY GOOD fit for the activity's volume of work.	
	1.1.3	Crew Composition	Integer numbers (no. journeymen, no. apprecntices)	Foreman			
	1.1.4	Crew Experience	Integer number (years of experience)	Foreman			
	1.1.8.1	Intensity of effort	1-5 Predetermined rating	Foreman		1- VERY LOW effort intensity to perform the task 2- LOW intensity of effort to perform the task 3- AVERAGE intensity of effort to perform the task 4- HIGH intensity of effort to perform the task 5- VERY HIGH intensity of effort to perform the task	
	1.1.8.2	Persistence of effort	1-5 Predetermined rating	Foreman		1- VERY LOW persistency of effort to perform the task 2- LOW persistency of effort to perform the task 3- AVERAGE persistency of effort to perform the task 4- HIGH persistency of effort to perform the task 5- VERY HIGH persistency of effort to perform the task	
	1.1.8.3	Direction of effort	1-5 Predetermined rating	Foreman		1- VERY LOW consistency between direction of effort and the assigned goals 2- LOW consistency between direction of effort and the assigned goals 3- AVERAGE consistency between direction of effort and the assigned goals 4- HIGH consistency between direction of effort and the assigned goals 5- VERY HIGH consistency between direction of effort and the assigned goals	
	1.1.9	Level of Interruptions and Disruptions	Real number (total time lost due to interruptions, min)	Foreman			
	1.1.11	Total Daily Overtime Work	Integer number (overtime Work, hr)	Foreman			
	1.1.13	Unscheduled Breaks	Real number (total time lost due to unscheduled breaks, min)	Foreman			
	1.1.14	Late Arrival / Early Quit	Real number (total time lost due to late arrival or early quit, min)	Foreman			
1.2 Material	1.2.1	Material Availability	Categorical	Foreman	Yes, No		
	1.2.2	Waiting Time for Material	Real number (total time lost due to waiting for materials, min)	Foreman			
	1.2.3	Material Quality	Real number (total time lost due to material quality problems, min)	Foreman			
	1.3.1	Number and Type of Active Equipment on the Task	Integer number (no. equipment), Categorical (Equipment type)	Researcher	Equipment Types: Dozers, Excavators, Trucks, Drills, etc.	Note: The idle pieces of equipment which are provided at the project site for substitution with the broken equipment should not be counted for this factor.	

Daily Field Factor Form

Project Code: | **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub factors/Categorie	Predetermined Ratings (1 - 5)/ Note	Input Value
1.3 Equipment	1.3.3	Equipment Breakdown Downtime	Real number (total time lost due to equipment breakdown, min)	Foreman		Note: If there is a replacement piece of equipment available at the project site to substitute with the broken equipment, this factor will only include the time lost for substitution not the total repair time. Note: Note: this factor will be recorded for each individual equipment independently, to identify the piece of equipment which governs the production rate of the operation.	
	1.3.4	Equipment Maintenance Downtime	Real number (total time lost due to equipment maintenance, min)	Foreman		Note: this factor will be recorded for each individual equipment independently, to identify and use the piece of equipment which governs the production rate of the operation.	
	1.3.5.1	Equipment Delivery to Working Area	Real number (total time lost due to delivery of equipment, min)	Foreman			
	1.3.5.2	Waiting Time for Equipment	Real number (total time lost due to waiting for equipment, min)	Foreman			
	1.3.5.3	Appropriateness of Equipment	1-5 Predetermined rating	Superintendent	Size (e.g., bucket size for dozers), Settings (e.g., type of blade for different material for excavators or TBM), and Power (i.e., total horsepower generated by the engine)	1- Equipment Size is a VERY POOR fit for the activity, equipment Setting is a VERY POOR fit for the activity or equipment Power is a VERY POOR fit for the activity. 2- Equipment Size is a POOR fit for the activity, equipment Setting is a POOR fit for the activity or equipment Power is a POOR fit for the activity. 3- Equipment Size is a FAIR fit for the activity, equipment Setting is a FAIR fit for the activity or equipment Power is a FAIR fit for the activity. 4- Equipment Size is a GOOD fit for the activity, equipment Setting is a GOOD fit for the activity or equipment Power is a GOOD fit for the activity. 5-Equipment Size is a VERY GOOD fit for the activity, equipment Setting is a VERY GOOD fit for the activity or equipment Power is a VERY GOOD fit for the activity.	
1.4 Task Related	1.4.1	Task Complexity	1-5 Predetermined rating	Foreman	Unknown or Uncertain alternatives, Inexact or Unknown means, Number of subtasks	1- MANY Alternatives, WELL KNOWN Means, VERY LOW No. subtasks 2- SOME Alternatives, WELL KNOWN Means, LOW No. subtasks 3- FEW Alternatives, KNOWN Means, AVERAGE No. subtasks 4- FEW Alternatives, UNKNOWN Means, HIGH No. subtasks 5- VERY FEW Alternatives, UNKNOWN Means, VERY HIGH No. subtasks	
	1.4.11	Balance between Labour and Equipment	Integer numbers (no. equipment, no. of labour)	Foreman			
1.5 Location	1.5.2	Site Restrictions	Real number (total time lost due to project site restrictions for use of equipment, min)	Superintendent			
1.6 Foreman	1.6.5	Coordination Between Labour and Equipment Operators	Real number (total time lost due to lack of coordination, min)	Foreman			
2.16 Miscellaneous Factors	2.16.2	Weather Conditions					
	2.16.2.1	Temperature	Real number (daily average temperature, Celsius)	Researcher			
	2.16.2.2	Humidity	Percentage (daily average humidity)	Researcher			
	2.16.2.3	Precipitation	Real number (daily total precipitation, mm)	Researcher			
	2.16.2.4	Wind Speed	Real number (wind speed, km/hr)	Researcher			
	2.16.2.5	Soalr Radiation	Real number (daily average radiation, Hz)	Researcher			

Weekly Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
1.1 Crew and Crew	1.1.5	Crew Makeup Changes	Percentage (occurrence of crew member changes divided by weekly average crew size)	Foreman			
	1.1.6	Crew Turnover Rate	Percentage (no. of separated crew members divided by weekly average crew size)	Foreman			
	1.1.15	Level of Absenteeism	Percentage (average no. of absent crew members to weekly average crew size)	Foreman		Note: the ansent crew member(s) should be counted for estimating the average weekly crew size.	
1.2 Material	1.2.4	Material Storage Practice	1-5 Predetermined rating	Foreman	Frequency of time loss, Arrangement of material	1- VERY POOR material storage practice, VERY FREQUENT time loss for delivering material from the storage, VERY POOR arrangement of material in the storage. 2- POOR material storage practice, FREQUENT time loss for delivering material from the storage, POOR arrangement of material in the storage. 3- FAIR material storage practice, INFREQUENT time loss for delivering material from the storage, FAIR arrangement of material in the storage. 4- GOOD material storage practice, RARE time loss for delivering material from the storage, GOOD arrangement of material in the storage. 5- VERY GOOD material storage practice, VERY RARE time loss for delivering material from the storage, VERY GOOD arrangement of material in the storage	
1.3 Equipment	1.3.2	Equipment Breakdown Frequency	Integer number (no. of breakdowns per week)	Foreman		Note: this factor will be recorded for each individual equipment independently, to identify and use the piece of equipment which governs the production rate of the operation.	
	1.3.4	Equipment Maintenance Frequency	Integer number (no. of breakdowns per week)	Foreman		Note: This factor measures the frequency of the maintenance services which occured during the project working hours only. Note: Note: this factor will be recorded for each individual equipment independently, to identify the piece of equipment which governs the production rate of the operation.	
1.4 Task Related	1.4.3	Task Repetitiveness	Percentage (identical work qty divided by the total work qty)	Foreman			
	1.4.4	Out of Sequence Work	Real number (total time lost due to ongoing prerequisite task, min)	Foreman	Stoppage of operation, Slow down of operation		
	1.4.5	Problems with Predecessors	Real number (total time lost for correction of predecessor, min)	Foreman	Correction of prerequisite task (rework)		
	1.4.7	Task Waste Disposal	Real number (total time lost for waste material disposal, min)	Superintendent			
	1.4.8	Level of Rework (Contractor Initiated)	Percentage (activity weekly volume of rework to total activity work volume [including rework])	Superintendent	Activity Construction Filed Rework Index (CFRI)		
	1.4.9	Frequency of Rework (Contractor Initiate	Integer number (number of reworks incidents weekly)	Superintendent			
	1.4.10	Rework Cost (Contractor Initiated)	Percentage (activity total weekly cost of rework divided by total activity cost [including rework])	Superintendent			

Weekly Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
1.6 Foreman	1.6.3	Work Planning Skills	1-5 Predetermined rating	Superintendent	Identifying and verifying that tools and materials are available and complete; Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; Translating general work requirements into a prioritized plan for individual tasks and assignments	1- VERY POOR in Identifying and verifying that tools and materials are available and complete; VERY POOR in Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; VERY POOR in Translating general work requirements into a prioritized plan for individual tasks and assignments; 2- POOR in Identifying and verifying that tools and materials are available and complete; POOR in Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; POOR in Translating general work requirements into a prioritized plan for individual tasks and assignments; 3- FAIR in Identifying and verifying that tools and materials are available and complete; FAIR in Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; FAIR in Translating general work requirements into a prioritized plan for individual tasks and assignments; 4- GOOD in Identifying and verifying that tools and materials are available and complete; GOOD in Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; GOOD in Translating general work requirements into a prioritized plan for individual tasks and assignments; 5- VERY GOOD in Identifying and verifying that tools and materials are available and complete; VERY GOOD in Identifying needs and deficiencies in the plan/schedule and communicating these to appropriate persons; VERY GOOD in Translating general work requirements into a prioritized plan for individual tasks and assignments	
	1.6.4	Leadership and Supervisory Skills	1-5 Predetermined rating	Superintendent	Orientation for new crew members, Assigning individual and crew tasks, Communicating the job to and with the crew, Controlling and maintaining work standards	1. INADEQUATE Orientation of crew members; VERY POOR in Assigning individual and crew tasks; VERY POOR in Communicating the job to and with the crew; VERY POOR in Controlling and maintaining work standards 2. INADEQUATE Orientation of crew members; POOR in Assigning individual and crew tasks; POOR in Communicating the job to and with the crew; POOR in Setting and maintaining work standards 3. ADEQUATE Orientation of crew members; FAIR in Assigning individual and crew tasks; FAIR in Communicating the job to and with the crew; FAIR in Setting and maintaining work standards 4. ADEQUATE Orientation of crew members; GOOD in Assigning individual and crew tasks; GOOD in Communicating the job to and with the crew; GOOD in Setting and maintaining work standards 5. ADEQUATE Orientation of crew members; VERY GOOD in Assigning individual and crew tasks; VERY GOOD in Communicating the job to and with the crew; VERY GOOD in Setting and maintaining work standards	
1.7 Engineering/Instructions	1.7.3	Number of Revisions on Drawings	Integer number (number of the drawing revisions per week)	Superintendent			
	1.7.4	Design Changes	Integer number (number of the design changes per week)	Superintendent		Note: this factor measures the number of the design changes not the revisions on drawings.	
	1.7.6	Time to Respond RFIs	Real number (average response time, hr)	Superintendent			
	1.7.7	Frequency of Rework (Design Initiated)	Integer Number (Number of reworks incidents weekly)	Superintendent			
	1.7.8	Level of Rework (Design Initiated)	Percentage (activity total volume of rework divided by total activity work volumne)	Superintendent		Activity Construction Filed Rework Index (CFRI) in terms of Activity total volume of rework to total work volume[7]	
	1.7.9	Rework Cost (Design Initiated)	Percentage (activity total weekly cost of rework divided by total activity cost [including rework])	Superintendent			
	1.7.10	Time to Do Inspections	Real number (time lost due to waiting for inspection, min)	Superintendent		Note: this factor will be evaluate only if execution of the successor activity or continuing the activity under study is needed to be on hold till the inspection completes.	

