AN ABSTRACT OF THE THESIS OF

Deepak Kumar for the degree of Master of Science in Civil Engineering Presented on August 12, 2019

Title: Optimization of Construction Equipment Efficiency and Cost using Simulation and Field Data

Abstract approved:

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Ingrid Arocho

Unlike other industries, overall efficiency of construction projects has been growing minimally which directly causes cost overruns of projects. Though reducing idle time and increasing operational efficiency of construction equipment could result in significant cost saving, there is lack of practical knowledge of adjusting operational efficiency and integrating cost and efficiency. Construction equipment being part of most of construction activities play an important role in the success of construction project. This study therefore focuses on increasing efficiency of construction equipment and its effects on cost of equipment. The study also aims to present suggestions to improve efficiency for the activities utilized for this study. The suggestions presented could be generalized for other activities. The methodology of integration of cost and idle time presented in this study aims to relate cost of construction equipment with its efficiency. The results of this study include idle and non-idle time of equipment measured using accelerometer, idle time of equipment

calculated using simulation and effects of wasteful hours on cost of equipment. The simulation was used to see the effects of different equipment fleet on idle time. Excavator I is responsible for contributing the least to the overall operation among all the equipment involved in this study. This is because, it was idle for more than 6 hours and, therefore wastes its operating and owning cost while its engagement in the activity. The results of the study present the following findings 1) Contractors should focus on allocating optimal number of equipment to reduce idle time 2) Proper planning of all resources including equipment operator is also required to increase efficiency of equipment. 3) Two Trucks should be used for the activity under study instead of one Truck to reduce overall necessary idle time of equipment and cost of all equipment involved in the activity. This could be achieved by running simulation of activity with different number of equipment and compare waiting time.

Optimization of Construction Equipment Efficiency and Cost Using Simulation and Field Data

by

Deepak Kumar

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented August 12, 2019
Commencement June 2020

Master of Science thesis of Deepak Kumar presented on August 12, 2019

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Deepak Kumar, Author

ACKNOWLEDGEMENTS

The completion this degree is depended on inspiration, hard work and emotional support from numerous people.

First, I would especially like to thank Dr. Ingrid Arocho for being my advisor and providing support and guidance not only in research but in every aspect of the academic life. She has been inspiration to me during these two year. It could not have been possible without her invaluable suggestions regarding conducting research and writing thesis document. Her mentoring has persuaded me to see research from different dimensions and has also brought personal growth to me. I would like to take this opportunity to thank my committee member Dr. John Gambatese for being inspiration and humble and supportive throughout these two years. I would also thank Dr. Michael Scott and Dr. Guillaume Mignot for being my committee member and supportive and encouragement in completing my thesis.

In addition, I am grateful to “Hyland Construction” and its project engineer Drew Ray for providing me opportunity to collect data and sharing data.

I would also like to say that this could not have been possible without constant support of my friends here and back home who have been checking for my continuous progress and health. I would like to specially thank Ashish for being so grateful and helping me in analyzing data for my thesis. Besides, I cannot thank enough Gustavo, Manoj, Hanif and Jonathan for being my family here and helping me in identifying my weaknesses for my acadmic and professional growth.

Finally, all small achievement in my life are because of my parents and family. My family has been pillar to me throughout my life and their principles and values have

given me insight to see the world in different way. My father who has been checking on me DAILY during these two years, is true motivation to me to achieve my goals. He and my Uncle have made me believe in myself and made me reach, where I am today. My mother for showing unconditional love and support and making me believe in myself.

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1.0 INTRODUCTION

The cost of construction projects has always been of interests for contractors. The construction industry is, therefore, constantly looking for the ways to reduce the cost of overall construction phase. The cost of construction project is directly associated with the resources used in the project. There are different resources used in construction project which can be divided into three major categories: labor, materials and equipment.

Construction projects are continuously facing challenges of cost overruns and reduced quality. The cost of construction project is affected by many factors which may include schedule delay, poor cost estimation, low productivity of resources, poor levelling of resources and many others. A major component of many projects is earthmoving activities, which utilize numerous equipment such as bulldozers, scrapers, and excavators (Lewis and Hajji 2013). This equipment comprises a large percentage of cost of construction projects and therefore reducing the cost of equipment will result in lowering overall cost of the project. One of the methods to reduce cost is to increase operational efficiency by reducing idle time of equipment. The study reported here focuses on efficiency of construction equipment and its effects on costs of equipment. The research addresses the importance of optimizing idle time of construction equipment, thereby managing efficiency of equipment. This would help contractors to reduce cost of construction equipment and cost of the projects. This study uses construction project to obtain real-time data regarding idle time and efficiency of construction equipment and utilizes simulation model to obtain efficiency related data of construction equipment. The idle time of construction equipment from real-world and simulation model is compared and analyzed their difference on cost of construction equipment.

The main objectives of this paper are: 1) Measure the efficiency of equipment during construction activities by using accelerometers and videotape data, 2) Develop a simulation model to determine the necessary idle time of the equipment, 3) Determine the effects of wasteful idle hours on cost of construction equipment, and 4) Present suggestion regarding reducing wasteful idle time and necessary idle time of construction equipment. The unique contribution of this paper is to integrate the cost of construction project with efficiency of construction equipment. Previous studies have focused on efficiency of construction equipment for measuring its environmental performance or measuring energy utilization of construction equipment. Construction equipment performance and its selection has also been related to its efficiency but none of those have focused on relating cost of construction equipment with its efficiency.

2.0 LITERATURE REVIEW

The following section explains the detailed literature relevant to efficiency and cost of construction equipment and gives an overview regarding simulation of construction operations.

2.1 Efficiency of Construction Equipment and Optimization

Many authors have called efficiency of construction equipment with different names and defined those in different ways. The operational efficiency is of great importance in analyzing construction equipment operations (Ahn et al 2015). Ahn and Lee (2012) have defined operational efficiency using the following formula:

$$\text{Operating Equipment Efficiency} = \frac{\text{Valueable Operating Time}}{\text{Total Operating Time}}$$

Valuable Operating Time here refers the amount of time when equipment is performing any physical activity e.g. digging, grading etc. Total Operating Time refers the amount of time the equipment is involved in any operation (Ahn & Lee, 2012). Ren et al (2017) defined efficiency of construction equipment in terms of utilization rate. Utilization rate is measured based on availability of equipment on site and its contribution to total production (Ren et al, 2017). The operational efficiency of equipment refers to the ratio of productive working hours to total operating time. It is generally used to calculate nonproductive equipment time including operator's need of personal time, operator's communication with other personnel as well as side effects from interacting with other crew members and equipment such as off-road trucks waiting in queues to be loaded by excavator (Ahn et al 2015).

