Factors Influencing Multifactor Productivity of Equipment Intensive Activities

Nima Gerami Seresht[1] and Aminah Robinson Fayek[1] (corresponding author)

[1]Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada

Abstract

Purpose: Due to its key role in the successful delivery of construction projects, construction productivity is one of the most researched topics in construction domain. While the majority of previous research is focused on the productivity of labor-intensive activities, there is a lack of research on the productivity of equipment intensive activities. The purpose of this paper is to address this research gap by developing a comprehensive list of factors influencing the productivity of equipment intensive activities and determining the most influential factors through interview surveys.

Design/methodology/approach: A list of 201 factors influencing the productivity of equipment intensive activities was developed through the review of 287 articles, selected from the 10 top-ranked construction journals, by searching for construction productivity in the articles' titles, abstracts, or keywords. Next, the most influential factors were determined by conducting interview surveys with 35 construction experts. To ensure that the interviewees were aware of the research objectives and the distinction between labor and equipment intensive activities, an information session was held prior to conducting the surveys, and the surveys were conducted in interview format to allow for clarification and discussion throughout the process.

Findings: Project management respondents identified foreman , safety , and crew related factors as the categories with the most influence on productivity; tradespeople respondents identified foreman , equipment , and crew related factors as the most influential categories. Fourteen factors were identified, for which there was a significant difference between the perspectives of project management and tradespeople regarding the factors' influence on productivity.

Originality/value: This paper provides a comprehensive list of factors influencing the productivity of equipment-intensive activities. It identifies the most influential factors through an interview survey of 35 construction experts, who are familiar with the challenges of equipment intensive activities based on their experience with such activities in the industrial construction sector of Alberta, Canada. Additionally, the differences between the factors that influence the productivity of labor and equipment intensive activities are discussed by comparing the findings of this paper with previous research focused on labor intensive activities.

Keywords: construction productivity, multifactor productivity, equipment-intensive activities, factors, interview survey

Paper type: Research paper

1. Introduction

Since construction productivity is vital to the successful delivery of construction projects, it has for many years been one of the most researched topics in the construction management domain. In previous studies, construction productivity was defined according to two different perspectives: the construction management perspective, which defines construction productivity at the micro level (i.e., activity-level productivity and project-level productivity), and the economic perspective, which defines construction productivity at the macro level (e.g., industry-level productivity or national-level productivity; see, for example, Eastman and Sacks, 2008). There are several studies in the literature on both the identification of key factors influencing construction productivity and on the development of predictive models for construction productivity. In previous research, construction productivity was studied at different levels (i.e., activity , project , national-, and industry level productivity) using different measures of productivity. Talhouni (1990) introduced three measures of construction productivity. The first measure is single-factor productivity (SFP), which measures construction productivity using only one input resource—labor—and which is also known as construction labor productivity (CLP). SFP is calculated using Equation 1 (Thomas et al., 1990).

$$SFP = \frac{O}{LI} \qquad (1)$$

where *O* stands for the output of the activity, which is measured using the appropriate unit, depending on the activity type (e.g., m3 for an excavation activity); *LI* stands for labor input, which is measured in either dollars (i.e., the cost of labor) or person-hours.

The second productivity measure is multifactor productivity (MFP), which measures construction productivity using any combination of three resource inputs (i.e., labor, equipment, and material). Equation 2 presents the formulation of MFP using all the three input resources (Naoum, 2016).

$$MFP = \frac{O}{LI+EqI+MI} \qquad (2)$$

where *O* stands for the output of the activity or project, which is measured using the appropriate unit depending on the activity or project type (e.g., m^3 of earth excavated for an excavation activity; or m of pipe installed for a pipe installation project). *LI*, *EqI*, and *MI* stand for labor input, equipment input, and material input respectively, which are all measured in dollars (i.e., the cost of input resources).

The third productivity measure is total factor productivity (TFP), which measures construction productivity using five resource inputs (i.e., labor, equipment, material, capital, and energy). Equation 3 presents the formulation of TFP (Eastman and Sacks, 2008).

$$TFP = \frac{O}{LI+EqI+MI+CI+EnI} \qquad (3)$$

where *O* stands for the output of the construction industry at either the national- or economic-level, which is measured in dollars. Since TFP is commonly measured at the national or economic level, the industry output can be the determined by different economic indicators such as domestic gross product (GDP) produced by the construction industry. *LI*, *EqI*, *MI*, *CI*, and *EnI* stand for *labor*, *equipment*, *material*, *capital*, and *energy input*, respectively, which are all measured in dollars (i.e., the cost of input resources).

National level and industry level construction productivity are often studied from the economic perspective using the TFP measure; from the construction management perspective, construction productivity is often studied at the activity or project level using the SFP or MFP measure. Since construction is a labor-intensive industry (Jarkas, 2010), previous research on activity-level productivity mainly focused on CLP. Therefore, the research either identified key factors that influence CLP (Tsehayae and Fayek, 2014) or developed predictive models for CLP (e.g., Heravi and Eslamdoost, 2015). Although these studies successfully addressed concerns regarding the productivity of some construction activities for which labor is the driver of productivity—known as labor intensive activities—the findings from these studies are not applicable to all types of construction activities. According to Ok and Sinha (2006), due to advances in construction equipment technology over the past few decades, there are some construction activities for which equipment, rather than labor, is the driver of productivity. These activities are called equipment-intensive activities. There are numerous equipment-intensive activities in different types of construction projects, including earthmoving (Ok and Sinha, 2006; Jabri and Zayed, 2017), pavement construction (Choi and Ryu, 2015), pile construction (Zayed and Halpin, 2005), and tunneling (Shaheen et al., 2009). CLP as a productivity measure does not provide any information about the resource input that drives the productivity of equipment intensive activities (equipment), and it is therefore not an appropriate productivity measure for these activities. In previous research, the efficiency of equipment intensive activities was commonly determined by either the production rate, measured as output per unit time (Jabri and Zayed, 2017), or MFP, measured as output per unit cost of the resource inputs (i.e., labor, equipment, and material) (Gerami Seresht and Fayek, 2018). The factors that influence the productivity of equipment intensive activities and labor intensive activities are different since (1) the resources that drive the productivity of these two types of construction activities are different and (2) the appropriate productivity measures for these two types of construction activities are different. Although there are several studies on the identification of factors influencing the productivity of labor-intensive activities, there is a lack of research on the identification of factors that influence the MFP of equipment-intensive activities, which is addressed in this paper. This paper presents a comprehensive list of the factors that influence the MFP of equipment intensive activities, which is measured as output per unit cost of the resource inputs, as presented in Equation 2.

In order to assess the most influential factors affecting the MFP of equipment intensive activities, an interview survey was developed to acquire expert knowledge from two perspectives, that of project management and that of tradespeople. The interview survey was designed to identify the key 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 respondent believes a given factor affects the productivity of the current project), as proposed by Tsehayae and Fayek (2014). The perspectives of project management and tradespeople regarding the most influential factors are then compared using the analysis of variance (ANOVA) F-test, which identifies 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.