Weekly Field Factor Form

Project Code: | **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.3 Project's Owner Nature	2.3.1	Owner's Supervision	1-5 Predetermined rating	Superintendent		1- VERY LOW Supervision 2- LOW Supervision 3- SOME Supervision 4- HIGH Supervision 5- VERY HIGH Supervision	
	2.3.2	Owner's Intervention	Real number (total time lost due to owner intervention, hr)	Superintendent			
	2.3.4	Clarity of Owner's Objectives	1-5 Predetermined rating	Superintendent		1- VERY POOR clarity of the owner's objectives. 2- POOR clarity of the owner's objectives. 3- FAIR clarity of the owner's objectives. 4- GOOD clarity of the owner's objectives. 5- VERY GOOD clarity of the owner's objectives.	
	2.3.6	Owner's Staff On-Site	Integer number (weekly average no. of owner's staff on site)	Superintendent			
	2.3.7.1	Frequency of Suspensions	Integer number (number of suspension occurrences per week)	Project Manager			
	2.3.7.2	Length of Suspensions	Real number (total days lost due to work suspensions)	Project Manager			
2.4 Project's Conditions	2.4.7	Restrictions for Project Site Access	1-5 Predetermined rating	Superintendent		1- TOO MANY Restrictions for project site access, VERY COMMON Time loss due to the restrictions. 2- MANY Restrictions for project site access, COMMON Time loss due to the restrictions. 3-SOME Restrictions for project site access, NOT COMMON Time loss due to the restrictions. 4- FEW Restrictions for project site access, RARE Time loss due to the restrictions. 5- VERY FEW Restrictions for project site access, VERY RARE Time loss due to the restrictions.	
2.6 Project Time Management	2.6.3.1	Project Activity Duration Estimation	1 - 5 Predetermined rating	Superintendent	Development of resource requirements, resource capabilities, Use of historical information (past project files, commercial databases like RS Means), Experience of estimator	1- Resource requirements and resource capabilities ARE NOT PROPERLY documented, NO Use of historical information, VERY POOR Experience of estimator 2- Resource requirements and resource capabilities ARE NOT PROPERLY documented, NO Use of historical information, POOR Experience of estimator 3- Resource requirements and resource capabilities ARE SOMEWHAT documented, SOME Use of historical information (past project files, commercial databases like RS Means), Experience of estimator FAIR; 4- Resource requirements and resource capabilities ARE WELL documented, AVERAGE Use of historical information, GOOD Experience of estimator 5- Resource requirements and resource capabilities ARE VERY WELL documented, EXCELLENT Use of historical information, VERY GOOD Experience of estimator	
	2.6.3.2	Activity Duration Prediction Accuracy	1 - 5 Predetermined rating	Superintendent	In terms of milestones and activity durations	1- VERY Unrealistic 2- Unrealistic 3- Common industry average 4- Realistic 5- VERY Realistic	
2.8 Project Quality Management	2.8.5.1	QC Inspection Delay	Real number (delay for inspection, min)	Superintendent		Note: Daily average delay for inspections	
	2.8.5.2	QC Interference	Real number (total time lost due to interruptions, hr)	Superintendent			
	2.8.5.3	QC Out of Sequence Inspection or Survey Work	Real number (no. of occurrence per week)	Superintendent			

Weekly Field Factor Form

Project Code: **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.10 Project Safety Management	2.10.7	Project Safety Administration and Reporting	1 - 5 Predetermined rating	Superintendent	Record keeping of Hazard assessment forms, inspections, incidents (near miss, injury, fatality), Use of photographs and video records, Reporting to project management staff	1- VERY POOR Record keeping, NO Use of visual aids; 2- POOR Record keeping, NO Use of visual aids; 3- FAIR Record keeping, Use of visual aids; 4- GOOD Record keeping, GOOD Use of visual aids; 5- VERY GOOD Record keeping, VERY GOOD Use of visual aids	
2.12 Project Communication Management	2.12.2	Communication between Trades	1 - 5 Predetermined rating	Superintendent		1- VERY POOR Communication 2- POOR Communication 3- FAIR Communication 4- GOOD Communication 5- VERY GOOD Communication	
3.4 Global	3.4.3.2	Oil Price Fluctuation	Percentage (weekly price change)	Researcher			
	3.4.4.2	Natural Gas Fluctuation	Percentage (weekly price change)	Researcher			

Monthly Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
1.6 Foreman	1.6.2	Change of Foreman (Supervisor)	Integer number (no. changes of foreman [supervisor] per month)	Project Manager			
1.7 Engineering/Instructions	1.7.1	Availability of Drawings	1-5 Predetermined rating	Superintendent		1- Always Not Available 2- Sometimes Not Available 3- Sometimes Available 4- Mostly Available 5- Always Available	
	1.7.2	Quality of Drawings	1-5 Predetermined rating	Superintendent	Completeness, Readability, Reusability (number of times a drawing printout can be referred at work locations), Unclear information, Updated	1- Incomplete, VERY POOR Readability, VERY LOW Reusability, TOO MANY Unclear information, NOT Updated; 2- Incomplete, POOR Readability, LOW Reusability, SOME Unclear information, NOT Updated; 3- Incomplete, AVERGAE Readability, AVERAGE Reusability, FEW Unclear information, NOT Updated; 4- Complete, GOOD Readability, HIGH Reusability, FEW Unclear information, Updated; 5- Complete, VERY GOOD Readability, HIGH Reusability, VERY FEW Unclear information, Updated	
2.1 Project Delivery and Contract	2.1.5	Contract Conditions for Changes	Real Number (No. of contract conditions changes divided by total number of contract clauses)	Project Manager			
	2.1.6	Lack of Information	Integer Number (No. RFIs per month)	Project Manager			
	2.1.7	Change in Specifications	Percentage (no. of changed specifications to total no. of specification clauses on specific scope)	Superintendent			
	2.1.8	Change in Design Drawings	Percentage (no. of changed drawings to total no. of drawings)	Superintendent			
2.4 Project Conditions	2.4.12	Governmental Inspections					
	2.4.12.1	Frequency of Inspections	Integer number (number of inspections per month)	Project Manager			
	2.4.12.2	Total Time for Inspections	Real number (total duration of inspections, hr)	Project Manager			
	2.4.13	Suspension of Project					
	2.4.13.1	Frequency of Project Suspensions	Integer number (number of suspension occurrences monthly)	Project Manager			
	2.4.13.2	Length of Suspensions	Real number (total time lost due to work suspensions, day)	Project Manager			

Monthly Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.6 Project Time Management	2.6.8	Schedule Compression	Percentage (total crashed duration divided by original duration)	Project Manager	Level of schedule compression against original schedule		
2.7 Project Cost Management	2.7.4	Project Cost Control	1 - 5 Predetermined rating	Project Manager	Use of project information (Cost baseline, performance reports, change requests), Use of cost control tools and techniques (Cost change control system which defines procedures to change cost baseline, Earned Value Management), Development of a revised project financial documents (cost estimate, cost budget and cost baseline)	1- VERY POOR Use of project information, NO Use of Cost control tools and techniques, VERY POOR Update of project financial documents 2- POOR Use of project information, NO Use of Cost control tools and techniques, POOR Update of project financial documents 3- FAIR Use of project information, SOME Use of Cost control tools and techniques, FAIR Update of project financial documents 4- GOOD Use of project information, Use of Cost control tools and techniques, GOOD Update of project financial documents 5- VERY GOOD Use of project information, ADVANCED Use of Cost control tools and techniques, VERY GOOD Update of project financial documents	
	2.7.5	Use of Earned Value Methods	1 - 3 Predetermined rating	Project Manager		1- Earned value methods NOT employed 2- Earned value methods SOMEWHAT Employed but NOT fully (in terms of forecasting application) 3- Earned value methods PROERLY employed	
2.8 Project Qiality Management	2.8.4	Quality Audits	Real number (no. of quality audits per month)	Project Manager			
...oject Safety Management	2.10.3	Project Safety Plan Execution					
	2.10.3.3	Site Safety Communication	1 - 5 Predetermined rating	Superintendent		1- Safety Meetings NOT conducted 2- Safety Meetings conducted BUT NOT regularly, Effectiveness of meetings is POOR 3- Safety Meetings conducted REGULARLY, Effectiveness of meetings is FAIR 4- Safety Meetings conducted REGULARLY, Effectiveness of meetings is GOOD 5- Safety Meetings conducted REGULARLY, Effectiveness of meetings is VERY GOOD	
	2.10.3.7	Safety Inspections	Integer number (no. of inspections per month)	Project Manager			
	2.10.3.8	Safety Audits	Integer number no. of audits per month)	Project Manager			
	2.10.4	Safety Incidents					
	2.10.4.1	Near Miss	Integer number (no. of reported near miss incidents per month)	Superintendent			
	2.10.4.2	First Aid	Integer number (no. of reported first aid per month)	Superintendent			
	2.10.4.3	Medical Aid	Integer (Number of reported medical aid per month)	Superintendent			
	2.10.4.4	Modified Work Incidents	Integer number (no. of reported modified work incident per month)	Superintendent			