Several emerging technologies allow measurement of operational efficiency by actions of equipment and automated tracking of construction operation. Global Positioning System (GPS) has been utilized for automated tracking of equipment but GPS based approaches are limited in providing information regarding stationary operation of construction equipment (Ahn et al, 2013). Azar and McCabe (2012), Heydarian et al. (2012), Gong and Caldas (2009) and Zou and Kim (2007) have emphasized on vision-based and location tracking-based monitoring of operational efficiency of equipment but it only provides limited information. This technique also cannot provide high level of accuracy in the presence of high level of noise due to uncontrolled environment of construction (Ahn et al. 2013). However, using accelerometer has been proven a promising approach for measuring operational efficiency of construction equipment (Ahn et al. 2013).

Measurement of construction equipment efficiency requires activity recognition of construction equipment by characterizing idle mode of equipment from other modes (engine off and working). The current technologies do not have sufficient accuracy in characterizing modes of operation of construction equipment. The accelerometer in this context has shown 93% accuracy in recognizing modes of operation into idle and non-idle mode using supervised classifiers. Supervised classifiers are used to characterize data from accelerometer mounted on equipment into different states (idle and non-idle). Some of those classifiers have less than 2% error in measuring operational efficiency of equipment (Ahn at al. 2013).

Practitioners take many factors into account while calculating cost and efficiency of construction equipment. One of the most common is taking 75% (45 min/h) and 83%

(50 min /h) of operational efficiency into account mainly for operator's breaks during which equipment in turned off (Ahn et al 2015). The visual monitoring of the equipment utilization by video tapping the activity concluded that accurate monitoring and data collection are important because they do not only support management but also are integral to cost control of a project (Ren et al 2017). The proposed methodology by Ren et al (2017) for monitoring the utilization rate of construction equipment consists of 1) equipment detection 2) equipment tracking 3) work zone classification and 4) equipment utilization analysis. This method can be important for contractors to generate accurate report regarding utilization rate of construction equipment and so to manage the construction equipment on site (Ren et al, 2017).

Abbasian-Hosseini et al (2016) described the effects of typical restrictions on maximum allowable idle times. Minimizing idle time of construction equipment by creating restrictions causes reduction in efficiency of equipment. The common practice to reduce idle time of truck is to turn off its engine after specified time of non-use while idle in queue. However, the truck in queue with engine shut off will not be able to resume the operation immediately as engine needs to be restarted and need to be warmed. This could also take considerable amount of time and so reducing overall efficiency of equipment involved in any activity-(Abbasian-Hosseini et al. 2016).

Equipment operational strategies, including operational training and idle management system can be used to reduce the idle time of construction equipment. Many operators are instructed to turn off engine when not in use. Besides this, operators must understand the needs of engine warm up and cool down between uses in the operation while considering reduction in idle time of construction equipment (Abbasian-Hosseini et al 2016).

There have also been many studies integrating emissions from construction equipment and its fuel usage with its operational efficiency. Generation of significant air pollution and emission of CO_2 have also been linked with operation efficiency of construction operations (Ahn and Lee, 2012). Ahn and Lee (2013) developed a methodology to assess impact of operational efficiency of construction equipment on the environment. The paper also aimed to investigate the effect of operational decision of equipment on environment (Ahn and Lee, 2012). For that, the paper presents a predictive assessment framework. The framework involves the calculation of emission from construction equipment using operational efficiency, determining different methods to calculate operation efficiency using Discrete Event Simulation and determining emission factors for equipment (Ahn and Lee, 2012). Besides, idle time and efficiency of construction equipment have been related to fuel use and pollutant emission by Lewis et al (2012). The results of the study have shown that as operational efficiency decreased, fuel use and CO_2 emission increased (Lewis et al, 2012).

This study defines efficiency as the ratio of working hours to total hours. Working hours refers to the time that the equipment is performing construction operations. Total number of hours refers to hours of equipment when it is available on construction site while it is engaged in any operation. Total number of hours include working hours, idle hours (engine on but not working) and hours of equipment when engine is off during the cycle.

Optimizing resources leveling has also been associated with increased construction efficiency. The impact of fluctuation of resources has negative impact on construction efficiency and cost of the project. To identify impact of fluctuations of resources on construction efficiency, the paper by EI-Rayes and Jun (2009) uses two different metrics: acceptable fluctuation (gradual increase of resources utilization to satisfy demand) and undesirable fluctuations (temporary decrease in demand of construction resources). A new optimization model is developed by incorporating these metrics to maximize efficiency of resources utilization. The optimization of resources utilization involves three steps: (1) Initialization module to calculate an initial project schedule and number of days of float; (2) Genetic algorithm to identify optimal schedule for maximum utilization of resources; and (3) Levelling of resources and shifting of activities within their available resources (EI-Rayes and Jun, 2009). The optimization of resources can lead to enhanced productivity. Optimization of construction resources can be achieved by incorporating genetic algorithm to simulation model of operations. The paper defines optimization of resource to allocate optimum resources which optimize cost and production (EI-Rayes and Jun, 2009).

2.2 Cost of Construction Equipment

A major concern of stakeholders throughout construction project's planning, design and construction phases is total cost of the project. The total cost of construction project can be broken down to direct and indirect cost. Direct costs are the cost of labor, equipment, material, production and supplies. Indirect costs are one which are not part of end or final product. This may include contractor's overhead, profit and contingency (Holland and Jr, 1999).

The costs associated with equipment can generally be divided into two categories: owning and operating costs. Owning costs include the price for equipment purchased plus insurance, license, title delivery, residual costs and set up fees and taxes. Owning costs also include costs of financing such as interest payment on purchase of equipment. Each of these elements is independent of actual use of machine (Lucko et al 2007).

Operating costs are costs associated with actual use of machine and vary according to hours of utilization of equipment. They consist of fuel, oil and gases, costs of preventive maintenance and repairs including labors and parts, and costs of frequent replacement of parts due to wear and tear. Operating costs also include any labor costs associated with equipment such as wages and benefits of operators (Lucko et al 2007).

Reducing construction activities cost has been related to many aspects of construction by different studies. One of the papers by Chassiakos and Sakellaropoulos (2005) focuses on time-cost optimization for lengthy and high budget projects. The paper utilizes linear programming and time-cost curve to select activity execution alternatives that minimize cost at various project completion deadlines (Chassiakos and Sakellaropoulos, 2005).

The integration of economic analysis of construction equipment into fleet management systems is of great significance as it promises success of a project as well as major improvements in efficiency of equipment. The paper by Jrade and

Markiz (2012) discusses the development of the model that can assist the contractors to choose heavy earthwork equipment with the integration of their cost. The developed model helps optimum equipment fleet to perform earthwork operation based on their economic analysis by providing final cost report including owning and renting costs of equipment (Jrade and Markiz, 2012).