The rest of this paper is organized as follows. The second section presents a review of the literature on the identification of the factors that influence construction productivity and provides a comprehensive list of factors that influence the MFP of equipment intensive activities. The third section describes the design of the interview survey and the methodology used for analyzing the interview survey results. Finally, the fourth section presents the findings regarding the factors that have the most influence on the MFP of equipment intensive activities in the industrial construction sector and compares the perspectives of project management and tradespeople on these factors. In the fourth section, the results of the research are compared with previous findings in order to clarify the differences between key factors influencing the productivity of labor and equipment intensive activities.

2. Literature Review

Previous research on construction productivity has focused on either the identification of the factors that influence productivity or the development of predictive models for activity- or project-level productivity. Since construction is a labor-intensive industry (Alaghbari et al. 2019), previous research on the identification of the factors influencing activity-level productivity is often focused on labor-intensive activities, where labor is the main driver of productivity (e.g., Tsehayae and Fayek 2014, Hwang et al. 2016, Naoum 2016, Gurmu and Aibinu 2018, Alaghbari et al. 2019). There is extensive literature on the identification of the factors influencing CLP, a critical review of which can be found in Hasan et al. (2018). Hasan et al. (2018) conducted a systematic literature review of papers published between 1986 and 2016 on the identification of the factors influencing construction productivity; they critically analyzed the construction productivity literature by discussing different characteristics of these studies, such as their countries of origins, the publication year, level of expertise of the survey respondents, and the most common factors between the different studies. Tsehayae and Fayek (2014) identified a total of 141 factors influencing CLP and, using interview surveys, identified the top 10 factors that affect productivity both positively and negatively. Tsehayae and Fayek (2014) conducted interview surveys with project management personnel and tradespeople of commercial building construction projects and compared the perspectives of the two groups of respondents. Naoum (2016) identified 46 factors that affect CLP and conducted interview surveys with 36 management personnel of construction contractor firms to identify the top 30 factors influencing CLP in the UK. Gurmu and Aibinu (2018) identified the managerial practices influencing CLP in multi storey buildings and ranked these practices based on the results of interview surveys conducted with 58 construction experts from contractor firms in Australia. Alaghbari et al. (2019) identified 52 factors that affect CLP in the Yemen construction industry and ranked these factors based on the results of a survey conducted with field and consulting engineers active in Yemen construction industry.

According to Tsehayae and Fayek (2016) and Hasan et al. (2018), the factors that influence construction productivity and the results of surveys that determine the rankings of such factors is dependent to the context of the study (e.g., country of origin, project size, activity type). While the majority of research conducted on the identification of the factors influencing construction productivity is focused on the productivity of labor intensive activities, construction equipment is an important resource that drives the productivity of numerous equipment-intensive construction activities. There are only a few studies that have focused specifically on the identification of the factors influencing the productivity of equipment intensive activities. Kannan (2011) identified 25 organizational-level factors influencing the production rate and total cost of earthmoving operations. Goodrum et al. (2011) identified 12 activity-level and organizational-level factors that influence the productivity of equipment intensive construction activities. Choi and Ryu (2015) identified nine activity-level factors influencing the productivity of highway pavement operations. Ghoddousi et al. (2015) identified 32 project-level factors that affect the productivity of road construction projects in Iran; they ranked these factors based on the results of an interview survey conducted with 60 chief executive officers of road construction companies. Based on the analysis of previous research, there is a gap in the literature on an extensive review of the studies that investigate the productivity of equipment intensive activities and the development of a comprehensive set of factors that influence the productivity of such activities, both of which are addressed in this paper. Additionally, previous studies focused on the two different performance measures of equipment intensive activities, CLP and production rate. In this paper, a comprehensive list of the factors that affect the MFP of equipment intensive activities are identified, including the factors that affect labor, material, and equipment costs and the factors that affect the output of equipment intensive activities.

3. Research Methodology

This section presents the research methodology for identifying the factors influencing productivity and determining the most influential factors using interview surveys. Figure 1 presents the steps in the research methodology.

The research methodology is divided into two major phases, as discussed in this section: first, conducting the literature review for the identification of the factors that influence the productivity of equipment intensive activities; and second, the design and analysis of the interview surveys for determining the most influential factors.

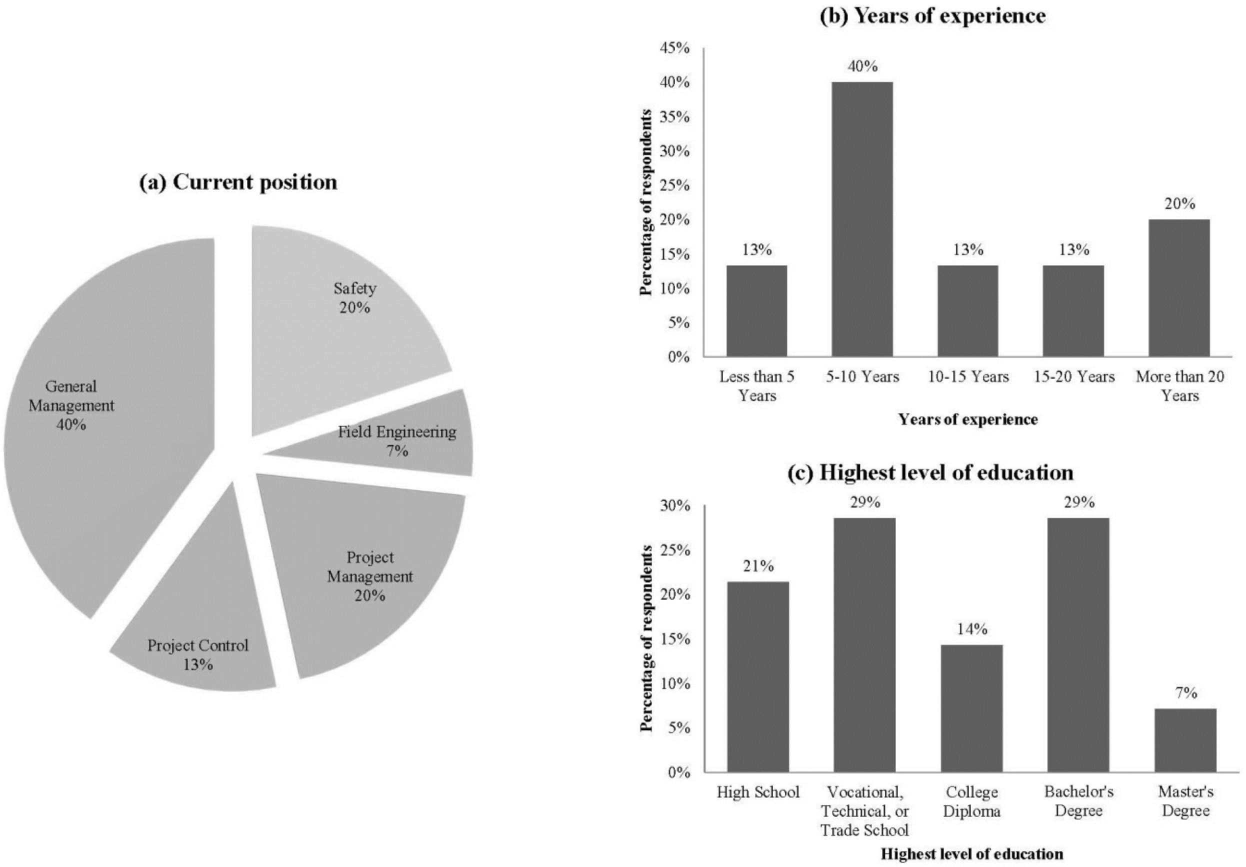


Figure 1. Demographics of project management survey respondents.