Monthly Field Factor Form

Project Code: | **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.10 Pr	2.10.4.5	Number of Modified Work Days	Integer number (no. of reported modified work days per month)	Superintendent			
	2.10.4.6	Lost Time Incident	Integer number (no. of reported lost time incident per month)	Superintendent			
	2.10.4.8	Fatality Incident	Integer number (no. of reported personnel fatality per month)	Superintendent			
	2.10.4.9	Equipment/Property Damage	Integer number (no. of reported equipment/property damage incident per month)	Superintendent			
	2.10.5	Safety Incident Investigation					
	2.10.5.1	Personnel Involved in Investigation	Integer number (no. of personnel involved in investigation)	Superintendent			
	2.10.5.2	Process Time	Real number (average time lost due to investigation, hr)	Superintendent			
2.11 Project Risk Management	2.11.3	Risk Monitoring and Control	1 - 5 Predetermined rating	Project Manager	Keeping track of identified risks, Monitoring residual risks and identifying new risks, Ensuring the execution of risk plans, Evaluating their effectiveness in reducing risk	1- NOT Keeping track of identified risks, VERY POOR Monitoring of residual risks and identifying new risks, VERY POOR in Ensuring the execution of risk plans, NO Evaluation on their effectiveness in reducing risk 2- NOT Keeping track of identified risks, POOR Monitoring of residual risks and identifying new risks, POOR in Ensuring the execution of risk plans, NO Evaluation on their effectiveness in reducing risk 3- Keeping SOME track of identified risks, FAIR Monitoring of residual risks and identifying new risks, FAIR in Ensuring the execution of risk plans, SOME Evaluation on their effectiveness in reducing risk 4- Keeping DETAIL track of identified risks, GOOD Monitoring of residual risks and identifying new risks, GOOD in Ensuring the execution of risk plans, DETAILED Evaluation on their effectiveness in reducing risk 5- Keeping DETAIL track of identified risks, VERY GOOD Monitoring of residual risks and identifying new risks, VERY GOOD in Ensuring the execution of risk plans, DETAILED Evaluation on their effectiveness in reducing risk	
	2.11.4	Crisis Management	1 - 5 Predetermined rating	Project Manager	Understanding possible crises (Crises Type), Understanding the time phase of crises (To be Reactive or Proactive), Having systems to prevent crises, Understanding stakeholders[8]	1- VERY POOR Understanding possible crises and stakeholders, REACTIVE Response to the crises, NO Prevention system from crises 2- POOR Understanding possible crises and stakeholders, REACTIVE Response to the crises, NO Prevention system from crises 3- FAIR Understanding possible crises and stakeholders, REACTIVE Response to the crises, SOME Prevention system from crises 4- GOOD Understanding possible crises and stakeholders, PROACTIVE Response to the crises, PROVIDED Prevention system from crises 5- VERY GOOD Understanding possible crises and stakeholders, PROACTIVE Response to the crises, PROVIDED Prevention system from crises	

Monthly Field Factor Form

Project Code: | **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.13 Project Human Resources Management	2.13.2	Project Staff Hiring Practice	1 - 5 Predetermined rating	Project Manager	Advertisement, Detailed job description, Fair screening, interview and selection process, Reasonable job requirements, [10,11]	1- VERY POOR Advertisement, NO Detailed job description, VERY UNFAIR Screening, interview and selection process, VERY UNREASONABLE Job requirements 2- POOR Advertisement, NO Detailed job description, UNFAIR Screening, interview and selection process, UNREASONABLE job requirements 3- FAIR Advertisement, SOME Detailed job description, FAIR Screening, interview and selection process, ALMOST REASONABLE job requirements 4- GOOD Advertisement, SOME Detailed job description, FAIR Screening, interview and selection process, REASONBLE job requirements 5- VERY GOOD Advertisement, Detailed job description, VERY FAIR screening, interview and selection process, REASONABLE job requirements	
	2.13.3.1	Team Building Activities	Integer number (no. team building events planned per month)	Project Manager			
	2.13.4.2	Layoff Practices	1 - 5 Predetermined rating	Project Manager	Reasonable rules, Informing the rules to employees, Fairness, Consistency, Follow through[13]	1- VERY POOR in informing rules to employees, UNFAIRNESS among workers, LACK of Consistency and Follow through, UNREASONABLE Rules 2- POOR in informing rules to employees, UNFAIRNESS among workers, LACK of Consistency and Follow through, UNREASONABLE Rules 3- FAIR in informing rules to employees, UNFAIRNESS among workers, GOOD Consistency and Follow through, UNREASONABLE Rules 4- GOOD in informing rules to employees, FAIRNESS among workers, GOOD Consistency and Follow through, REASONABLE Rules 5- VERY GOOD in informing rules to employees, FAIRNESS among workers, VERY GOOD Consistency and Follow through, REASONABLE Rules	
2.14 Project Environmental Management	2.14.3	Project Environmental Assurance	1 - 5 Predetermined rating	Project Manager	Use of recycling, Sorting waste materials (Concrete, Steel, Wood), Awareness trainings	1- VERY POOR Recycling practice, Waste material sorting IS NOT done, No Awareness trainings 2- POOR Recycling practice, Waste material sorting IS NOT done, NO awareness trainings; 3- FAIR Recycling practice, Waste material sorting IS DONE SOMEHOW done, AWARENESS trainings are provided 4- GOOD Recycling practice, Waste material sorting is STRICTLY done, Awareness trainings provided 5- VERY GOOD Recycling practice, Waste material sorting IS VERY STRICTLY done, Awareness trainings provided	
	2.14.4	Environmental Audits	Integer number (no. of audits per month)	Project Manager			
	2.14.5	Project Environmental Control	1 - 5 Predetermined rating	Project Manager	Use of checklists, Environmental inspections, Rework/remedial actions to attain environmental compliance	1- NO Use of checklist, NO Rework/remedial action 2- POOR Use of checklist, NO Rework/remedial action 3- FAIR Use of checklist, NO Rework/remedial action 4- GOOD Use of checklist, Rework/remedial action taken when needed 5- VER GOOD Use of checklist, Rework/remedial action taken when needed	
	2.14.4.1	Rework/Remedial Action	1 - 3 Predetermined rating	Project Manager	Corrective actions taken to meet environmental requirements due to felt impacts like Oil spill	1- Corrective action NOT done 2- Corrective action SOMEWHAT done 3- Corrective action PROPERLY done	
	2.14.4.2	Environmental Inspections	Integer number (no. of inspections per month)	Project Manager			
Claim Management	2.15.1	Project Claim Identification	1 - 5 Predetermined rating	Project Manager	Adequacy of claim statements (evidence, contract basis, description of time and cost requirements)	1- VERY INADEQUATE 2- INADEQUATE 3- FAIRLY ADEQUATE 4- ADEQUATE 5- VERY ADEQUATE	
	2.15.2.1	Experience of Claim Reviewer	Real number (no. of years working as claim expert)	Project Manager			

Monthly Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.15 Project C	2.15.2.2	Claim Review Process Time	Real number (average time taken to finalize a review, days)	Project Manager			
	2.15.3.1	Resolution Method	Categorical	Project Manager	Negotiation, mediation, arbitration, mini-trials or litigation	Note: this factor measures the most frequently used resolution method used to resolve the claims.	
2.16 Miscellaneous Factors	2.16.6	Project Completion Percentage	Percentage (total value of completed works divided by total project value)	Project Manager			
	2.16.7	Superintendent Management Style	1-5 Predetermined rating	Project Manager		1- ALWAYS Disrespectful to project team, Insincere, NO Counselling 2- OFTEN Disrespectful to project team, Insincere, NO Counselling 3- SOMETIMES Respectful to project team, Sincere, Counselling 4- OFTEN Respectful to project team, Sincere, Counselling 5- ALWAYS Respectful to project team, Sincere, Counselling	
	2.16.14	Level of Paperwork	Integer number (total number of docs per month)	Project Manager			
	2.16.15	Permits	Real number (total time lost due to permits approvals, hr)	Project Manager			
	2.16.18	Project Level Rework	Real number (project overall CFRI)	Project Manager	Project CFRI (Ratio of Total Cost of rework to total field construction phase cost) [8]		
	2.16.21	Labour Disputes	Integer number (no. of disputes)	Project Manager			

One-Off Field Factor Form

Project Code: | **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
1.1 Labour and Crew	1.1.7	Number of Languages Spoken in the Crew	Integer number	Foreman	Once, Crew Change			
	1.1.10	Number of Consecutive Working Days	Integer number (no. of consecutive days, day)	Project Manager	Once, Project Start			
	1.1.12	Crew Skill Level	1-5 Predetermined rating	Foreman	Once, Crew Change		1- Skill level of the crew is VERY LOW for execution of the activity. 2- Skill level of the crew is LOW for execution of the activity. 3- Skill level of the crew is FAIR for execution of the activity. 4- Skill level of the crew is HIGH for execution of the activity. 5- Skill level of the crew is VERY HIGH for execution of the activity.	
1.2 Material	1.2.5	Pre-installation Requirements for Materials	Real number (total waiting time, hr)	Project Manager	Once, Task Change			
	1.3.6	Equipment Ownership	Categorical	Project Manager	Once, Equipment Change	Own, Lease, Rental		
	1.3.7	Equipment Production Capacity	Real number (total power generated, hp-hour) Real number (context dependant, [e.g., m³/hr for excavator])	Project Manager	Once, Equipment Change		Note: For generalizing the factor to suit the different types of construction equipment, the total generated power can be measured for this factor. However, for one specific type of equipment this factor can be measured in terms of the relevant context dependant unit (e.g., m³ per hour for excavators).	
	1.3.8	Equipment Age	Real number (age of equipment, hr)	Project Manager	Once, Equipment Change			
	1.3.9	Equipment Operator Experience	Integer number (years of experience)	Project Manager	Once, Operator Change			
	1.3.10	Equipment Operator Education	Categorical	Equipment Operator	Once, Operator Change	Below Secondary, Secondary School, Technical or Apprentice, College, University		
	1.3.11	Equipment Operator Skill Level	1-5 Predetermined rating	Foreman	Once, Operator Change		1- Skill level of the operator is VERY LOW for execution of the activity. 2- Skill level of the operator is LOW for execution of the activity. 3- Skill level of the operator is FAIR for execution of the activity. 4- Skill level of the operator is HIGH for execution of the activity. 5- Skill level of the operator is VERY HIGH for execution of the activity.	
	1.3.12	Amplification of Human Energy	1-5 Predetermined rating	Foreman	Once, Equipment Change	Driving energy	1- Equipment supplies no driving energy 2- Equipment supplies some driving energy 3- Equipment supplies measurably more energy but not all 4- Equipment supplies all driving energy 5- Equipment supplies all driving energy plus more than the earlier generations of this type of equipment[1,2]	
	1.3.13	Level of Control	1-5 Predetermined rating	Foreman	Once, Equipment Change	Controlibility	1- Manual hand tools 2- Manually controlled devices 3- Assisted controlled devices 4- Tele-controlled devices 5- Preprogrammed devices[1,2]	
	1.3.14	Functional Range	1-3 Predetermined rating	Foreman	Once, Equipment Change	Human capability enhancement	1- Equipment provides no enhancement to human resources' capabilities 2- Equipment expands human resources' capabilities 3- Equipment expands human resources' capabilities more than the previous generations of the equipment[1,2]	
	1.3.15	Equipment Ergonomic Design	1-3 Predetermined rating	Equipment Operator	Once, Equipment Change	Relief from physical stress	1- Equipment provides no relief from physical stresses 2- Equipment provides relief from physical stresses 3- Equipment provides relief from physical stresses as well as recovery from the existing physical fatigue (e.g., heated and ventilated seats)[1,2]	
	1.3.16	Information Feedback Provision	1-5 Predetermined rating	Foreman	Once, Equipment Change	Information processing	1- Equipment provides no level of information feedback to the operator 2- Equipment provides basic level of information feedback to the operator regarding internal operating factors 3- Equipment provides internal information to the operator and is able to respond to its own information 4- Equipment provides information regarding external and internal factors to the operator 5- Equipment provides information to the operator regarding internal and external factors and responds to both[1,2]	