There has been enormous amount of work focusing on cost of construction equipment. Lucko et al (2007) highlights effects of residual costs on owning costs and ultimately on total hourly cost of construction equipment. Residual value is the price which can be achieved by disposing of the construction equipment at end of its life. Residual value has been identified as an important asset while measuring owning and operating costs of construction equipment (Lucko et al, 2007). The study describes importance of residual value of construction equipment while calculating its owning cost (Lucko et al, 2007). The authors for this study performed a statistical analysis for calculating residual value of construction equipment by including the collection of four data categories including auction records, size class parameters, list prices and macroeconomics indicators. The regression model resulting from statistical analysis was implemented to give insight of influence of manufacturer, condition rating, and auction region on residual value of equipment (Luko et al, 2007).

In heavy earthwork construction projects, selection of construction equipment based on their cost plays a primary role in optimizing cost of construction project (Jrade and Markiz, 2012). Jrade and Markiz developed a model that could perform economic analysis of selected equipment performing seven activities (clearing and grubbing, excavating, loading, hauling, backfilling, grading and compacting). The proposed model is developed in Microsoft environment using Visual Basics for Application (VBA) and can be merged with other simulation software (Jrade and Markiz, 2012). The results of the study include the model that could integrate operational analysis of heavy equipment with its corresponding cost. The model is of great significance for contractors while selecting equipment for performing construction activity.

Unlike other papers, one papers by Barati and Shen (2018) specifically focuses on fuel usage for optimizing operating costs of construction equipment and reducing energy usage of the construction industry globally. The study first investigates factors affecting fuel usage and comes up with four factors: acceleration rate, driving speed, equipment weight, and road slope. Field data was collected on seven trucks to determine effects of the four factors on fuel usage of equipment by employing GPS-aided inertial navigation system and Bluefire engine data logger. The results of the study indicated that increasing weight factor of equipment increases speed and fuel usage. The study also concluded that 9% of fuel usage of construction equipment accounts for idling mode of equipment (Barati and Shen, 2018).

The emission of construction equipment can also be related to cost of equipment. Hummer et al (2016) presented a methodology to select construction equipment that can minimize pollutant emission and keeps project on budget. The paper presented an optimization model to select equipment based on minimum cost and pollution. The study found that emission from construction could be affected by changing equipment fleet or construction activities schedule. The model presented in this paper is very useful in selecting construction equipment to minimize one of six pollutants: HC, CO, NO_x, PM, CO_2, SO_2 (Hummer et al, 2016).

The optimization of earthmoving activity of construction project can result in substantial savings. As large scale of earthmoving operations require construction equipment, so the optimizing utilization rate of the equipment would be crucial task for project management team in saving cost of project (Moselhi and Alshibani, 2009). Moselhi and Alshibani (2009) created a model by utilizing genetic algorithm, linear programming and GIS maps to optimize the equipment utilization rate of equipment. The model specifically focuses on optimizing three areas of earthmoving operation: (1) quantity of earth to be moved; (2) type of equipment required to move the earth; and (3) travelled road distance (Moselhi and Alshibani, 2009).

2.3 Simulation of Construction Operations

Simulation is a new area of construction engineering and its implementation in construction industry helps to reduce research efforts. Simulation reduces the effort of researchers of collecting data by offering real environment presented through simulation model. Simulation is defined as the process of designing a model of a system to understand its behavior or to evaluate various strategies for the operation of the system (ElNimr and Mohammed, 2012).

Construction simulation and visualization have enabled us to see the construction virtually in such settings as they would happen in real world (Louis et al, 2014). Simulation involves deciding and selecting how much amount of resources and which elements to be mimicked from real world system under study (Zhang, et al, 2013). Modelling simulation of construction activities provides many pieces of information that could be utilized for improving the operation in real world. The information which is of interest of this paper is average waiting time of equipment. Average waiting is time in each cycle that an equipment requires to be idle in order to wait in queue or wait for other equipment to complete its cycle (Martinez, 2001). Therefore, it is inevitable and necessary idle time of equipment while it is involved in operation. Modelling and then simulation of those construction operations require rich real-life data which is seldom available for construction operations and require enormous time and effort. The study by Louis et al (2014) attempted to provide alternative solution to reduce time and effort of collecting data by using robot simulation. The research methodology involved employing virtual CAD objects (robot simulators) to be programmed to perform construction operations. The robot simulators are directed by agent/applicant using sensors and actuators with due consideration of possible site conditions and environment (Louis et al, 2014).

Construction operations have many interruptions and variations, which cause randomness associated with data. The generation of random numbers is useful in creating possible scenario of operations. In designing the simulation, the input modelling is one of the most important steps to show the random behavior of the system. Input modelling includes probability distribution, which can produce random behavior of the system under study. The gathering and validation of data are therefore important steps in simulation of operations and account for 10% to 40% of the total time of building a simulation model (Al Alawi et al, 2016). Perera and Liyanage (2017) stated that the development of simulation model is delayed or not validated when the right data is not available in the right format and at the right time (Perera and Liyanage, 2017). The simulation inputs for the model incorporated in this study have been based on actual data from real-world construction operation.

Louis and Dunston (2016) have validated the implementation of Discrete Event Simulation (DES) model processing algorithm for modelling and controlling operations performed on construction sites in real time. DES models operation as discrete sequences of event in time. The research combines the analytical power of DES model and real time nature of sensors to provide the operation managers insight into process of construction operation (Louis and Dunston, 2016). The graphical user interface used in developing the software is of great importance to develop the activity cycle diagrams of DES models of construction activity and the interface that communicates current state of simulation, thereby providing the oversight of the operation.

There have been many simulation-based studies focusing on different aspects of construction operations. One of the studies by Zhang (2008) et al focuses on a solution for avoiding time constraints including cyclical break, preemption and over time use using simulation modelling.

One study by Zhang (2013) has focused on calculating emission from construction equipment by using DES as current approaches to estimate emission are unable to model uncertainties or randomness of construction operations. The proposed DES simulation method estimates emission from construction equipment by taking change in equipment load factors into account and can help stakeholders to plan emission reduction policies (Zhang, 2013).

The paper by Lee et al (2010) exhibited the approach of analyzing productivity of construction operations as well as performance of project schedule. The paper does this by incorporating an intergraded simulation system named "construction operation and project scheduling" (COPS), which has been developed in MATLAB. COPS synthesis productivity of construction operations from DES-based simulation operation and schedule performance of construction operation obtained from DES-project scheduling model. Construction operations and project scheduling (COPS) does this by estimating best-fits probability distribution functions of duration of activities and corresponding cost from historical tasks duration. The system then runs the model for suitable number of cycles of simulation, runs CPM for appropriate number of iterations and generate expected cost and project completion date. The method introduced in this article is beneficial in handling the operations consisting of large number of activities (Lee et al, 2010).