3.1 Identification of Factors Influencing the Productivity of Equipment-Intensive Activities

In order to develop a comprehensive list of factors that influence the MFP of equipment intensive activities, relevant studies on construction productivity were reviewed using a literature review methodology that was applied in previous critical reviews (e.g., Tsai and Wen, 2005; Ke et al., 2009; Hong et al., 2011; Yi and Chan, 2013; Naoum, 2016). The scientific search engine, Scopus, was used to search for any articles that included “productivity” in their title and “construction” in their title, abstract, or keywords. Further refinement of the search results was accomplished by limiting those results to articles published in the 10 top-ranked construction journals, as listed by Wing (1997): *Construction Engineering and Management*; *Construction Management and Economics*; *Engineering, Construction and Architectural Management*; the *Journal of Management in Engineering*; the *International Journal of Project Management*; *Automation in Construction*; *Proceedings of the Institution of Civil Engineers*; the

International Journal of Construction Information Technology; *Transactions of the American Association of Cost Engineers*; and the *Journal of Construction Procurement*. Additionally, based on the search results, the two other journals that had the highest number of publications on this topic, the *Canadian Journal of Civil Engineering* and the *International Journal of Productivity and Performance Management*, were added to the list. In the end, 287 articles were reviewed to identify the factors that influence the MFP of equipment-intensive activities.

Construction productivity tends to be considered a micro-level issue, wherein 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 MFP of equipment-intensive activities includes both micro-level and macro-level factors. Since the MFP of equipment intensive activities is determined by dividing the output of these activities by the sum of the costs of three input resources (labor, equipment, and material), all factors that may affect the output of these activities and/or the input resources are considered as influential factors in this paper. Accordingly, in addition to studies that investigate the efficiency measures (i.e., production rate or productivity) of equipment intensive activities, studies that explore the productivity of labor intensive activities were also reviewed to identify the factors that influence the cost of labor in construction activities. Of the 287 articles selected for detailed review, 37 articles were selected, from which the factors influencing the MFP of equipment intensive activities are identified. All the selected articles provided a list of the factors that influence productivity and a clear description of the context variables of the study (i.e., country of origin, construction sector, the level of productivity studied, and the measure of productivity studied); these studies also validated the list of influencing factors using questionnaire or interview surveys. Table

1 lists the 37 articles used in this study to identify the factors that influence the MFP of equipment intensive activities; it also describes the context of each study and the number of factors identified.

Table 1. Articles used to identify factors influencing MFP of equipment-intensive activities.

#	Authors	Country of Origin	Activity/ Project/ Sector	Number of Factors	Productivity Level	Efficiency Measure
1	Herbsman and Ellis (1990)	USA	Various activities	16	Activity-level	CLP*
2	Smith and Hanna (1993)	Canada	Concrete formwork	14	Activity-level	CLP
3	Hanna and Heale (1994)	Canada	Various activities	35	Project-level	MFP**
4	Zakeri, Olomolaiye, Holt and Harris (1996)	Iran	Various activities	18	Activity-level	CLP
5	Portas and AbouRizk (1997)	USA	Concrete	34	Activity-level	CLP
6	Kaming, Olomolaiye, Holt and Harris (1997)	Indonesia	Commercial	13	Project-level	CLP
7	Smith (1999)	USA	Earthmoving	16	Activity-level	Production rate
8	Proverbs, Holt and Olomolaiye (1999)	UK/France/ Germany	Concrete placing	9	Activity-level	Production rate
9	Rojas and Aramvareekul (2003)	USA	Mechanical/ electrical	17	Project-level	CLP
10	Rojas and Aramvareekul (2003)	USA	Various activities	16	Activity-level	CLP
11	Goodrum and Haas (2004)	USA	Various activities			CLP
12	Zayed and Halpin (2004)	USA	Pile construction	27	Activity-level	Productivity index
13	Zayed and Halpin (2005).	USA	Pile construction	23	Activity-level	Production rate
14	Choi and Minchin (2006)	USA	Pavement construction	9	Activity-level	CLP
15	Ok and Sinha (2006)	North America	Earthmoving	13	Activity-level	Production rate
16	Ali, Zayed and Hegab (2007)	USA/Canada	Trenchless technology	12	Activity-level	Productivity index
17	Dai *et al.* (2009)	USA	Civil/ mechanical/ piping/ electrical	83	Project-level	CLP
18	Mawdesley and Al-jibouri (2009)	Netherlands	Various activities	24	Project-level	MFP
19	Kannan (2011)	USA	-	25	Activity-level	MFP
20	Rivas *et al.* (2011)	Chile	Mining project	38	Project-level	MFP

#	Authors	Country of Origin	Activity/ Project/ Sector	Number of Factors	Productivity Level	Efficiency Measure
21	Dai and Goodrum (2011)	USA	Civil/ mechanical/ piping/ electrical	83	Project-level	CLP
22	Jarkas and Bitar (2012)	Kuwait	Civil/building sector	45	Project-level	CLP
23	Chanmeka, Thomas, Caldas and Mulva (2012)	Canada	Oil and gas	41	Project-level	CLP
24	Dai and Goodrum (2012)	USA	Various activities	83	Project-level	CLP
25	Mahamid (2013)	Palestine	Building sector	31	Project-level	CLP
26	Jarkas and Rodosavljevic (2013)	Kuwait	Various activities	23	Project-level	CLP
27	El-Gohari and Aziz (2014)	Egypt	-	30	Project-level	CLP
28	Tsehayae and Fayek (2014)	Canada	Concrete/ electrical	141	Activity-level	CLP
29	Ghoddousi, Poorafshar, Chileshe and Hosseini (2015)	Iran	Road construction	32	Activity-level	CLP
30	Heravi and Eslamdoost (2015)	Iran	Power plant construction	49	Activity-level	CLP
31	Hwang, Zhu and Ming (2016)	Singapore	Green building	26	Project-level	TFP***
32	Kisi, Mani, Rojas and Foster (2016)	USA	Electrical	50	Activity-level	CLP
33	Tsehayae and Fayek (2016)	Canada	Building sector	39	Activity-level	CLP
34	Naoum (2016)	UK	Various activities	46	Project-level	CLP
35	Gurmu and Aibinu (2017)	Australia	Multistory building	52	Project-level	CLP
36	El-Gohary Aziz and Abdel-Khalek (2017)	Egypt	Residential/ commercial	30	Project-level	CLP
37	Gurmu and Aibinu (2018)	Australia	Multistory building	47	Project-level	CLP

* CLP: Construction labor productivity
** MFP: Multifactor productivity
*** TFP: Total-factor productivity

Based on the review of the 37 selected articles (Table 1), 201 micro- and macro-level factors influencing the MFP of equipment-intensive activities were identified. The factors presented in Table 2 affect the MFP of equipment intensive activities, which is measured as output per unit cost of resource inputs (refer to Equation 2). The denominator of MFP presented in Equation 2 is equal to the total direct cost of the activity; thus, the factors presented in Table 2 can also be considered the factors that influence the direct cost of equipment intensive activities.