One-Off Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
	1.3.17	Moving Technology	Categorical	Researcher	Once, Equipment Change	Crawling, Wheels		
	1.3.18	Equipment Warranty	Categorical	Project Manager	Once, Equipment Change	Yes, No		
	1.3.19	Equipment Specification	Nominal value	Project Manager	Once, Equipment Change	Equipment Make, Equipment Model, Equipment Size (e.g., bucket size for excavators)		
1.4 Task Related	1.4.2	Total Volume of Work	Real number (approved quantity for construction)	Foreman	Once, Task Change			
	1.4.6	Construction Method	Categorical (context dependant)	Foreman	Once, Task Change	Spoil removal method, Drilling method		
1.5 Location Properties	1.5.1	Spaciousness of Working Area	1-5 Predetermined rating	Superintendent	Once, Working Area Change	Equipment Selection Limitation, Crew size selection limitation	1- Working area Spaciousness is VERY LOW and STRICTLY affect the selection of Equipment and the Crew Size. 2- Working area Spaciousness is LOW and STRICTLY affect the selection of Equipment and MODERATELY affect the selection of Crew Size. 3- Working area Spaciousness is AVERAGE and MODERATELY affect the selection of Equipment and the Crew Size. 4- Working area Spaciousness is HIGH and SLIGHTLY affect the selection of Equipment and the Crew Size. 5- Working area Spaciousness is VERY HIGH and DOES NOT affect the selection of Equipment and the Crew Size.	
	1.5.3	Soil Conditions (Dependency)	1-5 Predetermined rating	Foreman	Once, Activity Start	Subsurface (soil) conditions[6] (i.e., Type of soil, Soil Moisture)	1- Activity execution IS NOT dependant to the soil conditions, VERY HIGH tolerance to the properties. 2- Activity execution is RARELY dependant to the soil conditions, HIGH tolerance to the soil properties. 3- Activity execution is MODERATELY dependant to the soil conditions, MODERATE tolerance to the soil properties. 4- Activity execution is HIGHLY dependant to the soil conditions, LOW tolerance to the soil properties. 5- Activity execution is EXTREMELY dependant to the soil conditions, VERY LOW tolerance to the soil properties.	
	1.5.4	Soil Properties (Type, Moisture and etc.)				Soil Type, Soil Moisture		
	1.5.4.1	Soil Type	Categorical	Project Manager	Once, Activity Start	Gumbo Clay Loam, Silty Clay Loam, Silty Loam, Sandy Loam, Sandy/Coarse		
	1.4.5.2	Soil Moisture	Percentage (weight of water content of soil divided by total weight of soil)	Project Manager	Once, Activity Start			
	1.5.5	Unseen Subsurface Conditions				Groundwater level, Underground urban facilities		
	1.5.5.1	Groundwater Level	Real number (groundwater level, m)	Project Manager	Once, Activity Start		Note: This factor is considered at the activity level as it does not affect all the project activities evenly.	
	1.5.5.2	Underground Facilities	Categorical	Project Manager	Once, Activity Start	Yes, No	Note: This factor is considered at the activity level as it does not affect all the project activities evenly.	
	1.5.6	Hauling/Delivery Elevation Difference	Real number (elevation difference, m)	Project Manager	Once, Activity Start		Note: This factor is considered at the activity level since in road construction the elevation is variable throughout the project site and it can be measured at the activity level with more accuracy.	
	1.5.7	Hauling/Delivery Distance	Real number (distance, km)	Project Manager	Once, Activity Start	Hauling Distance	Note: This factor is considered at the activity level since in road construction the distance is variable throughout the project site and it can be measured at the activity level with more accuracy.	
1.6 Foreman	1.6.1	Foreman (Supervisor) Experience	Integer number (years of experience)	Superintendent	Once, Change of Foreman (Supervisor)			
Contract	2.1.1	Level of Sub-Contracting						
	2.1.1.1	Subcontracted amount	Percentage ($ value subcontracts divided by total $ value of contract)	Project Manager	Once, Project Start			

One-Off Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.1 Project Delivery and	2.1.1.2	Number of subcontractors	Integer number (total number of subcontractors per project)	Project Manager	Once, Project Start			
	2.1.2	Delivery System	Categorical	Project Manager	Once, Project Start	Design Bid Build (DBB), Design Build (DB), Build Operate Transfer (BOT), Private Public Partnership (PPP)		
	2.1.3	Contract Type	Categorical	Project Manager	Once, Project Start	Lump Sum, Unit Rate, Cost Reimbursable		
	2.1.4	Level of Fast Tracking	Percentage (% Overlap between design and construction schedule)	Project Manager	Once, Project Start			
2.2 Project Best Practices	2.2.1	Use of Automation and Information Technology	1-5 Predetermined rating	Project Manager	Once, Project Start	Note: this factor does not evaluates the use of the traditional planning software such as Primavera or Microsoft Project for project scheduling purposes.	1- NO Use of IT in planning of project, NO Use of IT for project monitoring and controlling 2- POOR Use of IT in planning of project, POOR Use of IT for project monitoring and controlling 3- FAIR Use of IT in planning of project, FAIR Use of IT for project monitoring and controlling 4- GOOD Use of IT in planning of project, GOOD Use of IT for project monitoring and controlling 5- VERY GOOD Use of IT in planning of project, VERY GOOD Use of IT for project monitoring and controlling	
	2.2.2	Constructability Review						
	2.2.2.1	Constructability Review Participants	Categorical	Project Manager	Once, Project Start	Owner, Engineering, Contractor, Sub-contractor, Project manager, Superintendent		
	2.2.2.2	Constructability Review Implementation	1-5 Predetermined rating	Project Manager	Once, Project Start	Project objectives definition, Constructability reviews objectives, Project performance improvements	1- Objectives of Constructability Reviews are VERY POORLY defined, and VERY POORLY match the Project Objectives, VERY LOW improvement on project performance are made. 2- Objectives of Constructability Reviews are POORLY defined and POORLY match the Project Objectives, LOW improvement on project performance are made. 3- Objectives of Constructability Reviews are FAIRLY defined, and FAIRLY match the Project Objectives, FAIR improvement on project performance are made. 4- Objectives of Constructability Reviews are WELL defined, and WELL match the Project Objectives, HIGH improvement on project performance are made. 5- Objectives of Constructability Reviews are VERY WELL defined, and VERY WELL match the Project Objectives, VERY HIGH improvement on project performance are made.	
	2.2.3	Start-up Planning	1-5 Predetermined rating	Project Manager	Once, Project Start	Technology used in evaluation (e.g., simulation engines), Evaluation for alternate options, Risk analysis[1]	1- NO Use of technological methods, ONLY FEW Alternative evaluated, NO Risk analysis; 2- NO Use of technological methods, FEW Alternative evaluated, NO Risk analysis; 3- NO Use of technological methods, SOME Alternatives evaluated, SOME form of Risk analysis; 4- SOME Use of technological methods, SOME Alternatives evaluated, SOME form of Risk analysis; 5- DETAILED Use of technological methods, MANY Alternatives evaluated, DETAILED Risk analysis	