The simulation modelling can be an important tool to manage complicated construction project. A paper by Zankoul and Khoury (2017) uses generic discrete event simulation modelling and visualization to design and manage on-shore construction projects efficiently. Typical construction of on-shore projects can be divided into topographical services, earthwork, road construction, electrical works, foundation construction and wind turbines installation. These packages can be categorized depending on their complexity. The sub-activities of these packages have been used to form a simulation model using AnyLogic 7.0. In this research optimization tool, OptQuest has been adapted by AnyLogic 7.0. The model takes different inputs of total cost and duration of each activity into account for all project and other input of model may vary from project to project. These inputs include soil type, efficiency factors and country practices. After that, the model was run and results consisted of a pictorial representation of construction operations in 3D virtual environment, accompanied by time and cost for each package. The simulation model is run with average number of resources and gives required period with those resources. The resources then can be adjusted to minimize cost of the project (Zankoul and Khoury, 2017).

One of the papers by Cheng et al (2012) has emphasized on utilization of simulation model to allocate construction equipment on construction site. The paper presents petri-net model for optimization of allocation of construction equipment on site for construction project with certain period, cost and labor. The petri-net model considers different criteria and preference of decision makers before allocating resources (equipment) when loaded with dynamic constraints of various equipment. Petri-net model was developed by Carl Adam Petri while defending his thesis at Technical University of Darmstadt, Germany in 1962 (Cheng et al, 2012).

One of the studies by Kim and Kim (2010) has utilized agent-based simulation model to develop effects of traffic congestion on work efficiency. The paper defined work efficiency as hauling number per truck per hour. They have analyzed how hauling speed of trucks decreases because of traffic jams and so work efficiency using simulation model of the case study (Kim and Kim, 2010).

There have been many previous studies focusing on optimization of equipment selection in heavy civil work based on a variety of factors but very few of them have included economical operational analysis. There have also been a variety of studies focusing on calculating operational efficiency and operating and owning costs of construction equipment, however none of those has presented the effects of optimization of efficiency of construction equipment on the cost of project.

3.0 METHODOLOGY

Previous studies have focused on various methods of determining operational efficiency of equipment while performing construction activities. Previous studies have also laid their focus on measuring operational efficiency of construction equipment to reduce emission of construction equipment. Most of the studies have opted this by using accelerometer, as it is readily available, is inexpensive and gives reliable results. However, none of the studies has diverted their attention towards integration of cost with operational efficiency of construction activity. Contractors always look for different ways to reduce construction cost; therefore, this paper aims to assess the relationship of operational efficiency of construction equipment with construction cost. For that, this study measures idle time of construction equipment using accelerometer on construction site while equipment is engaged in real-world activity and calculate cost of those hours. The study then develops a simulation model to obtain necessary idle time and so optimized operational efficiency of equipment and calculates cost for those hours. The difference between costs obtained from both real-world data and simulation is presented and suggestions to improve operational efficiency are provided. The following sections present further detailed methodology used for this study

3.1 Data Collection

A construction project was used to collect data regarding efficiency of construction equipment. The construction site utilized for the data collection was a private housing project at Corvallis, Oregon, USA. The construction phase of the project mainly consists of three sections based on their usage: construction of residential building;

construction of parking lot; and construction of storage area. The general contractor involved in the project is Hyland Construction and excavation services for this project are K&E Excavating Inc.

Earthmoving activities were selected for the analysis, as they are equipment abundant activities. The earthmoving activities observed in this study consisted of digging of earth by Excavator I (CAT 316), loading of dirt by Truck (FL70), and dumping at disposal site. The observed activity also involved transportation of dirt by Wheel Loader (CAT 930) near foundation and back filling of foundation by Excavator II (CAT321). The specifications of equipment involved in selected activity are shown in Table 3.1.

Table 3.1: Equipment Specifications

Equipment Type	Manufacturer	Model
Excavator II	Caterpillar	CAT321DL
Excavator I	Caterpillar	CAT 316EL
Truck	Freightliner	FL70 20-23
Wheel loader	Caterpillar	CAT 930K

In the first step of data collection, data regarding two modes of construction equipment is collected which were idling with engine on and non-idling. The time spent by equipment in two different modes was collected using accelerometer and videotaping. As different modes generate different ranges of signal energy, the vibration signal from accelerometer can be used to detect mode of energy and time of equipment in different modes. The underlying idea of vibration signal is that any stationary operating construction equipment will generate distinguishable patterns of acceleration signal compared to idling mode (Ahn et al 2015). The data regarding acceleration using accelerometer was measured for 12 hours. The activity was observed for two consecutive days and observation time of each day consisted of 6 hours. Initial experiments were conducted in order to analyze the patterns of accelerometer data for two modes of equipment and video tapping was used to label the equipment as working or idle.

Next, the accelerometer was employed to collect data regarding acceleration of equipment during their operation on the site. The device used for this study was "SparkFun 9DoF Razor IMU MO" which is three-axis sensors-gyroscope, accelerometer and magnetometer. This study is only interested in acceleration data using accelerometer, therefore, output of device was programmed to discard results other than acceleration. Figure 3.1 and Figure 3.2 show the top and bottom of the board respectively. The Razor IMU is designed to work with either USB power source or battery. The accelerometer used in this activity has frequency of 100. The accelerometer generates acceleration in three axes and 100 acceleration points per second for each axis.

For this study, lithium ion battery was used as accelerometer needed to be mobile while mounted on equipment to collect the data on site. The Razor IMU accelerometer was placed in a magnetic cage to protect it from any damage while it is mounted on equipment and to stick on equipment. Figure 3.3 shows the magnetic cage used to mount the accelerometer on equipment.

The location of accelerometer was chosen carefully as it is a critical factor in getting viable data regarding idle and non-idle acceleration patterns of equipment. This is because, placing accelerometer in driver cabin of excavator may not be able to record data regarding up and down movement of boom while it is stationary and performing any activity. For this study, accelerometer was stuck on boom of Excavators so that it could record acceleration while equipment is moving and is stationary and performing activity with movement of its boom. For Truck, accelerometer was mounted on the bucket so that it could record movement of Truck while it is moving and loading and unloading of dirt to and from the truck. For same purpose as Excavator, accelerometer was mounted on bucket of Wheel Loader.

Data collection also involved videotaping activity to build a simulation model. The activity was videotaped for three hours in order to observe the cycles of each equipment and collect required data to model simulation of the activity. Data gained from videotaping of activity which was used in the simulation is further elaborated in "Developing a Simulation Model" section of the Methodology.