The 201 factors listed in Table 2 that influence the productivity of equipment intensive activities range from micro-level (i.e., crew , activity and project level) to macro level (e.g., provincial , national and global level). These factors are further categorized into 27 categories based on their nature, such as material and consumables or foreman-related factors. Although there are several similarities between the factors that influence the productivity of labor intensive activities and equipment intensive activities, there are 25 factors (shown in italics in Table 2) that are specific to equipment intensive activities. In addition, the majority of factors that are specific to equipment intensive activities are at the crew- or activity-levels. In other words, due to the fact that any given construction project may include both labor and equipment intensive activities, and the majority of the project and macro level factors influencing the productivity of equipment intensive activities are the same as those influencing the productivity of labor intensive activities.

3.2 Interview Survey Design and Analysis

Once a comprehensive list of the factors influencing the MFP of equipment intensive activities had been developed, interview surveys were designed for the identification of the factors with the most influence on productivity. Two different surveys were designed: a project management survey, which includes all micro- and macro-level factors included in Table 2, and a tradespeople survey, which includes all crew- and activity-level factors and some project-level factors (shown in bold in Table 2). 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 were compared. To ensure that the interviewees were aware of the research objectives and the distinction between labor and equipment intensive activities and the different measures of productivity (i.e., CLP and MFP, an information session

Table 2. Micro- and macro-level factors influencing MFP 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, work equipment availability, appropriateness of equipment, equipment production capacity, equipment operator experience, equipment operator education, equipment operator skill level, information feedback provision, equipment specifications** ***Equipment breakdown frequency, equipment breakdown downtime, equipment maintenance frequency, equipment maintenance downtime, equipment delivery to working area, waiting time for equipment, equipment ownership, equipment age, amplification of human energy, equipment level of control, functional range, equipment ergonomic design, moving technology, equipment warranty***
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, dependency on soil conditions, 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 subcontracting (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, personal 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 the nation, availability of labor in the nation, foreign construction worker recruitment, Canadian 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 fluctuations (natural gas price, natural gas fluctuations)

Note 1: Factors that are common to both surveys (project management survey and tradespeople survey) are shown in bold.

Note 2: Factors that are specific to equipment-intensive activities are shown in italics.

was held prior to conducting the surveys, and the surveys were conducted in interview format to allow for clarification and discussion throughout the process.

The first section of each survey was 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 was 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 respondent believes that a given factor affects the productivity of the current project). Table 3 presents two examples of survey questions measuring agreement and impact.

Table 3. Examples of interview survey questions.

Factors	Agreement							Impact						
	Strongly disagree	*Disagree*	*Slightly disagree*	*Neither disagree nor 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
There are frequent unscheduled breaks during work hours	1	2	3	4	5	6	7	1	2	3	4	5	6	7

The surveys were designed to elicit responses using statements that describe either positive or negative factors affecting productivity. In Table 3, the first example describes a positive factor affecting productivity, and the second example describes a negative factor affecting productivity. As proposed by CII (2006) and Dai (2006), a seven-point Likert scale to measure agreement and impact was adopted. 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 nor 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 nor positive”), and three levels of positive impact (i.e., “slightly positive,” “positive,” and “strongly positive”).

In order to identify the most influential factors affecting the MFP of equipment intensive activities, factors were ranked based on their total evaluation scores, which were in turn determined based on their agreement and impact scores using the methodology proposed in previous research (Raoufi and Fayek, 2018; Tsehayae and Fayek, 2014; Dai et al., 2009). This methodology identifies the most influential factors that positively or negatively affect the MFP of equipment intensive activities. All factors were analyzed as follows.

First, the weighted percentage of agreement RA and the weighted percentage of disagreement RD of a given factor were calculated using Equation 4 and Equation 5, respectively.

$$R_A = \frac{(A\times1+B\times2+C\times3)}{(1+2+3)} \times 100, \qquad (4)$$

where A, B, and C are the percentages of respondents rating the agreement score of the factor as 5 (“slightly agree”) to 7 (“strongly agree”).

$$R_D = \frac{(D\times1+E\times2+F\times3)}{(1+2+3)} \times 100, \qquad (5)$$

where D, E, and F are the percentages of respondents rating the agreement score of the factor as 3 (“slightly disagree”) to 1 (“strongly disagree”). Next, the weighted percentage of positive impact IP and the weighted percentage of negative impact I_N for a given factor were calculated using Equation 6 and Equation 7, respectively.

$$I_P = \frac{(X\times1+Y\times2+Z\times3)}{(1+2+3)} \times 100 \qquad (6)$$

where X, Y, and Z are the percentages of respondents rating the impact score of the factor as 5 (“slightly positive”) to 7 (“strongly positive”).

$$I_N = \frac{(U\times1+V\times2+W\times3)}{(1+2+3)} \times 100 \qquad (7)$$

where U, V, and W are the percentages of respondents rating the impact score of the factor as 3 (“slightly negative”) to 1 (“strongly negative”).

Next, the evaluation score for the positive effect of each individual factor on productivity was calculated using Equation 8 for the positive factors (refer to Table 3) and Equation 9 for the negative factors (refer to Table 3).

$$EV_{PE}^{+} = \frac{R_A \times I_P}{2500} \times 100 \qquad (8)$$

$$EV_{PE}^{-} = \frac{R_D \times I_N}{2500} \times 100 \qquad (9)$$

where EV_{PE}^{+} and EV_{PE}^{-} stand for the evaluation score for the positive effect of the positive factors (i.e., caused by the existence of such factors) and negative factors (i.e., caused by the non existence of such factors) respectively. Similarly, the evaluation score for the negative effect of each individual factor on productivity was calculated using Equation 10 for the positive factors (refer to Table 3) and Equation 11 for the negative factors (refer to Table 3).