One-Off Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
	2.2.4	Productivity Measurement Practice	1-5 Predetermined rating	Project Manager	Once, Project Start	Use of standard systems to measure outputs (e.g., units complete, percent complete) and inputs (e.g., cost, labour-hours), Frequency of data collection, Productivity evaluation and forecasting (e.g., performance factor, earned value method)²	1- NO Use of Standard systems to measure the outputs and inputs, Frequency of data collection NOT properly established, VERY POOR Productivity evaluation and forecasting; 2- NO Use of Standard systems to measure the outputs and inputs, Frequency of data collection NOT properly established, POOR Productivity evaluation and forecasting; 3- Use of SOME Standard systems to measure the outputs and inputs, Frequency of data collection SOMEWHAT established, FAIR Productivity evaluation and forecasting; 4- Use of SOME Standard systems to measure the outputs and inputs, Frequency of data collection PROPERLY established, GOOD Productivity evaluation and forecasting; 5- Use of PROPER Standard systems to measure the outputs and inputs, Frequency of data collection PROPERLY established, VERY GOOD Productivity evaluation and forecasting	
	2.2.5	Use of Workface Planning	1-5 Predetermined rating	Project Manager	Once, Project Start		1-VERY POOR Implementation of workforce planning in the project 2- POOR Implementation of workforce planning in the project 3- FAIR Implementation of workforce planning in the project 4- GOOD Implementation of workforce planning in the project 5- VERY GOOD Implementation of workforce planning in the project	
2.3 Project Owner's Nature	2.3.3	Owner's Primary Driver	Categorical	Project Manager	Once, Project Start	Time, Cost, Quality		
	2.3.5	Delivery of Site to Contractor	Real number (total delay to handover the project site to contractor, days)	Project Manager	Once, Project Start			
	2.4.1	Camp Conditions	1-5 Predetermined rating	Superintendent	Once, Project Start	Room conditions, Food services, Site facilities (e.g., gym)	1- VERY POOR Room condition, POOR Food service, NO Facilities 2- POOR Room condition, POOR Food service, NO Facilities 3- FAIR Room condition, FAIR Food service, SOME Facilities 4- GOOD Room condition, GOOD Food service, SOME Facilities 5- VERY GOOD Room condition, VERY GOOD Food service, MANY Facilities	
	2.4.2	Total Project-Site Area	Real number (total project site area, m²)	Project Manager	Once, Project Start			
	2.4.3	Site Facilities Conditions						
	2.4.3.1	Project Site Lunchroom for Workers	Real number (total area, m²) Integer number (no. of seats)	Project Manager	Once, Project Start			
	2.4.3.2	Project Site Washroom for Workers	Integer number (no. washrooms)	Project Manager	Once, Project Start			
	2.4.4	Project Working Time	Time (start time and finish time)	Project Manager	Once, Project Start			
	2.4.5	Project Working Cycle	Integer numbers (no. consecutive working days, no. of consecutive off days)	Project Manager	Once, Project Start		Note: This factor should be measure at project level and activity level since, the working cycle for a trade or a sub-contractor may be different from the working cycle of the general contractor or owner team.	
	2.4.6	Site Layout				Temporary facility, Equipment shelter, Access roads and on-site paths, Workspace and site objects		
	2.4.6.1	Temporary Facilities	1-5 Predetermined rating	Project Manager	Once, Project Start	Identification, Size requirement, Placement	1- VERY POOR Identification, POOR Placement, VERY LARGE Size requirement; 2- POOR Identification, POOR Placement, LARGE Size requirement; 3- GOOD Identification, POOR Placement, LARGE Size requirement; 4- GOOD Identification, GOOD Placement, AVERAGE Size requirement; 5- VERY GOOD Identification, VERY GOOD Placement, SMALL Size requirement	

One-Off Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.4 Project Conditions	2.4.6.2	Equipment Storage Location	1-5 Predetermined rating	Project Manager	Once, Project Start	Closeness to workspace (moving equipment), Space for operation (steady equipment)	1- The shelter for moving equipment is TOO FAR from the workspace, VERY LIMITED space for operation of steady equipment. 2- The shelter for moving equipment is FAR from the workspace, LIMITED space for operation of steady equipment. 3- The shelter for moving equipment is in FAIR DISTANCE from the workspace, FAIR space for operation of steady equipment. 4- The shelter for moving equipment is CLOSE to the workspace, ENOUGH space for operation of steady equipment. 5- The shelter for moving equipment is VERY CLOSE to the workspace, MORE THAN ENOUGH space for operation of steady equipment.	
	2.4.6.3	Access Roads and On-Site Paths	Real number (no. access roads and on-site paths divided by project site area)	Project Manager	Once, Project Start			
	2.4.6.4	Workspace and Site Objects	1-5 Predetermined rating	Project Manager	Once, Project Start		1- Project workspace is VERY POORLY designed, VERY FREQUENT conflict between the workspace and the site objects happens. 2- Project workspace is POORLY designed, FREQUENT conflict between the workspace and the site objects happens. 3- Project workspace is FAIRLY designed, NOT FREQUENT conflict between the workspace and the site objects happens. 4- Project workspace is WELL designed, RARE conflict between the workspace and the site objects happens. 5- Project workspace is VERY WELL designed, VERY RARE conflict between the workspace and the site objects happens.	
	2.4.8	Construction Method	Categorical (context dependant)	Project Manager	Once, Project Start	e.g., open cut and trenchless methods for pipe installation		
	2.4.9	Distance between Project Site and City	Real number (distance to the nearest city, km)	Project Manager	Once, Project Start			
	2.4.10	Project Size	Real number (Project contract value, $ Million)	Project Manager	Once, Project Start			
	2.4.11	Project Type (Industry Sector)	Categorical	Project Manager	Once, Project Start	Industrial, Residential, Commercial and Institutional, Civil		
	2.4.14	Project Complexity				Use of unproven technology, Number of process steps (take it as average), Facility size or process capacity, Past experience with configuration or geometry, Construction methods		
	2.4.14.1	Use of Unproven Technology	1-5 Predetermined rating	Project Manager	Once, Project Start		1- VERY LOW use of unproven technologies in the project. 2- LOW use of unproven technologies in the project. 3- AVERAGE use of unproven technologies in the project. 4- HIGH use of unproven technologies in the project. 5- VERY HIGH use of unproven technologies in the project.	
	2.4.14.2	Facility Size and Process Capacity	Real number (context dependant)	Project Manager	Once, Project Start			
	2.4.14.3	Past Experience with the Configurations and Geometry	Integer number (no. of similar project completed)	Project Manager	Once, Project Start			
	2.4.14.4	Familiarity with Construction Methods	1-5 Predetermined rating	Project Manager	Once, Project Start		1- VERY POOR Experience with methods and technology, LACK of proper procedure 2- POOR Experience with methods and technology, LACK of proper procedure 3- FAIR Experience with methods and technology, WITH proper procedure 4- GOOD Experience with methods and technology, WITH proper procedure 5- VERY GOOD Experience with methods and technology , WITH proper procedure	
	2.4.15	Year of Construction	Date (project construction start date)		Once, Project Start			
	2.4.16	Level of Modularization	Percentage (off-site construction cost divided by the total project cost)	Project Manager	Once, Project Start			
	2.4.17	Site Congestion	Percentage (free site space area divided by total site area)	Project Manager	Once, Project Start			

One-Off Field Factor Form

Project Code: | **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.5 Project Scope Management	2.5.1	Project scope definition	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Use of defined project scope, Experience in work decomposition, Comprehensiveness of developed WBS	1- Defined project scope IS NOT properly used to define project WBS, VERY POOR Experience in work decomposition, Developed WBS DOES NOT cover the project scope 2- Defined project scope IS NOT properly used to define project WBS, POOR Experience in work decomposition, Developed WBS covers the project scope POORLY; 3- Defined project scope IS USED properly to define project WBS, FAIR Experience in work decomposition, Developed WBS covers the project scope FAIRLY; 4- Defined project scope IS USED properly to define project WBS, GOOD Experience in work decomposition, Developed WBS covers the project scope SOMEHOW 5- Defined project scope IS USED properly to define project WBS, VERY GOOD Experience in work decomposition, Developed WBS covers the project scope COMPREHENSIVELY	
	2.5.2	Project scope verification	1 - 3 Predetermined rating	Project Manager	Once, Project Start		1- Project scope verification IS NOT conducted; 2- Project scope verification IS SOMEWHAT conducted 3- Project scope verification IS PROPERLY conducted	
	2.5.3	Project scope change control	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Existence of required project change documents (WBS, Performance reports, Contracts, Formal change requests), Procedures for change management (paperwork, tracking system, approval levels), Performance measurement and planning processes to identify effect of changes and address implementation of changed scope, Integration with other control process (schedule, cost, quality controls)	1- LACK of project change documents, NO procedure for change management tracking and approval, VERY POOR performance measurement system, VERY POOR Integration with other control processes 2- LACK of project change documents, NO procedure for change management tracking and approval, POOR performance measurement system, POOR Integration with other control processes 3- PRESENCE of project change documents, NO procedure for change management tracking and approval, FAIR performance measurement system, FAIR Integration with other control processes 4- PRESENCE of project change documents, EXISTING procedure for change management tracking and approval, GOOD performance measurement system, GOOD Integration with other control processes 5- PRESENCE of project change documents, EXISTING procedure for change management tracking and approval, VERY GOOD performance measurement system, VERY GOOD Integration with other control processes	
	2.6.1	Project Activity Definition	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Use of project information (WBS, Scope statement, Historical information, making appropriate assumptions), Decomposition of WBS to activity, Use of concurrent engineering	1- VERY POOR Use of project information (WBS, Scope statement), assumptions ARE NOT Documented, VERY POOR decomposition of activities from WBS, NOT Using concurrent engineering ideas 2- POOR Use of project information (WBS, Scope statement), assumptions ARE NOT Documented properly, POOR decomposition of activities from WBS, NOT Using concurrent engineering ideas 3- AVERAGE Use of project information (WBS, Scope statement), assumptions ARE NOT Documented properly, FAIR decomposition of activities from WBS, NOT Using concurrent engineering ideas 4- GOOD Use of project information (WBS, Scope statement), assumptions ARE Documented properly, GOOD decomposition of activities from WBS, Using SOME concurrent engineering ideas; 5- VERY GOOD Use of project information (WBS, Scope statement), assumptions ARE Documented properly, VERY GOOD decomposition of activities from WBS, Using many concurrent engineering ideas	
	2.6.2	Project Activity Sequencing	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Understanding of dependencies, Use of activity sequencing tools (network diagrams)	1- VERY POOR Understanding of technical and resource dependencies between activities, NOT Using activity sequencing tools 2- POOR Understanding of technical and resource dependencies between activities, NOT Using activity sequencing tools 3- FAIR Understanding of technical and resource dependencies between activities, FAIR Use of activity sequencing tools 4- GOOD Understanding of technical and resource dependencies between activities, GOOD Use of activity sequencing tools 5- VERY GOOD Understanding of technical and resource dependencies between activities, VERY GOOD Use of activity sequencing tools	