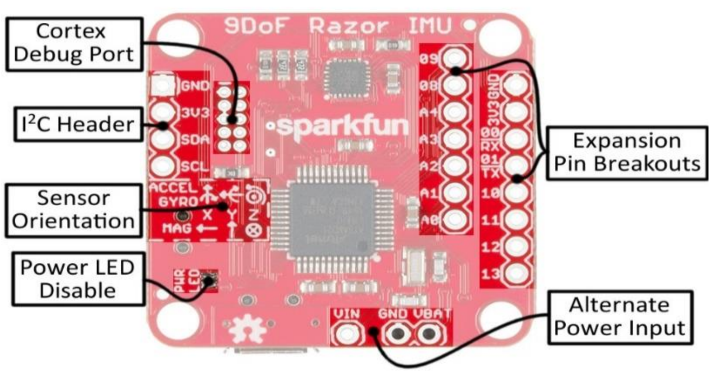

Figure 3.1: Top of the borad (RazorIMU 2019)

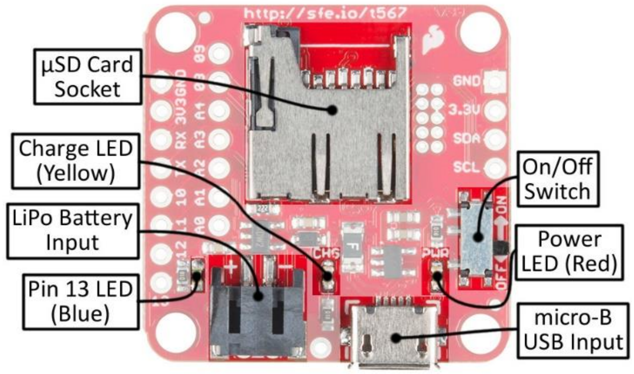

Figure 3.2: Bottom of board (RazorIMU 2019)

Figure 3.3: Magnetic Cage

3.2 Computing Equipment Cost per Hour

Next step to methodology consists of obtaining information and calculating cost of construction equipment utilized in the activity. For this study, hourly cost of each construction equipment was computed and multiplied by the total number of hours for which data was collected.

The cost of construction equipment has been divided into operating and owning cost. Owning costs included (i) purchase price (ii) interest (iii) insurance and (iv) residual costs. Operating costs included (i) fuel consumption (ii) service (iii) tire replacement and (iv) repair costs.

The cost of construction equipment is usually presented in terms of cost per operating hour of equipment (Hummer et al, 2016). For this paper, cost per hour of equipment was calculated based on owning and operating costs per hour.

Owning costs were obtained by subtracting residual cost from sum of purchasing price, insurance and interest on equipment. Owning cost of each equipment can also be referred as cost which contractor needs to recover during whole life cycle of equipment. Owning cost of each equipment was divided by total number of hours of operation over its life span to obtain equipment owning cost per hour. The number of hours of operation were obtained from contractor owning the equipment which are based on previous year (2018) average usage of equipment. Equipment life for this study has been chosen as 8 years.

Some of the elements of owning costs were obtained for actual price of equipment and were obtained from contractor who owns the equipment. These elements include purchasing price, insurance and interest per year however, residual price of equipment was calculated using following formula presented by Lucko et al, 2007:

$$RV = K*PP*\frac{1}{\sqrt{\frac{h}{1000}}} \qquad (1)$$

Where “PP” is purchase price of equipment, “h” is total operational hours of equipment during its whole life, and “K” is adjustment factors. K accounts for wear and tear of equipment due of which the value of equipment decreases with time (Lucko et al, 2007).

K was calculated using deduction factors shown in Table 1. K for this study was obtained by subtracting all suitable deduction factors for each equipment from Table 3.2. The deduction factors used in this study were for strong market and according to specification of equipment. Those factors were selected after conversation with representative from Hyland Construction. Table 3.3 provides residual value and corresponding parameters of equipment obtained by applying Equation (1).

Table 3.2: Deductions for Adjustment Factor K (Lucko et al, 2007)

Item	Condition	Deduction
Equipment type	Few moving parts	0.0
	Many moving parts	0.1
	Vibrates and shakes	0.2
Manufacturer	Industry leader	0.0
	Exotic	0.1
	Standards, multiuse	0.0
Equipment model	Current	0.0
	Exotic, special use	0.1
	Discontinued	0.1
Condition rating	Excellent	0.0
	Good	0.1
	Bad	0.2
Local market	Strong	0.0
	Weak	0.1
	Poor	0.2

Table 3.3. Residual Value Calculations

Equipment	Model	K value	Hours of operation	Residual value ($)
Hydraulic Excavator (II)	CAT 321 DL	0.60	950	151164
Hydraulic Excavator (I)	CAT 316 EL	0.70	1100	97977
Truck	FL70 20-23	0.70	5140	7780
Wheel Loader	CAT 930K	0.60	930	83059

For operating cost of each equipment, repair and maintenance costs were calculated using following formula listed by Lucko et al, (2007):

$$MRP = CCI*PP \qquad (2)$$

Where “MRP” is cumulative cost of repair and maintenance. MRP includes maintenance and replacement costs of all parts including labor so it covers repair, tire replacement and service costs. “CCI” is cumulative cost index and is calculated using the following formula:

$$CCI = \beta_2 \left(\frac{h}{1000}\right)^2 + \beta_1 \left(\frac{h}{1000}\right) + 1 \qquad (3)$$

CCI allows comparing different machine with different conditions (Lucko et al, 2007). “β_1”and “β_2” are repair cost coefficients and h is cumulative hours of use of equipment over its life span. Table 3.4 shows β_1 and β_2 values for equipment used in this study, which depend on size of equipment. MRP costs obtained using Formula (2) are total maintenance and repair costs of equipment over its life span (Lucko et, al2007). MRP for each equipment was divided by total number of hours of operation of equipment over its life span.

Fuel cost of equipment was determined using Caterpillar Performance Handbook 45 (CAT, 2015). CAT Performance Handbook gives estimated average fuel used by equipment in an hour. Due to unavailability of the manual for the Truck utilized in the activity (FL70 20-23), fuel consumption of articulated truck (CAT 735C) mentioned in CAT 45 manual with same capacity as FL70 20-23 was used to calculate fuel consumption per hour. For this study, medium average load factor has been chosen for extracting fuel consumption per hours of equipment.