$$EV_{NE}^{+} = \frac{R_D \times I_P}{2500} \times 100 \qquad (10)$$

$$EV_{NE}^{-} = \frac{R_A \times I_N}{2500} \times 100 \qquad (11)$$

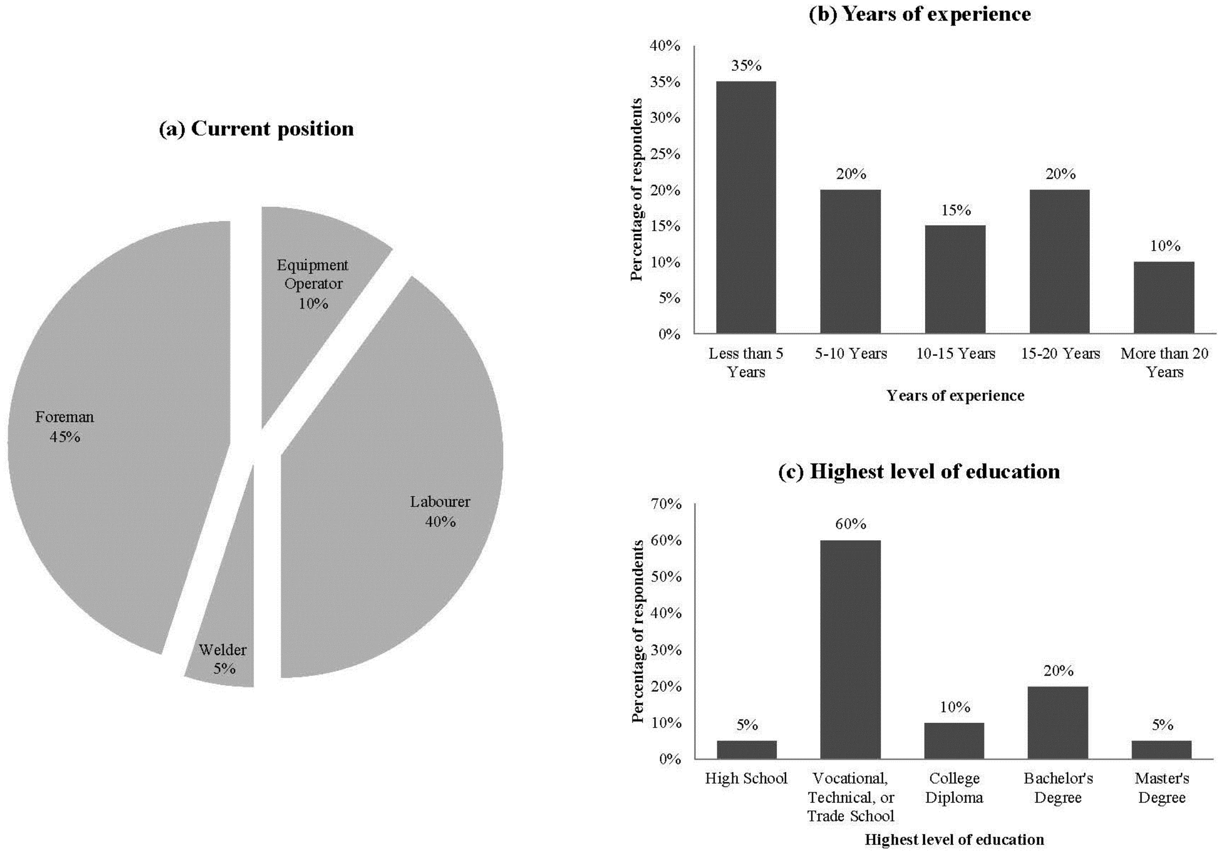
where EV_{NE}^{+} and EV_{NE}^{-} stand for the evaluation score for the negative effect of the positive factors (i.e., caused by the non-existence of such factors) and negative factors (i.e., caused by the existence of such factors) respectively. Finally, in order to identify the most influential factors that positively (or negatively) affect productivity, the factors were ranked based on the evaluation score for positive or negative effect in descending order.

4. Research Findings and Discussion

In order to identify the factors with the most influence on the MFP of equipment intensive activities, 35 construction experts who are active in the industrial construction sector in Alberta, Canada, were interviewed. There were 15 respondents to the project management survey, who were randomly selected from among 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. There were 20 respondents to the tradespeople survey, who were randomly selected from among the following positions: foreman, equipment operator, welder, and laborer.

4.1 Interview Survey Respondents' Demographics

The analysis results for the demographic information of the project management survey respondents are presented in Figure 2. The mode category (40% of respondents) of current position is "general management" (i.e., vice president, general manager, main office project manager, project controller, project coordinator, scheduler, and safety officer). The mode category (40% of respondents) of years of experience in the construction industry is "5–10 years." It should be mentioned that three of the categories in Figure 2(b) ("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%. In terms of the highest level of education, there are two mode categories, "vocational, technical, or trade school diploma" and "bachelor's degree," each including 29% of respondents.


(a) Current position

(b) Years of experience

(c) Highest level of education

Figure 2. Demographics of tradespeople survey respondents.

The analysis results for the demographics of the tradespeople survey respondents are [as follows:] The mode category (45% of respondents) of current position is "foreman." The mode category (35% of respondents) of years of experience in the construction industry is "≤5 years," and the mode category (60% of respondents) of the highest level of education is "vocational, technical, or trade school diploma."

4.2 Factors that Influence the MFP of Equipment-Intensive Activities

The project management survey includes all micro- and macro-level factors, which are ranked using the methodology discussed in the section Interview Survey Design and Analysis. Table 4 presents the top 10 most influential factors that positively or negatively affect the MFP of equipment intensive activities based on project management survey responses.

Table 4. Project management survey: top 10 positive and negative influential factors.

Positive effect			Negative effect		
Factors	EV_{PE}^{*}	Rank	Factors	EV_{NE}^{**}	Rank
Personal protective equipment	100.00	1	Oil price and its fluctuations	100.00	1
Past experience of crew with project configurations	91.67	2	Weather conditions	86.90	2
Equipment operator experience	91.58	3	Global economic outlook	75.86	3
Safety training	89.87	4	Soil conditions	60.98	4
Crew skill level	85.86	5	Natural gas price and its fluctuations	58.62	5
Equipment level of control	81.17	6	Population aging	51.72	6
Equipment operator skill level	81.17	6	Underground facilities	40.83	7
Project quality control	81.17	6	Productivity measurement practices	39.67	8
Daily job hazard assessment	78.27	9	Provincial unemployment rate of construction workers	35.93	9
Crew size	77.78	10	National unemployment rate of construction workers	35.39	10

[*] EV_{PE}: Evaluation score for positive effect (refer to Equation 8 and Equation 9)
[**] EV_{NE}: Evaluation score for negative effect (refer to Equation 10 and Equation 11)

According to the project management survey respondents, the top three most influential factors that positively affect the MFP of equipment-intensive activities are (1) personal protective equipment, (2) past experience of the crew with project configurations, and (3) equipment operator experience. The top three most influential factors that negatively affect the MFP of equipment-intensive activities are (1) oil price and its fluctuations, (2) weather conditions, and (3) global economic outlook. Once the project management survey analysis had been completed, the same analysis was 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 2), which are ranked using the methodology discussed in the section Interview Survey Design and Analysis. Table 5 presents the top 10 most influential factors that positively or negatively affect the MFP of equipment intensive activities based on the tradespeople survey responses.

Table 5. Tradespeople survey: top 10 positive and negative influential factors.

Positive effect			Negative effect		
Factors	EV_{PE}[*]	Rank	Factors	EV_{NE}[**]	Rank
Number of languages spoken in the crew	100.00	1	Crew turnover rate	100.00	1
Equipment operator experience	90.34	2	Safety incidents	68.27	2
Personal protective equipment	90.22	3	Delay in project team payments	56.19	3
Crew motivation	86.54	4	Weather conditions	54.33	4
Foreman leadership and supervisory skills	84.70	5	Rework	51.60	5
Lack of late arrival/early quit	84.21	6	Project staff hiring practices	46.60	6
Crew experience	82.86	7	Total volume of work	32.51	7
Foreman work planning skills	82.69	8	Total daily overtime work	31.29	8
Crew skill level	79.21	9	Project safety administration and reporting	30.19	9
Coordination between labor and equipment operators	79.17	10	Soil conditions	28.95	10

[*] EV_{PE}: Evaluation score for positive effect (refer to Equation 8 and Equation 9)
[**] EV_{NE}: Evaluation score for negative effect (refer to Equation 10 and Equation 11)

According to the tradespeople survey respondents, the top three most influential factors that positively affect the MFP of equipment-intensive activities are (1) number of languages spoken in the crew, (2) equipment operator experience, and (3) personal protective equipment. The top three most influential factors that negatively affect the MFP of equipment-intensive activities are (1) crew turnover rate, (2) safety incidents, and (3) project team payments (i.e., fair assignment of salaries and timely payments). Finally, the 16 categories of factors in the project management survey and the 10 categories of factors in the tradespeople survey were ranked based on their positive effect on productivity, as presented in Table 6. The evaluation score for each category was calculated as the mean value of the evaluation scores for positive effect of all factors in each specific category.