One-Off Field Factor Form

Project Code:	Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.6 Project Time Management	2.6.4	Project Schedule Development	1 - 5 rating	Project Manager	Once, Project Start	Understanding of constraints, project calendar, resource plans, Development of activity attributes (responsible party, location of activity), Use of scheduling techniques (CPM, PERT, Simulation), Use of resource leveling heuristics, Use of project management software's (P6, P3, Microsoft Project)	1- VERY POOR Understanding of constraints, project calendar, resource plans, VERY POORLY Developed activity attributes, NOT Using scheduling techniques, NO Use of resource leveling and Project management software 2- POOR Understanding of constraints, project calendar, resource plans, POORLY Developed activity attributes, NOT Using scheduling techniques, NO Use of resource leveling and Project management software 3- FAIR Understanding of constraints, project calendar, resource plans, FAIRLY Developed activity attributes, FAIR Use of scheduling techniques, FAIR Use of resource leveling and Project management software 4- GOOD Understanding of constraints, project calendar, resource plans, WELL Developed activity attributes, GOOD Use scheduling techniques, GOOD Use of resource leveling and Project management software 5- VERY GOOD Understanding of constraints, project calendar, resource plans, WELL Developed activity attributes, VERY GOOD Use scheduling tools, VERY GOOD Use of resource leveling and Project management software	
	2.6.5	Project Duration Accuracy	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Based on contract or owner determination	1- VERY Unrealistic duration for activities 2- Unrealistic duration for activities 3- Common industry average duration for activities 4- Realistic duration for activities 5- VERY Realistic duration for activities	
	2.6.6	Project Schedule Criticality Index	Percentage (no. of critical activities divided by the total no. of activities)	Project Manager	Once, Project Start			
	2.6.7	Project Schedule Control	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Documentation of change requests, use of performance reports, development of detailed schedule updates and corrective actions	1- LACK of proper change request documents, VERY POOR Use of Performance reports, NO Schedule Updates schedule, NOT taking corrective actions; 2- LACK of proper change request documents, POOR Use of Performance reports, NO Schedule updates, NOT taking corrective actions 3- Use of proper change request documents, FAIR Use of Performance reports, PROPER Schedule updates, NOT taking corrective actions 4- Use of proper change request documents, GOOD Use of Performance reports, PROPER Schedule updates, Taking UNTIMELY corrective actions 5- Use of proper change request documents, VERY GOOD Use of Performance reports, PROPER Schedule updates, Taking TIMELY corrective actions	
	2.6.9	Project Activity Weights Definition	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Defining activity attributes in terms of durations, costs, resource needs, quantities; Using expert judgment, Using percentage calculation	1- Defining activity attributes in terms of durations, costs, labour hours, quantities NOT DONE, NO Use of expert judgment, NO Use of percentage calculation 2- Defining activity attributes in terms of durations, costs, labour hours, quantities SOMEWHAT, NO Use of expert judgment, NO Use of percentage calculation 3- Defining activity attributes in terms of durations, costs, labour hours, quantities PARTIALLY DONE, NO Use of expert judgment, YES to Use of percentage calculation 4- Defining activity attributes in terms of durations, costs, labour hours, quantities MOSTLY DONE, YES Use of expert judgment, YES Use of percentage calculation 5- Defining activity attributes in terms of durations, costs, labour hours, quantities FULLY DONE, YES Use of expert judgment, YES Use of percentage calculation	
	2.6.10	Project progress curves development and Progress monitoring	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Use of project schedule, activity weights, Development of standard curves, Use of project management software	1- NO Use of project schedules, activity weights, Standard Performance curves ARE NOT developed, Project management software IS NOT USED 2- POOR Use of project schedules, activity weights, Standard Performance curves ARE NOT developed, Project management software IS NOT USED 3- FAIR Use of project schedules, activity weights, Standard Performance curves ARE POORLY developed, Project management software IS NOT USED 4- GOOD Use of project schedules, activity weights, Standard Performance curves ARE WELL developed, Project management software IS USED 5- VERY GOOD Use of project schedules, activity weights, Standard Performance curves ARE VERY WELL developed, Project management software IS USED.	

One-Off Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.7 Project Resource Management	2.7.1	Project Resource Planning	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Use of project information (Scope, WBS, Historical information, Contract requirement, Activity duration), Understanding of construction methods, Use of Project management software's, Development of detailed resource requirement with a resource profile and schedule	1- VERY POOR Use of project information, NO Use of Project management software, INADEQUATELY Developed resource plan 2- POOR Use of project information, NO Use of Project management software, INADEQUATELY Developed resource plan 3- FAIR Use of project information, NO Use of Project management software, INADEQUATELY Developed resource plan 4- GOOD Use of project information, Use of Project management software, ADEQUATELY Developed resource plan 5- VERY GOOD Use of project information, ADVANCED Use of Project management software, ADEQUATELY Developed resource plan	
	2.7.2	Project Cost Estimate				Basic estimation process (developing material & equipment list, project schedule), Site requirements, Cost estimator experience, Time allowed for estimation, Bidding and labour climate	Note: This factor measures the different aspects of the contractor original estimate	
	2.7.2.1	Development of Material, Equipment Requirement List	1 - 5 Predetermined rating	Project Manager	Once, Project Start		1- VERY POOR Material and Equipment requirement list is developed 2- POOR Material and Equipment requirement list is developed 3- FAIR Material and Equipment requirement list is developed 4- GOOD Material and Equipment requirement list is developed 5- VERY GOOD Material and Equipment requirement list is developed	
	2.7.2.2	Project Cost Estimator Experience	Real number (average years of experience of estimation team)	Project Manager	Once, Project Start			
	2.7.2.3	Time Allowed for Cost Estimate	Real number (total time spent for estimation, days)	Project Manager	Once, Project Start			
	2.7.2.4	Bidding Process Conditions	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Uncertainty in future, Quality of bid document, Competition level, Type of project	1- VERY HIGH Uncertainty in future, VERY POOR Quality of bid document, VERY HIGH Competition level, UNFAVOURABLE Type of project 2- HIGH Uncertainty in future, POOR Quality of bid document, HIGH Competition level, UNFAVOURABLE Type of project 3- FAIR Uncertainty in future, AVERAGE Quality of bid document, MEDIUM Competition level, FAVOURABLE Type of project 4- FAIR Uncertainty in future, GOOD Quality of bid document, LOW Competition level, FAVOURABLE Type of project 5- LOW Uncertainty in future, VERY GOOD Quality of bid document, VERY LOW Competition level, FAVOURABLE Type of project	
	2.7.2.5	Labour Force Conditions	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Availability of labour, Quality of labour, Agreements with Unions	1- VERY LOW Availability of labour, VERY POOR Quality of labour, NO Agreement with Unions; 2- LOW Availability of labour, POOR Quality of labour, NO Agreement with Unions; 3- FAIR Availability of labour, FAIR Quality of labour, YES Agreement with Unions; 4- HIGH Availability of labour, GOOD Quality of labour, YES Agreement with Unions; 5- VERY HIGH Availability of labour, VERY GOOD Quality of labour, YES Agreement with Unions	
	2.7.3	Project Cost Budgeting	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Use of project information (Cost estimates, WBS, project schedule), Use of cost budgeting tools and techniques (Computerized tools), Development of a cost baseline (a time-phased budget to be used for measuring and monitoring cost performance of project)	1- VERY POOR Use of project information, NO Use of computerized tools, INADEQUATE Cost baseline is developed 2- POOR Use of project information, NO Use of computerized tools, INADEQUATE Cost baseline is developed 3- FAIR Use of project information, SOME Use of computerized tools, INADEQUATE Cost baseline is developed 4- GOOD Use of project information, Use of computerized tools, ADEQUATE Cost baseline is developed 5- VERY GOOD Use of project information, ADVANCED Use of computerized tools, ADEQUATE Cost baseline is developed	

One-Off Field Factor Form

Project Code: | **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.8 Project Quality Management	2.8.1	Project Quality Planning	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Use and understanding of project specification, design requirements, Development of clear project quality policy	1- VERY POOR Understanding of project specification and design requirements, VERY VAGUE project quality policy 2- POOR Understanding of project specification and design requirements, VAGUE project quality policy 3- FAIR Understanding of project specification and design requirements, UNCLEAR project quality policy 4- GOOD Understanding of project specification and design requirements, CLEAR project quality policy 5- VERY GOOD Understanding of project specification and design requirements, VERY CLEAR project quality policy	
	2.8.2	Demand for Over Quality Work	1-5 Predetermined rating	Project Manager	Once, Project Start		1- VERY LOW Demand for exceeding the quality levels of drawings 2- LOW Demand for exceeding the quality levels of drawings 3- MODERATE Demand for exceeding the quality levels of drawings 4- HIGH Demand for exceeding the quality levels of drawings 5- VERY HIGH Demand for exceeding the quality levels of drawings	
	2.8.3	Project Quality Assurance	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Use of quality audits, Implementation of quality improvements	1- VERY INFREQUENT Quality audits, VERY POOR Quality improvement Implementation 2- INFREQUENT Quality audits, POOR Quality improvement Implementation 3- INFREQUENT Quality audits, FAIR Quality improvement Implementation 4- FREQUENT Quality audits, GOOD Quality improvement Implementation 5- VERY FREQUENT Quality audits, VERY GOOD Quality improvement Implementation	
2.9 Project Procurement Management	2.9.1	Procurement Planning	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Make-or-buy analysis, Developing and selecting alternatives, Developing a solicitation and administration plan	1- NO make-or-buy analysis, Developing and selecting alternatives is VERY POORLY done, VERY POOR solicitation and administration plan; 2- IMPRECISE make-or-buy analysis, Developing and selecting alternatives is POORLY done, POOR solicitation and administration plan; 3- FAIR make-or-buy analysis, Developing and selecting alternatives is FAIRLY done, FAIR solicitation and administration plan; 4- DETAILED make-or-buy analysis, Developing and selecting alternatives is WELL done, GOOD solicitation and administration plan; 5- DETAILED make-or-buy analysis, Developing and selecting alternatives is VERY WELL done, VERY GOOD solicitation and administration plan	
	2.9.2	Procurement Solicitation Planning	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Preparing procurement documents for bids, Decisions on contract types, Detail evaluation criteria	1- VERY POOR Procurement documents for bids, VERY POOR Decisions on contract types, NO Detailed evaluation criteria 2- POOR Procurement documents for bids, POOR Decisions on contract types, NO Detailed evaluation criteria 3- FAIR Procurement documents for bids, FAIR Decisions on contract types, SOME Detail evaluation criteria; 4- GOOD Procurement documents for bids, GOOD Decisions on contract types, PROVIDED Detailed evaluation criteria 5- VERY GOOD procurement documents for bids, VERY GOOD Decisions on contract types, Detailed evaluation criteria	
	2.9.3	Procurement Solicitation Execution	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Use of prequalification process, Advertisement, Evaluation of proposals, Award of contract	1- NO Use of prequalification process, NO PROPER Advertisement, VERY POOR Practice in evaluation of proposals, NO PROPER Award of contract 2- NO Use of prequalification process, SOME Advertisement, POOR Practice in evaluation of proposals, NO PROPER Award of contract 3- SOME Use of prequalification process, SOME Advertisement, FAIR Practice in evaluation of proposals, PROPER Award of contract 4- DETAILED prequalification process, PROPER Advertisement, GOOD Practice in evaluation of proposals, PROPER Award of contract 5- DETAILED prequalification process, PROPER Advertisement, VERY GOOD Practice in evaluation of proposals, PROPER Award of contract	