Table 3.4: Repair Cost Co-efficient for each equipment (Lucko et al, 2007)

Fleet Type	**Size(yd^3)/Capacity(yd^3)**	**β_1**	**β_2**
Hydraulic Excavator II	6	0.00630	0.001893
Hydraulic Excavator I	6	0.00603	0.001893
Truck	28	-0.00246	0.004753
Wheel Loader	22	0.00881	0.002543

3.3 Developing a Simulation Model

The third phase of methodology consists of developing a simulation model of operation under observation using jStrobe to obtain necessary idle time of construction equipment and its effects on cost of equipment.

Besides, simulation was also utilized to study effect of necessary idle time on cost of all equipment. For this, simulation model with two Trucks was developed to lessen cost per hour of Excavator I as Excavator I has more cost per hour comparing to other equipment involved in the activity. By adding two Trucks, necessary idle time of

Excavator I would decrease causing increase in necessary idle time of Trucks. However, Truck would be affected less by increase in necessary idle time as it has less total cost per hour comparing to other equipment.

The software, jStrobe was developed by Joseph Louis for his PhD dissertation at Purdue University while working under the guidance of Dr. Phillip S. Dunston (Louis, 2016). jStrobe is a simulation software which uses network activity diagram to model real-world construction operations. The software utilizes discrete event simulation (DES) to calculate the waiting time of equipment.

Waiting time of equipment represents necessary idle time of equipment which cannot be avoided. DES is very effective for the purpose of building computer models that involve overall logic of work required to complete activity under consideration with various resources. DES allows engineers to generate overall performance of system with interaction of resources an activity (Larson, 2016). The material carrying capacity of each resource is required for discrete event simulation (Martinez, 2010). The simulation model contains various sub-activities that include operation, resources involved in each activity and conditions needed to start the activity. The inputs for the simulation were obtained by videotape of the activity. Video recording was used to obtain duration of each sub-activity involved in the operation. It was also utilized to obtain sequence of sub-activities of the operation. The sequence of activities incorporated into the model is therefore same as the one observed in real world. Table 3.5 shows activities, conditions needed to start those activities and equipment involved in each activity.

Table 3.5: Activity, condition to start activity and equipment required to perform activity

Activity	Condition to start	Equipment
Loading of dirt for excavating	Excavator I is idle. Truck is available. 8.79m^3 soil in stockpile	Truck and Excavator I
Hauling for dumping	Loaded truck ready to haul	Truck
Dumping at disposal site	Loaded truck ready to dump	Truck
Hauling back for filling	Empty truck ready to return	Truck
Loading of dirt for backfilling	Wheel loader is idle 5.0m^3 soil in stockpile	Wheel loader
Hauling for backfilling	Loader wheel loader ready to haul	Wheel loader
Unloading of dirt for back filling	Loaded wheel loader ready to dump	Wheel loader
Hauling back for loading	Unloaded wheel loader ready to return	Wheel loader
Loading and back filling	Excavator II is idle. 0.95m^3 soil is available.	Excavator II
Moving back of boom	Unloaded excavator ready to move	Excavator II

The inputs required by the software include sequence of activities in the operation, distribution of time to complete each cycle in activity, simulation run time, constraints of the proposed operation, and capacity of each resource. The sequence of activities followed by the model is the same as the one observed in real world during earthmoving activity.

Start and end time of each cycle for each equipment were determined by watching videotape. Duration of each equipment to complete its cycle is named as instance of the equipment. Instance is time for each equipment to complete a cycle of sub-activity, it is involved in. Every sub-activity has different instance during each cycle due to constraints and disturbances on construction site.

jStrobe requires duration of each activity in the statistical distribution form. The instances of all the cycle of each equipment of performing sub-activity were therefore, fitted into statistical distributions. Minitab was used to fit the instances into distributions. The p-value shows probability of data to fit into certain distribution. Therefore, for choosing better fit of data into distribution, the distribution with maximum p-value has been chosen. For that statistical hypothesis test was performed. The example of fitting data into certain distribution is shown in Figure 3.4, which depicts result of data analysis of one sub-activity after fitting the data into distribution with maximum p-value. The distribution of duration shown in Figure 3.4 is for sub-activity “Hauling of Truck”. Figure 3.4 shows type of distribution on top and parameters for distribution on the right of figure. Figure 3.4 also shows how good the distribution is fitting instance of each cycle, which is governed by p-value as shown on the right of the figure.

Fitting instances of performing activity by equipment into the correct distribution is crucial for modelling simulation of the activity. The model simulates each cycle according to duration from distribution for each equipment. Distribution of each equipment should, therefore represents actual instance of equipment performing any activity. However, for some of the activities, distribution type with maximum p-value was not available in jStrobe. Therefore, second maximum p-value was chosen according to availability of distribution in jStrobe. After fitting duration into distribution, the parametric duration (mean, average and standard deviation) for every distribution of data have been chosen based on type of distribution. Table 3.6 shows distribution and duration for each sub activity obtained by analyzing instances to complete each cycle using Minitab.

Table 3.6: Duration of each sub-activity

Sub-Activity	Equipment involved	Distribution and Parameters	Duration
Loading of dirt for excavating	Truck and Excavator I	Normal (mean, standard deviation)	Normal (378.5,105.43)
Hauling for dumping	Truck	Normal (mean, standard deviation)	Normal (107.5,13.17)
Dumping at disposal site	Truck	Normal (mean, standard deviation)	Normal (36.5, 10.75)
Haling back for filling	Truck	Exponential (mean)	Exponential (108.75)
Loading of dirt for backfilling	Wheel loader	Exponential (mean)	Exponential (5.58)
Hauling for back filling	Wheel loader	Gamma (shape factor, rate parameter)	Gamma (7.903,1.12)
Unloading of dirt for back filling	Wheel loader	Normal (mean, standard deviation)	Normal (4.47054,1.73)
Hauling back for loading	Wheel loader	Gamma (shape factor, rate parameter)	Gamma (7.91,1.14)
`Loading and Back filling	Excavator II	Normal (mean, standard deviation)	Normal (17.34,11.24)
Moving back of boom	Excavator II	Normal (mean, standard deviation)	Normal (6.90,6.20)

The model was run for 12 hours, the same time for which data was collected. The CAT 45 Manual (CAT, 2015) provided the material carrying capacity of each equipment utilized in the activity.

The model can produce many different outputs but the output which is of interest for this study is necessary waiting time of each equipment. The elements of the model are described below in detail.

Queue: Queue is an element that holds idle resources. The name of the queue is on the center of queue. At the beginning of simulation, queue holds the amount of idle resources that are involved in the activity, which are shown below the name of queue as depicted in Figure 3.5 (a). After starting of simulation, resources present in queue are released to perform succeeding activity.

Combi: Combi represents the activity of the operation. It starts when resources present in preceding queue are enough for the activity to start. The name of combi is shown on its center. The formula below the name of combi is to determine its duration of instance. The depiction of combi is shown by Figure 3.5 (b).