Table 6. Project management and tradespeople surveys: rankings of factor categories.

Project management survey			Tradespeople survey		
Factors	EV_{PE}^*	Rank	Factors	EV_{PE}^*	Rank
Foreman-related factors	100.00	1	Foreman-related factors	100.00	1
Safety	95.16	2	Equipment and tools	76.07	2
Crew-related factors	89.68	3	Crew-related factors	75.44	3
Equipment and tools	84.40	4	Safety	58.47	4
Project management	63.32	5	Material and consumables	54.14	5
Task-related factors	54.84	6	Project management	42.58	6
Project owner-related factors	44.90	7	Task-related factors	35.40	7
Engineering and instructions	40.79	8	Engineering and instructions	34.22	8
Project conditions	32.71	9	Project conditions	19.80	9
Provincial	27.35	10	Location-related factors	15.55	10
Organization-related factors	27.15	11			
Project best practices	19.46	12			
National	16.30	13			
Location-related factors	16.01	14			
Material and consumables	11.73	15			
Global	4.45	16			

* EV_{PE}: Evaluation score for positive effect of factors' categories

According to the project management survey respondents, the top three categories with the highest positive effect on the MFP of equipment intensive activities are (1) foreman-related factors, (2) safety, and (3) crew related factors. According to the tradespeople survey respondents, the top three most influential categories of factors with the highest positive effect on the MFP of equipment-intensive activities are (1) foreman related factors, (2) equipment and tools, and (3) crew related factors. While both groups of the respondents agreed that foreman and crew related factors are among the top three categories of the factors influencing productivity, project management respondents selected safety as the second top category and tradespeople respondents selected equipment and tools as the second top category. Such lack of consensus may stem from the fact that the majority of safety factors are project or organizational level factors (refer to Table 2), and tradespeople on site may not encounter safety challenges at the crew or activity level if the higher level safety practices and safety factors are properly addressed at the project and organizational levels.

4.3 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 influential factors affecting construction productivity. In this paper, those two perspectives on the impact of the factors common to both surveys are compared. There are 84 factors common to both surveys, which are shown in bold in Table 2. The perspectives of project management and tradespeople respondents were compared based on the impact score, but the amount of information available to each respondent group about the existence of each factor in the current project (i.e., the agreement score) is different. Thus, the comparison of evaluation scores (Equation 8 to Equation 11), which were calculated using the agreement and impact 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. A comparison of the two perspectives using only the impact score also allows for a comparison using data collected from multiple projects. In this paper, a comparison of the two perspectives is made 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 employment 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 was 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 was 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 was selected for the F-test, the critical F-value was 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 scores 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 7 shows the factors for which the null hypothesis was rejected and presents the following information for each factor: the variance and mean value of the impact score evaluated by the two surveys and the F value and the critical F value for each factor.

Table 7. Factors with a significant difference between the perspectives 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 to 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 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 was only slightly less than the tradespeople survey, due to the difference between their variances, the null hypothesis of the F-test was rejected for this factor.

4.4 Discussion

In order to validate the findings of this research and distinguish between the factors that have the most influence on the productivity of equipment intensive versus labor intensive activities, the findings of this research were compared to previous research conducted by Tsehayae and Fayek (2014), Dai et al. (2009), and Dai et al. (2007). There are seven factors in common between the factors (refer to Table 4 and Table 5) positively or negatively influencing the MFP of equipment-intensive activities (identified in this research) and the factors positively or negatively influencing the CLP of labor intensive activities (identified by Tsehayae and Fayek, 2014): daily job hazard assessment, project quality control, rework, weather conditions, global economic outlook, oil price fluctuations, and population aging. The majority of the factors influencing the productivity of labor intensive activities are, according to Tsehayae and Fayek (2014), related to crew characteristics or safety, but there are three equipment related factors—equipment operator experience and skill level and equipment level of control—among the top 10 most influential factors affecting the MFP of equipment intensive activities. The majority of the factors that negatively influence the productivity of both labor and equipment intensive activities are macro level factors (i.e., national and global level factors).

Based on a comparison of the findings of this paper with the findings of previous research conducted by Dai et al. (2009) and Dai et al. (2007), the following conclusions can be drawn. From the tradespeople perspective, there are four factors that negatively influence both the MFP of equipment intensive activities (refer to Table 5) and the CLP of labor intensive activities (refer to Dai et al., 2007): delay in project team payments, crew turnover rate, project staff hiring practices, and weather conditions. According to Dai et al. (2009), for labor intensive activities, the most important competency for foremen is establishing effective communication with crew members; however, for equipment intensive activities, the foreman competencies for work planning and coordination between labor and equipment operators are more important than their communication skills. The comparisons of the findings of this paper with previous research shows that (1) there are commonalities between the factors that influence the MFP of equipment intensive activities and those that influence the CLP of labor intensive activities, (2) the "equipment and tools" factor category has a more significant influence on the MFP of equipment intensive activities than it does on the CLP of labor intensive activities, and (3) the most influential foreman competencies that affect the MFP of equipment intensive activities are different from those that influence the CLP of labor intensive activities.

5. Conclusions and Future Research

Although construction productivity is a well-researched topic in the construction management domain because of its impact on project performance, there is still a lack of research on the identification of factors that influence the productivity of equipment-intensive activities. To fill this gap, this paper presents the results of an extensive literature review to identify a comprehensive list of 201 factors that influence the productivity of equipment intensive activities, based on 37 articles selected from the 10 top ranked construction journals.

The findings of this paper reveal that the project management survey respondents selected “personal protective equipment,” “past experience of crew with project configurations,” and “equipment operator experience” as the top three most influential factors that positively affect productivity and “oil price and its fluctuations,” “weather conditions,” and “global economic outlook” as the top three most influential factors that negatively affect productivity. Thus, the findings show that according to the project management survey, the majority of influential factors that negatively affect productivity are macro level factors, which cannot be controlled by the project team. According to the project management survey respondents, the top three most influential categories of factors that affect productivity are (1) foreman related factors, (2) safety, and (3) crew-related factors. On the other hand, the tradespeople survey respondents selected “number of languages spoken in the crew,” “equipment operator experience,” and “personal protective equipment” as the top three most influential factors that positively affect productivity and “crew turnover rate,” “safety incidents,” and “project team payments” as the top three most influential factors that negatively affect productivity. According to the tradespeople survey respondents, the top three most influential categories of factors that affect the MFP of equipment-intensive activities are (1) foreman related factors, (2) equipment and tools, and (3) crew related factors. The project management and tradespeople survey respondents agreed on the fact that “equipment operator experience” and “personal protective equipment” are among the top three most influential factors that positively affect productivity and that “foreman related factors” and “crew related factors” are among the top three most influential categories of factors affecting productivity.