One-Off Field Factor Form

Project Code: | **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
	2.9.4	Procurement Administration	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Proper contact with suppliers, Placing orders, Developing and following deliveries and returns[7]	1- INADEQUATE Contact Process, UNORGANIZED Placement of Orders, VERY POOR Follow-up 2- INADEQUATE Contact Process, UNORGANIZED Placement of Orders, POOR Follow-up 3- ADEQUATE Contact Process, FAIRLY ORGANIZED Placement of Orders, FAIR Follow-up 4- ADEQUATE Contact Process, ORGANIZED Placement of Orders, GOOD Follow-up 5- ADEQUATE Contact Process, WELL ORGANIZED Placement of Orders, VERY GOOD Follow-up	
2.10 Project Safety Management	2.10.1	Project Safety Planning	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Understanding of regulatory laws, regulations and contract requirements, Detailed hazard analysis of project, Development of clear project safety plan, Development of budget and time for implementation of safety plan	1- INADEQUATE Understanding of regulatory laws and contract requirements, VERY POOR project hazard assessment, INADEQUATE Project Safety plan, VERY POOR Budget and time development 2- INADEQUATE Understanding of regulatory laws and contract requirements, POOR project hazard assessment, INADEQUATE Project Safety plan, POOR Budget and time development 3- ADEQUATE Understanding of regulatory laws and contract requirements, FAIR project hazard assessment, ADEQUATE Project Safety plan, FAIR Budget and time development 4- ADEQUATE Understanding of regulatory laws and contract requirements, ADEQUATE project hazard assessment, ADEQUATE Project Safety plan, GOOD Budget and time development 5- ADEQUATE Understanding of regulatory laws and contract requirements, VERY GOOD project hazard assessment, ADEQUATE Project Safety plan, VERY GOOD Budget and time development	
	2.10.2	Use of Site Safety Officer	Categorical	Project Manager	Once, Project Start	Yes, No		
	2.10.3	Project Safety Plan Execution				Use of daily job Hazard assessment forms, Personnel protective equipment (PPE), Site safety communication, Safety equipment, Drug testing, Training, Safety Inspection		
	2.10.3.1	Daily Job Hazard Assessment Forms	Categorical	Superintendent	Once, Project Start	Yes, No		
	2.10.3.2	Personnel Protective Equipment	Categorical	Superintendent	Once, Project Start	Yes, No		
	2.10.3.4	Project Safety Equipment	Categorical	Superintendent	Once, Project Start	Yes, No		
	2.10.3.5	Drug testing	Categorical	Superintendent	Once, Project Start	Yes, No		
	2.10.3.6	Safety training	Real number (no. trainings attended x duration of Training, hrs)	Foreman	Once, Project Start		Safety orientation, Fall protection (harness), First aid, H2S.	
	2.10.6	Uniformity of Safety Procedures	1 - 5 Predetermined rating	Superintendent	Once, Project Start	Among crews, Among work times and work days	1- HIGHLY VARIABLE among crews and HIGHLY VARIABLE in daily work times and work days 2- VARIABLE among crews and VARIABLE in daily work times and work days 3- UNIFORM among crews and VARIABLE in daily work times and work days 4- ALMOST UNIFORM among crews, ALMOST UNIFORM in daily work times and work days 5- UNIFORM among crews, UNIFORM in daily work times and work days	
ct Risk Management	2.11.1	Risk Identification and Planning	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Proper risk identification, Development of an overall risk management plan with risk response planning	1- NO Proper risk identification, VERY POOR Overall risk management plan with risk response planning 2- NO Proper risk identification, POOR Overall risk management plan with risk response planning 3- SOME Risk identification, FAIR Overall risk management plan with risk response planning 4- SOME Risk identification, GOOD Overall risk management plan with risk response planning 5- DETAILED Risk identification, VERY GOOD Overall risk management plan with risk response planning	

One-Off Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.11 Proje	2.11.2	Use of Risk Assessment Tool	1 - 3 Predetermined rating	Project Manager	Once, Project Start	Qualitative risk assessment techniques (probability/impact risk rating matrix), quantitative risk assessment techniques (Decision tree, simulation, sensitivity analysis) risk assessment tools	1- Risk assessment ARE NOT used; 2- Qualitative risk assessment ARE used, Quantitative risk assessment ARE NOT used 3- Qualitative risk assessment ARE used, Quantitative risk assessment ARE used	
2.12 Project Communication Management	2.12.1	Project Communication Plan and Implementation	1 - 5 Predetermined rating	Superintendent	Once, Project Start	Communication plan, Clear roles and responsibilities, Identification of stakeholders, Distribution of information including reports[9]	1- VERY POOR Communication plan, NO Clear roles and responsibilities, NO Identification of stakeholders, VERY POOR Distribution of information 2- POOR Communication plan, NO Clear roles and responsibilities, NO Identification of stakeholders, POOR Distribution of information 3- GOOD Communication plan, PROPER Clear roles and responsibilities, PROPER Identification of stakeholders, POOR Distribution of information 4- GOOD Communication plan, PROPER Clear roles and responsibilities, PROPER Identification of stakeholders, GOOD Distribution of information 5- VERY GOOD Communication plan, PROPER Clear roles and responsibilities, PROPER Identification of stakeholders, VERY GOOD Distribution of information	
	2.12.3	Communication Devices	Real number (no. communication devices divided by no. of crews)	Superintendent	Once, Project Start			
2.13 Project Human Resources Management	2.13.1	Project Interface Development	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Development of site interfaces between project manager, superintendent and foreman with clear project roles, Established reporting system	1- Interfaces between project team INADEQUATELY developed, NO Clearly established reporting system 2- Interfaces between project team INADEQUATELY developed, POORLY established reporting system 3- Interfaces between project team ADEQUATELY developed, FAIRLY established reporting system 4- Interfaces between project team ADEQUATELY developed, WELL Established reporting system 5- Interfaces between project team ADEQUATELY developed, VERY WELL Established reporting system	
	2.13.3	Project Team Development				Team building activities, Reward and recognition systems, Trainings		
	2.13.3.2	Reward and Recognition System	Integer number (no. recognition and reward occurrences per year)	Superintendent	Once, Project Start			
	2.13.3.3	Work Culture	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Fragmentation, Antagonism, Mistrust, Poor communication, Short-term mentality, Blame, Casual approach to recruitment[12]	1- VERY HIGH Fragmentation, Antagonism, Mistrust, POOR communication, COMMON Short-term mentality, VERY FREQUENT Blames, VERY COMMON Approach to recruitment 2- HIGH Fragmentation, Antagonism, Mistrust, POOR communication, COMMON Short-term mentality, FREQUENT Blames, COMMON Approach to recruitment 3- NORMAL Fragmentation, Antagonism, Mistrust, FAIR communication, COMMON Short-term mentality, INFREQUENT Blames, UNCOMMON Approach to recruitment 4- LOW Fragmentation, Antagonism, Mistrust, GOOD communication, UNCOMMON Short-term mentality, RARE Blames, UNCOMMON Approach to recruitment 5- VERY LOW Fragmentation, Antagonism, Mistrust, VERY GOOD communication, UNCOMMON Short-term mentality, VERY RARE Blames, VERY UNCOMMON Approach to recruitment	
	2.13.4	Project Team Closeout				Use of personal exit interviews, Layoff practices, Development of personnel records		
	2.13.4.1	Use of Personal Exit Interviews	1 - 3 Predetermined rating	Superintendent	Once, Project Start		1- Exit interview NOT conducted 2- Exit interview SOMEWHAT conducted 3- Exit interview PROPERLY conducted	
	2.13.4.3	Personnel Record Development	Categorical	Superintendent	Once, Project Start	Yes, No		
ent	2.14.1	Environmental Rating of Project	Categorical	Project Manager	Once, Project Start	LEED (Certified, Silver, Gold, Platinum), BREEAM, BOMA BESt		

One-Off Field Factor Form

Project Code: | **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.14 Project Environmental Manageme	2.14.2	Project Environmental Planning	1 - 5 Predetermined rating	Project Manager	Once, Project Start	Understanding of contract environmental provisions (conditions stated in permit applications, project scope statement, and project execution characteristics), Site and neighborhood condition analysis, Development of Environmental management plan, impact analyses, and mitigation strategies, Use of environmental checklists	1- VERY POOR Understanding of contract provisions, VERY POOR Site and neighborhood condition analysis, INADEQUATE Environmental management plan, VERY POOR Use of checklists 2- POOR Understanding of contract provisions, POOR Site and neighborhood condition analysis, INADEQUATE Environmental management plan, POOR Use of checklists 3- FAIR Understanding of contract provisions, FAIR Site and neighborhood condition analysis, INADEQUATE Environmental management plan, FAIR Use of checklists 4- GOOD Understanding of contract provisions, GOOD Site and neighborhood condition analysis, ADEQUATE Environmental management plan, GOOD Use of checklists; 5- VERY GOOD Understanding of contract provisions, VERY GOOD Site and neighborhood condition analysis, ADEQUATE Environmental management plan, VERY GOOD Use of checklists	
2.15 Project Claim Managem	2.15.3	Project Claim Resolution				Resolution method, Resolution Process Time		
	2.15.3.2	Resolution process	Real number (average time taken to resolve claim, month)	Project Manager	Once, Project Start			
6. Miscellaneous Factors	2.16.1	Job Security	Real number (Yearly average length of unemployment, month)	Superintendent	Once, Project Start			
	2.16.3	Contractor Financial Status	1-5 Predetermined rating	Project Manager	Once, Project Start		1- Project contractor has VERY POOR Financial conditions 2- Project contractor has POOR Financial conditions 3- Project contractor has FAIR Financial conditions 4- Project contractor has VERY POOR Financial conditions 5- Project contractor has VERY GOOD Financial conditions	
	2.16.4	Research and Development	Categorical	Project Manager	Once, Project Start	Yes, No		
	2.16.5	Coordination between Trades	1-5 Predetermined rating	Project Manager	Once, Project Start	Conflicts between trades, Time loss due to conflicts	1- VERY POOR Coordination, VERY FREQUENT Conflicts between the trades, VERY FREQUENT Time loss due to the conflicts. 2- POOR Coordination, FREQUENT Conflicts between the trades, FREQUENT Time loss due to the conflicts. 3- FAIR Coordination, NOT FREQUENT Conflicts between the trades, NOT FREQUENT Time loss due to the conflicts. 4- GOOD Coordination, RARE Conflicts between the trades, RARE Time loss due to the conflicts. 5- VERY GOOD Coordination, VERY RARE Conflicts between the trades, VERY RARE Time loss due to the conflicts.	
	2.16.8	Superintendent Trainings	Integer number (no. of trainings attended) Real number (total hours of training, hr)	Superintendent	Once, Project Start	Time management, Leadership for Safety Excellence, CSTS, Standard First Aid Certificate, Supervisory Training Program[7]		
	2.16.9	Superintendent Education	Categorical	Superintendent	Once, Project Start	Below Secondary, Secondary School, Technical or Apprentice, College, University		
	2.16.10	Uniformity of Work Rules by Superintendent	1-5 Predetermined rating	Project Manager	Once, Project Start		1- VERY Irregular among crews and HIGHLY Variable in daily work times and work days 2- Irregular among crews and Variable in daily work times and work days 3- Uniform among crews and Variable in daily work times and work days 4- Uniform among crews, Always the same in daily work times and work days 5- VERY Uniform among crews, Always the same in daily work times and work days	
	2.16.11	Project Management Team Experience	Real number (average years of experience, yr)	Project Manager	Once, Project Start			
	2.16.12	Project Manager Trainings	Integer number (no. of trainings attended) Real number (total hours of training, hr)	Project Manager	Once, Project Start			
	2.16.13	Project Manager Education	Categorical	Project Manager	Once, Project Start	Below Secondary, Secondary School, Technical or Apprentice, College, University		