Normal activity: Normal activity is an element of model representing activity which starts when preceding activity ends. The name of activity is shown on its center and the formula below it decides its duration of its instance. Figure 3.5 (c) shows depiction of Normal activity.

Normal and combi both are used for depicting activities in the simulation, but combi activity requires condition to start.

Release link: A release link connects normal activity to another normal activity or combi activity. The information shown on release link is amount of resources released from queue to perform activity, which is shown by Figure 3.5 (d).

Draw link: It connects queue to combi. There are two pieces of information shown on draw link which are separated by comma, which is shown on Figure 3.5 (e). The first number on link shows condition for succeeding activity to start and second number shows amount of resources to be drawn from proceeding queue to succeeding combi.

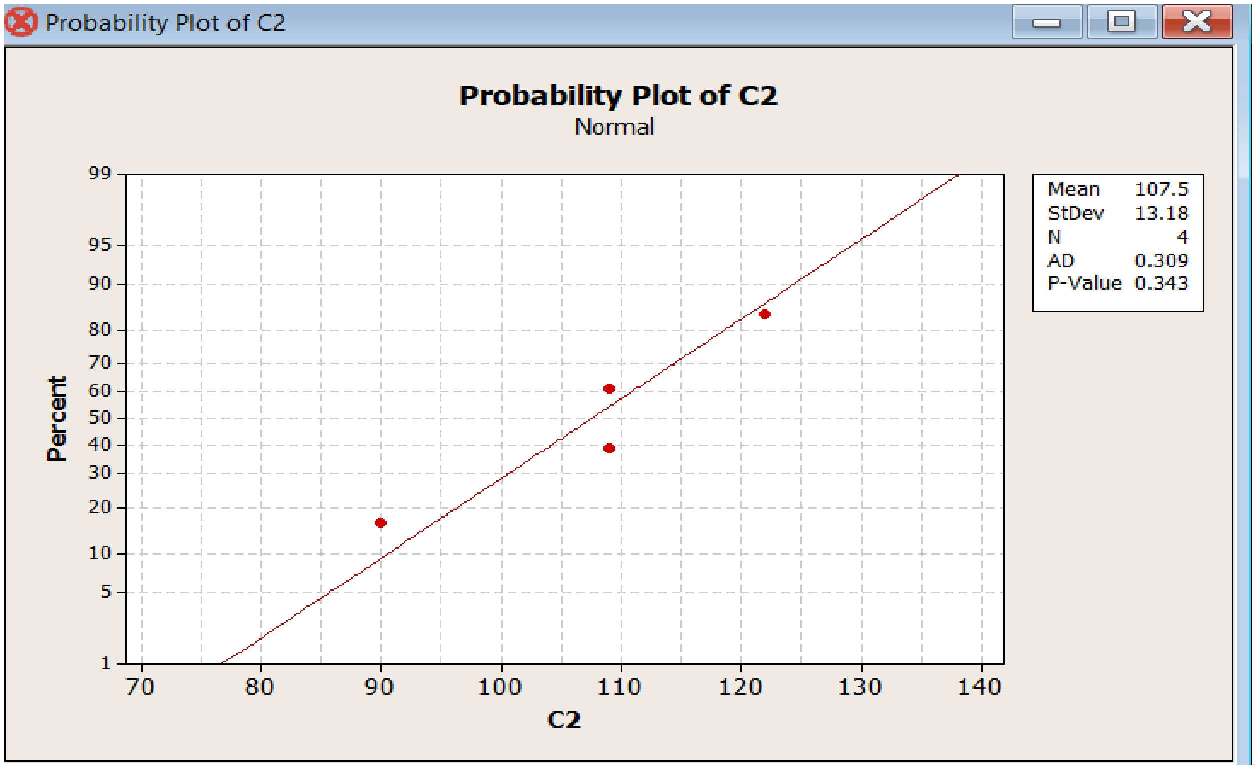

Figure 3.4: Probability Plot of Duration of Hauling of Truck (snapshot from Minitab)

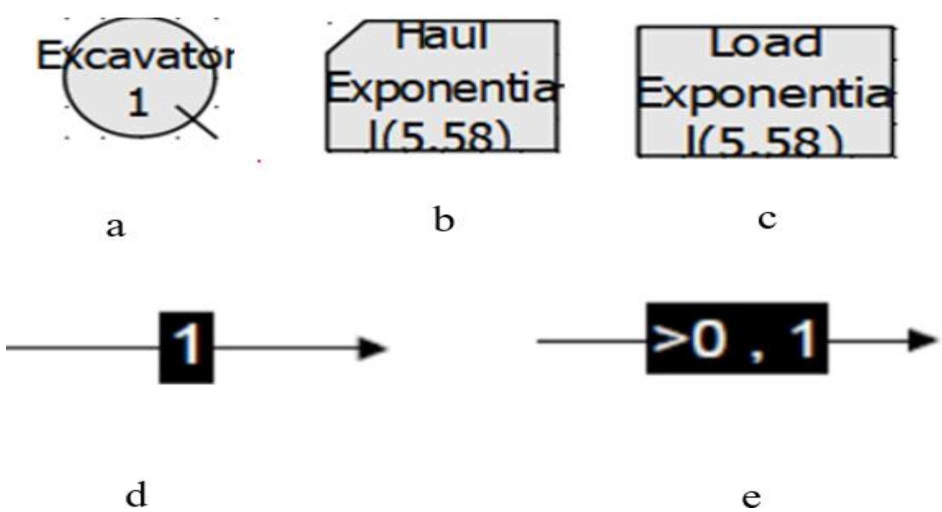

Figure 3.5: Visual representation of jStrobe elements (snapshot from jStrobe)

3.4 Accelerometer Data Processing and Classification

After collecting data of construction equipment acceleration using accelerometer, the raw data was processed and analyzed. In order to achieve the classification of equipment's state into idle and non-idle mode, signal based accelerometer data is processed by labelling the data, selecting and extracting appropriate features, training the classifier model and classifying the data using statistical classifier. Classification of accelerometer data is done by performing the step-by-step procedure shown in Figure 3.6.

3.4.1 Labelling the data

Many researchers have utilized the videotaping of activity to label actual operational modes of construction equipment involved in the operation. Ahn et al (2013) utilized videotaping to classify acceleration signal from equipment and determined idle and non-idle state of construction equipment (Ahn et al, 2013).

The data from accelerometer was labelled as idle or non-idle based on action of the equipment while observing it through videotape. The equipment was determined to be idle if it does not show any physical movement for more than 10 seconds. The timing of the instance of videotape was matched with accelerometer time reading to know the actual state of equipment (idle or non-idle).