A comparative analysis of the perspectives of the two groups of survey respondents using the ANOVA F-test shows that the perspectives of the two groups are significantly different regarding the impact of 14 factors on productivity. The three factors with the most significant difference between the two perspectives are (1) foreman work planning skills, (2) activity duration prediction accuracy, and (3) total volume of work. The comparison of the findings with previous research on the productivity of labor intensive activities shows that, while the majority of influential factors affecting the productivity of labor intensive activities are related to crew or safety, equipment related factors play an important role in the productivity of equipment intensive activities. While the foreman related factor category is identified as the most influential category by both project management and tradespeople survey respondents, the comparison of the findings of this paper with previous findings shows that the most influential foreman competencies for labor and equipment intensive activities are different. According to the findings of this paper, the most influential foreman competencies for equipment intensive activities are work planning and coordination between labor and the equipment, while for labor intensive activities, the most influential foreman competency is effective communication with crew members.

The contributions of this paper to the existing body of knowledge of construction productivity are as follows. First, a comprehensive list of the factors that influence the productivity of equipment-intensive activities is identified through an extensive literature review. Second, the most influential factors are identified using interview surveys with construction experts, who were selected from the industrial construction sector and who were familiar with the challenges faced in executing equipment intensive activities. While there is an ample research on the identification of the most influential factors on the productivity of labor intensive activities, there are very few studies that focus on the productivity of equipment intensive activities, which is a gap addressed in this paper. The third contribution of this paper is in highlighting the significant differences between the perspectives of project management personnel and tradespeople regarding the factors that influence the productivity of equipment intensive activities. While project management respondents generally have on overall perspective on the challenges encountered in a project during its lifecycle, tradespeople respondents are more familiar with the daily challenges encountered during project execution. Thus, presenting the two perspectives regarding the most influential factors on construction productivity and discussing the significant differences between the two perspectives contributes to the existing body of knowledge on construction productivity. The fourth contribution is in providing a discussion on the differences between labor and equipment intensive activities by comparing the findings of this paper with previous research in order to identify the differences between the factors influencing the productivity of labor and equipment intensive activities. The comprehensive list of factors presented in this paper that influence the productivity of equipment-intensive activities can be used for developing predictive models of productivity for equipment-intensive activities. The findings of this paper regarding the most influential factors affecting the MFP of equipment intensive activities and their comparative analysis can be used by construction practitioners for more effective planning of equipment intensive activities. This study will be extended in the future by identifying a comprehensive list of factors influencing the productivity of labor-intensive activities. By integrating the list of factors influencing the productivity of equipment- and labor-intensive activities and taking into account factors influencing project-level productivity, a multilevel list of factors that influence construction productivity at different levels of detail will be developed. Finally, the multilevel list of factors will be used to develop predictive models of productivity at different levels of detail, including activity- and project-level productivity models.

Acknowledgments

This research is 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. Aminah Robinson Fayek. The authors gratefully acknowledge the support and data provided by industry partners and all personnel who participated in this research study. The authors would like to thank Mr. Ming kit Yau, who diligently helped in the data entry process.

List of Abbreviations

CLP	construction labor productivity
SFP	single factor productivity
MFP	multifactor productivity
TFP	total factor productivity
GDP	gross domestic product
ANOVA	analysis of variance
RFI	request for information

References

Alaghbari, W., Al-Sakkaf, A. A., & Sultan, B. (2019). “Factors affecting construction labour productivity in Yemen”, International Journal of Construction Management, Vol. 19 No. 1, pp. 79-91.

Ali, S., Zayed, T. and Hegab, M. (2007), “Modeling the effect of subjective factors on productivity of trenchless technology application to buried infrastructure systems”, Journal of Construction Engineering and Management, Vol. 133 No. 10, pp. 743-748.

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

Chanmeka, A., Thomas, S.R., Caldas, C.H. and Mulva, S.P. (2012), “Assessing key factors impacting the performance and productivity of oil and gas projects in Alberta”, Canadian Journal of Civil Engineering, Vol. 39 No. 3, pp. 259-270.

Choi, J. and Minchin, R.E. (2006), “Workflow management and productivity control for asphalt pavement operations”, Canadian Journal of Civil Engineering, Vol. 33 No. 8, pp. 1039-1049.

Choi, J. and Ryu, H. (2015), “Statistical analysis of construction productivity for highway pavement operations”, KSCE Journal of Civil Engineering, Vol. 19 No. 5, pp. 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.

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. and Goodrum, P.M. (2011), “Differences in perspectives regarding labor productivity between Spanish-and English-speaking craft workers”, Journal of Construction Engineering and Management, Vol. 137 No. 9, pp. 689-697.

Dai, J. and Goodrum, P.M. (2012), “Generational differences on craft workers’ perceptions of the factors affecting labour productivity”, Canadian Journal of Civil Engineering, Vol. 39 No. 9, pp. 1018-1026.

Dai, J., Goodrum, P.M. and Maloney, W.F. (2007), “Analysis of craft workers’ and foremen’s perceptions of the factors affecting construction labour productivity”, Construction Management and Economics, Vol. 25 No. 11, pp. 1139-1152.

Dai, J., Goodrum, P.M. and Maloney, W.F. (2009), “Construction craft workers’ perceptions of the factors affecting their productivity”, Journal of Construction Engineering and Management, Vol. 135 No. 3, pp. 217-226.

Eastman, C.M. and Sacks, R. (2008), “Relative productivity in the AEC industries in the United States for on-site and off-site activities”, Journal of Construction Engineering and Management, Vol. 134 No. 7, pp. 517-526.

El-Gohary, K.M. and Aziz, R.F. (2014), “Factors influencing construction labor productivity in Egypt”, Journal of Management in Engineering, Vol. 30 No. 1, pp. 1-9.

El-Gohary, K.M., Aziz, R.F. and Abdel-Khalek, H.A. (2017), “Engineering approach using ANN to improve and predict construction labor productivity under different influences”, Journal of Construction Engineering and Management, Vol. 143 No. 8, pp. 04017045.

Gerami Seresht, N. and Fayek, A. Robinson (2018), “Dynamics modeling of multifactor construction productivity for equipment intensive activities”, Journal of Construction Engineering and Management (Accepted manuscript).

Ghoddousi, P., Poorafshar, O., Chileshe, N. and Hosseini, M.R. (2015), “Labour productivity in Iranian construction projects: Perceptions of chief executive officers”, International Journal of Productivity and Performance Management, Vol. 64 No. 6, pp. 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”, Journal of Construction Engineering and Management, Vol. 130 No. 1, pp. 124-133.

Goodrum, P.M., Haas, C.T., Caldas, C., Zhai, D., Yeiser, J. and Homm, D (2011), “Model to predict the impact of a technology on construction productivity”, Journal of Construction Engineering and Management, Vol. 137 No. 9, pp. 678-688.

Gurmu, A.T. and Aibinu, A.A. (2018), “Survey of management practices enhancing labor productivity in multi-storey building construction projects”, International Journal of Productivity and Performance Management, Vol. 67 No. 4, pp. 717-735.