One-Off Field Factor Form

Project Code: | **Date:**

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
2.1	2.16.16	Availability of Labour	1-5 Predetermined rating	Project Manager	Once, Project Start		1- VERY LOW labour availability for the project, VERY LONG Time loss for completion of the project team. 2- LOW labour availability for the project, LONG Time loss for completion of the project team. 3- AVERAGE labour availability for the project, AVERAGE Time loss for completion of the project team. 4- HIGH labour availability for the project, SHORT Time loss for completion of the project team. 5- VERY HIGH labour availability for the project, VERY SHORT Time loss for completion of the project team.	
	2.16.17	Contractor experience	Integer number (no. of years of experience)	Project Manager	Once, Project Start			
	2.16.19	Parking Facilities	Real number (no. of project workers divided by the no. parking spots)	Project Manager	Once, Project Start			
	2.16.20	Project Financial Management (Payments, Salary)						
	2.16.20.1	Project Team Salary				Craftsperson, Journeyman, Foreman, Superintendent, Project manager		
	2.16.20.1.1	Craftsperson Income	Real numbers (average annual salaries or hourly payment, $)	Human Resources	Once, Project Start			
	2.16.20.1.2	Journeyman Income	Real numbers (average annual salaries or hourly payment, $)	Human Resources	Once, Project Start			
	2.16.20.1.3	Foreman Income	Real numbers (average annual salaries or hourly payment, $)	Human Resources	Once, Project Start			
	2.16.20.1.4	Superintendent Income	Real numbers (average annual salaries or hourly payment, $)	Human Resources	Once, Project Start			
	2.16.20.1.5	Project Manager Income	Real numbers (average annual salaries or hourly payment, $)	Human Resources	Once, Project Start			
	2.16.20.2	Project Team Payments	1-5 Predetermined rating	Human Resources	Once, Project Start		1- VERY FREQUENT Delays for payments, VERY LONG Delays for payments. 2- FREQUENT Delays for payments, LONG Delays for payments. 3- NOT FREQUENT Delays for payments, AVERAGE Delays for payments. 4- RARE Delays for payments, SHORT Delays for payments. 5- VERY RARE Delays for payments, VERY SHORT Delays for payments.	
3.1 Organization Properties	3.1.1	Organization's Principal Project Type	Categorical	Project Manager	Once, Project Start	Industrial, Commercial, Infrastructure, Institutional, Other		
	3.1.2	Organization Experience	Integer number (experience in industry, yr)	Project Manager	Once, Project Start			
	3.1.3	Organization Annual Turnover	Real number (annual turnover, $)	Project Manager	Once, Project Start			
	3.1.4	Annual Employee Turnover	Integer number (annual turnover)	Project Manager	Once, Project Start			
	3.1.5	Number of Active Projects	Integer number (no. of active projects)	Project Manager	Once, Project Start			
	3.1.6	Organizational Structure	Categorical	Project Manager	Once, Project Start	Matrix, Project based, Mixed		
	3.1.7	Organization Level of Subcontracting	Percentage (average value of subcontracted work divided by average projects' values of organization, $/$)	Project Manager	Once, Project Start			
	3.1.8	Organization Construction Equipment Fleet	Integer number (no. of equipment) Nominal (equipment type)	Project Manager	Once, Project Start			
	3.1.9	Organization Equipment Maintenance Policy	Categorical	Project Manager	Once, Project Start	Operate to fail, Condition based maintenance, Fixed time-based maintenance[1]		
	3.1.10	Equipment Fleet Inspections and Analysis	Real number (no. of inspections done per year)	Project Manager	Once, Project Start	Equipment fleet analysis (age, cost, reliability)[1]		
	3.1.11	Equipment Operator Trainings	Real number (no. of hours of training per year)	Project Manager	Once, Project Start			

One-Off Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
	3.1.12	Organization Policy for Equipment Ownership	Categorical	Project Manager	Once, Project Start	Own, Lease, Rent	Note: the most frequent category should be selected.	
	3.1.13	Organization Equipment Warranty Policy	Categorical	Project Manager	Once, Project Start	Yes, No	Note: the most frequent category should be selected.	
	3.1.14	Ownership Period and Economic Analysis	Categorical	Project Manager	Once, Project Start	Repair, Replace, Rebuild, Retire (Salvage) [1]	Note: the most frequent category should be selected.	
3.2 Provincial Factors	3.2.1	Provincial Economy	Real number (Provincial GDP, Billion $)	Researcher	Once, Project Start		Note: This factors measures the annual provincial gross domestic product.	
	3.2.2	Number of Provincial Construction Projects	Integer (Number of projects under construction per year)	Researcher	Once, Project Start			
	3.2.3	Provincial Codes and Regulations	1 - 5 Predetermined rating	Researcher	Once, Project Start		1- VERY STRICT regulations 2- STRICT regulations 3- NORMAL regulations 4- FLEXIBLE regulations 5- VERY FLEXIBLE regulations	
	3.2.4	Unemployment Rate of Construction Workers	Percentage (annual unemployment rate)	Researcher	Once, Project Start			
	3.2.5	Labour Strikes	Integer number (no. of annual recorded labour strike in construction workforce)	Researcher	Once, Project Start			
	3.2.6	Available Supervisor Pool in Province	Integer number (no. of qualified supervisors in province, annual)	Researcher	Once, Project Start			
	3.2.7	Tax		Researcher	Once, Project Start			
	3.2.7.1	Income tax	Percentage (average income tax)	Researcher	Once, Project Start			
	3.2.7.2	GST	Percentage (GST)	Researcher	Once, Project Start			
	3.2.8	Construction Material Price Fluctuation	Percentage (Industrial product price index change)	Researcher	Once, Project Start			
	3.2.9	Availability of Labour in Province	Real number (annual unemployment rate of construction labours)	Researcher	Once, Project Start			
	3.2.10	Expenditure Level towards Projects						
	3.2.10.1	Residential	Real number (annual invested amount, Billion $)	Researcher	Once, Project Start			
	3.2.10.2	Non-residential	Real number (annual invested amount, Billion $)	Researcher	Once, Project Start			
	3.2.10.3	Energy	Real number (annual invested amount, Billion $)	Researcher	Once, Project Start			
	3.2.11	Cost of Project (index)	Real number (Average cost of project per index)	Researcher	Once, Project Start		Note: cost of project need to be measure in the appropriate unit for the specific type of the project (i.e., $/m² for residential and commercial buildings, $/ km for road construction projects).	
3.3 National Factors	3.3.1	Political System	1 - 4 Predetermined rating	Researcher	Once, Project Start		1- VERY LOW Stability 2- LOW Stability 3- AVERAGE Stability 4- HIGH Stability 5- VERY HIGH Stability	
	3.3.2	Competing Project Across Nation	Real number (no. of projects in per province)	Researcher	Once, Project Start			
	3.3.3	Availability of labour in Nation	Percentage (annual unemployment rate of construction labours)	Researcher	Once, Project Start			
	3.3.4	Foreign Construction Workers Recruitment	Percentage (total number of foreign construction workers divided by total construction workers)	Researcher	Once, Project Start			
	3.3.5.1	Size of population	Real number (population)	Researcher	Once, Project Start			
	3.3.5.2	Growth of population	Percentage (annual growth rate)	Researcher	Once, Project Start			

One-Off Field Factor Form

Project Code:

Date:

Factor Group	Factor ID	Sub - Factors	Scale of Measure	Data Source	Data Collection Cycle	Sub Factors/Categories	Predetermined Ratings (1 - 5)/ Note	Input Value
	3.3.5.3	Aging of population	Real number (median age of Canada's population)	Researcher	Once, Project Start			
	3.3.6	Interest Rates	Real number (annual interest rate)	Researcher	Once, Project Start		Note: the annual interest rate should be collected from Bank of Canada	
	3.3.7	Inflation Rate	Real number (Change of CPI)	Researcher	Once, Project Start			
	3.3.8	Construction Price Index	Real number (Construction Price Index)	Researcher	Once, Project Start			
3.4 Global Factors	3.4.1	Global Economic Outlook	Percentage (GDP growth)	Researcher	Once, Project Start		Note: Based on the IMF world economy outlook [2]	
	3.4.2.1	Global Energy Demand	Real number (energy demand, quadrillion BTUs)	Researcher	Once, Project Start			
	3.4.2.2	Global Energy Supply	Real number (energy supply, quadrillion BTUs)	Researcher	Once, Project Start			

Daily Productivity Data Form

Project Code:		Data Collector:		Date:	
Task Code:		Location:			

Labour	Foreman	No. of foremen	
		Hourly cost	
	Equipment Operator	No. of operators	
		Hourly cost	
	Labourer	No. of labourers	
		Hourly cost	
	Work Hours		
Equipment	Equipment Code		
	Equipment Ownership		
	Equipment Hourly Cost		
	Operation Hours		
Material	Material Code		
	Matrial Unit Cost		
	Total Material Quantity		
Total Units Completed			