Gurmu, A.T. and Aibinu, A.A. (2017), “Construction equipment management practices for improving labor productivity in multistory building construction projects”, Journal of Construction Engineering and Management, Vol. 143 No. 10, pp. 04017081.

Hanna, A. and Heale, D.G. (1994), “Factors affecting construction productivity: Newfoundland versus rest of Canada”, Canadian Journal of Civil Engineering, Vol. 21 No. 4, pp. 663-673.

Hasan, A., Baroudi, B., Elmualim, A., & Rameezdeen, R. (2018). “Factors affecting construction productivity: a 30 year systematic review”, Engineering, Construction and Architectural Management, Vol. 25 No. 7, pp. 916-937.

Heravi, G. and Eslamdoost, E. (2015), “Applying artificial neural networks for measuring and predicting construction-labor productivity”, Journal of Construction Engineering and Management, Vo. 141 No. 10, p. 04015032.

Herbsman, Z. and Ellis, R. (1990), “Research of factors influencing construction productivity”, Construction Management and Economics, Vol. 8 No. 1, pp. 49-61.

Hong, Y., Chan, D.W., Chan, A.P. and Yeung, J.F. (2011), “Critical analysis of partnering research trend in construction journals”, Journal of Management in Engineering, Vol. 28 No. 2, pp. 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”, Journal of Management in Engineering, Vol. 33 No. 3, pp. 04016052.

Jabri, A. and Zayed, T. (2017), “Agent-based modeling and simulation of earthmoving operations”, Automation in Construction, Vol. 81, pp. 210-223.

Jarkas, A.M. (2010), “Critical investigation into the applicability of the learning curve theory to rebar fixing labor productivity”, Journal of Construction Engineering and Management, Vol. 136 No. 12, pp. 1279-1288.

Jarkas, A.M. and Bitar, C.G. (2012), “Factors affecting construction labor productivity in Kuwait”, Journal of Construction Engineering and Management, Vol. 138 No. 7, pp. 811-820.

Jarkas, A.M. and Radosavljevic, M. (2013), “Motivational factors impacting the productivity of construction master craftsmen in Kuwait”, Journal of Management in Engineering, Vol. 29 No. 4, pp. 446-454.

Kaming, P.F., Olomolaiye, P.O., Holt, G.D. and Harris, F. C. (1997), “Factors influencing craftsmen’s productivity in Indonesia”, International Journal of Project Management, Vol. 15 No. 1, pp. 21-30.

Kannan, G. (2011), “Field studies in construction equipment economics and productivity”, Journal of Construction Engineering and Management, Vol. 137 No. 10, pp. 823-828.

Ke, Y., Wang, S., Chan, A.P. and Cheung, E. (2009), “Research trend of public-private partnership in construction journals”, Journal of Construction Engineering and Management, Vol. 135 No. 10, pp. 1076-1086.

Kisi, K.P., Mani, N., Rojas, E.M. and Foster, E. T. (2016), “Optimal productivity in labor-intensive construction operations: Pilot study”, Journal of Construction Engineering and Management, Vol. 143 No. 3, pp. 04016107.

Knight, K. and Fayek, A. Robinson (2000), “A preliminary study of the factors affecting the cost escalation of construction projects”, Canadian Journal of Civil Engineering, Vol. 27 No. 1, pp. 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.

Mahamid, I. (2013), “Contractors perspective toward factors affecting labor productivity in building construction”, Engineering, Construction and Architectural Management, Vol. 20 No. 5, pp. 446-460.

Mawdesley, M.J., and Al-Jibouri, S. (2009), “Modelling construction project productivity using systems dynamics approach”, International Journal of Productivity and Performance Management, Vol. 59 No. 1, pp. 18-36.

Naoum, S.G. (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, Vol. 65 No. 3, pp. 401-421.

Ok, S.C., and Sinha, S.K. (2006), “Construction equipment productivity estimation using artificial neural network model”, Construction Management and Economics, Vol. 24 No. 10, pp. 1029-1044.

Portas, J., and AbouRizk, S. (1997), “Neural network model for estimating construction productivity”, Journal of Construction Engineering and Management, Vol. 123 No. 4, pp. 399-410.

Proverbs, D., Holt, G. and Olomolaiye, P.O. (1999), “Construction resource/method factors influencing productivity for high rise concrete construction”, Construction Management and Economics, Vol. 17 No. 5, pp. 577-587.

Rivas, R.A., Borcherding, J.D., González, V. and Alarcón, L.F. (2011), “Analysis of factors influencing productivity using craftsmen questionnaires: Case study in a Chilean construction company”, Journal of Construction Engineering and Management, Vol. 137 No. 4, pp. 312-320.

Rojas, E.M. and Aramvareekul, P. (2003), “Labor productivity drivers and opportunities in the construction industry”, Journal of Management in Engineering, Vol. 19 No. 2, pp. 78-82.

Rojas, E.M. and Aramvareekul, P. (2003), “Is construction labor productivity really declining?” Journal of Construction Engineering and Management, Vo. 129 No. 1, pp. 41-46.

Smith, G.R. and Hanna, A.S. (1993), “Factors influencing formwork productivity”, Canadian Journal of Civil Engineering, Vol. 20 No. 1, pp. 144-153.

Smith, S.D. (1999), “Earthmoving productivity estimation using linear regression techniques”, Journal of Construction Engineering and Management, Vol. 125 No. 3, pp. 133-141.

Talhouni, B.T. (1990), “Measurement and analysis of construction labour productivity”, Doctoral dissertation, University of Dundee, UK.

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”, Journal of Construction Engineering and Management, Vol. 116 No. 4, pp. 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”, International Journal of Science Education, Vol. 27 No. 1, pp. 3-14.

Tsehayae, A.A. and Fayek, A. Robinson (2014), “Identification and comparative analysis of key parameters influencing construction labour productivity in building and industrial projects”, Canadian Journal of Civil Engineering, Vol. 41 No. 10, pp. 878-891.

Tsehayae, A.A. and Fayek, A. Robinson (2016), “Developing and optimizing context-specific fuzzy inference system-based construction labor productivity models”, Journal of Construction Engineering and Management, Vol. 142 No. 7, pp. 04016017.

Wing, C.K. (1997), “The ranking of construction management journals”, Construction Management & Economics, Vol. 15 No. 4, pp. 387-398.

Yi, W. and Chan, A.P. (2013), “Critical review of labor productivity research in construction journals”, Journal of Management in Engineering, Vol. 30 No. 2, pp. 214-225.

Zakeri, M., Olomolaiye, P.O., Holt, G.D. and Harris, F.C. (1996), “A survey of constraints on Iranian construction operatives’ productivity”, Construction Management & Economics, Vol. 14 No. 5, pp. 417-426.

Zayed, T.M. and Halpin, D.W. (2004), “Quantitative assessment for piles productivity factors”, Journal of Construction Engineering and Management, Vol. 130 No. 3, pp. 405-414.

Zayed, T.M. and Halpin, D.W. (2005), “Productivity and cost regression models for pile construction”, Journal of Construction Engineering and Management, Vol. 131 No. 7, pp. 779-789.