The model that classifies data into certain classes requires training and test data to develop and validate the model. The labelled data from videotape was, therefore divided into training and test data. Two third data was used for training the classifier model and one third was used for testing the validity of the classifier model.

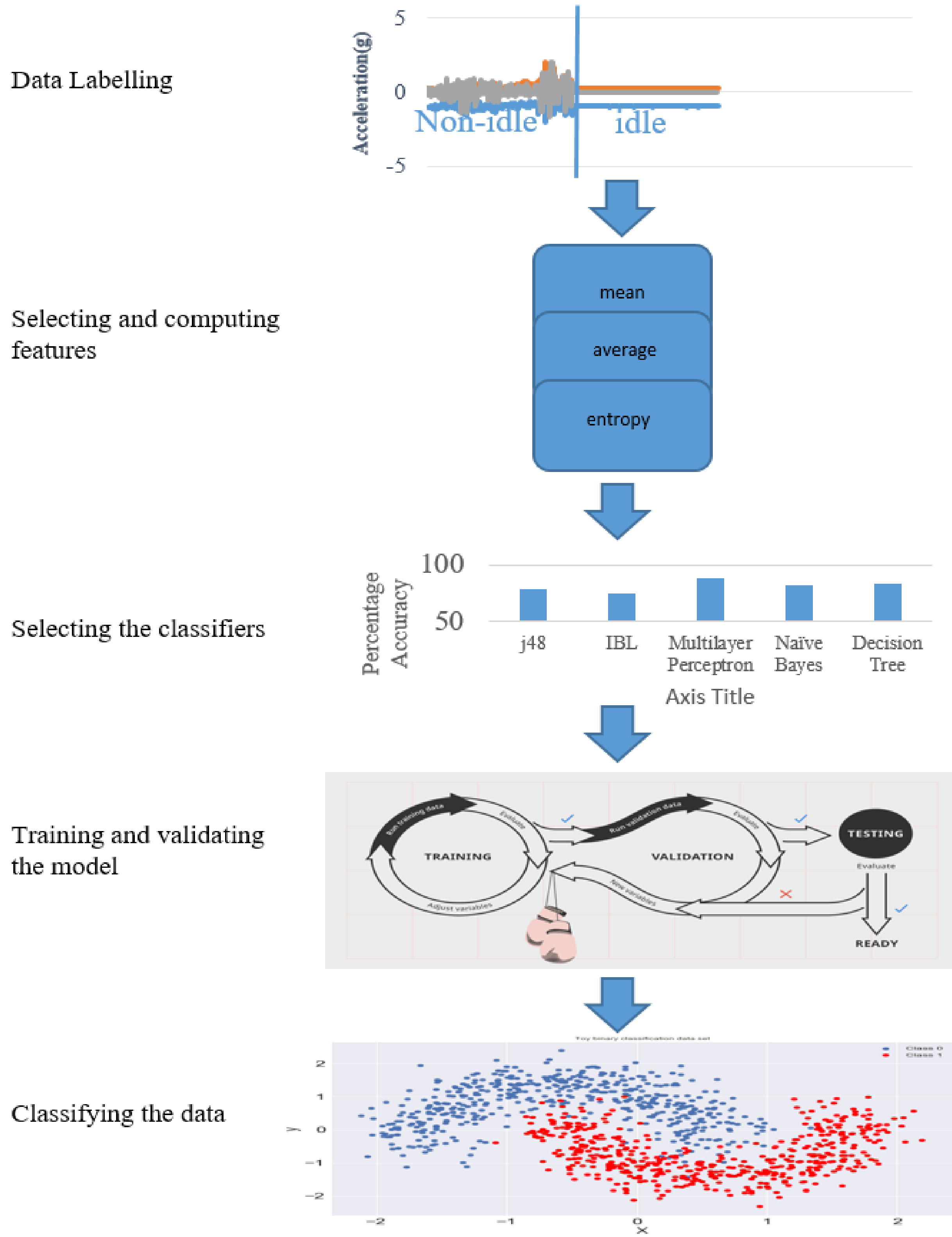

Figure 3.6: Depiction of Analysis of Accelerometer Data

3.4.2 Selecting and computing features

The statistical features representing data were computed for accelerometer data. The set of features of data represents unique patterns of acceleration signals. Therefore, selecting features is one of crucial processes in characterizing states of equipment (Reyu et al, 2018).

In this study, the labelled data and data with unknown states of equipment were divided into equal segments called window size. The windows size should be multiple of frequency of accelerometer so that window size could represent data for certain amount of time. For this study window size of 1,000 data points was selected and each window size represents 10 seconds of data. The previous study by Ahn et al (2013) selected the window size of 128 samples as accelerometer utilized in the study consists of 64 samples per seconds. According to Preece at al. (2009), previous studies have used a range of window sizes from 0.25 to 6.7 times the frequency of signal data (Preece, 2009). However, the window size selected for this study represents data of 10 seconds which means it is 10 times the sample frequency. The reason for selecting larger window size is to reduce the time to analyze the large amount of data.

The features for each segment of accelerometer data were then extracted. Accelerometer generates data with respect to time. The mixed features, time and frequency domain have shown success for classifying signal-based data in previous studies (Reyu et al, 2018). Time-domain and frequency-domain features represent various useful context characterizing information in the selected segment (Preece et al. 2009). Besides, the features to show the relationship between two axis and three axis acceleration have also been extracted to classify the data. Time domain features were computed using raw segmented data; however, frequency domain features like energy and entropy were calculated using frequency domain data. The frequency component of data is obtained using Fast Fourier Transform (FFT) (Preece et al. 2009). For this study, FFT was used to convert time domain signal data into frequency domain data. A total of 7 types of features were computed in this study which include:

1. Mean: The feature is evaluated by averaging all values in segment and dividing it by window size. The mean is calculated for each axis acceleration separately which results in three mean features.
2. Standard deviation: This feature represents deviation of data from its mean. The total of three standard deviation are calculated, one for each axis.
3. Peak: Peak value represents maximum absolute value in each window. This feature is extracted for each axis separately.
4. Correlation: This feature represents dependence for each axis acceleration with other axis. Three features are computed for each window size: correlation between x and y, correlation between y and z, and correlation between x and z. The correlation feature can help classifying activities that involve movement of multiple body parts (Bao and Intille, 2004).
5. Average resultant acceleration: The average resultant acceleration is calculated by averaging the root mean square values for all axes of

acceleration. Root mean square for each axis was calculated by squaring root of the arithmetic mean of square of values in a segment.

6. Energy: This feature represents area under the squared magnitude of signal data. Energy is frequency domain feature and is calculated using frequency component which are obtained by performing FFT of raw data from accelerometer. Energy is calculated for each segment in three axis separately, therefore three energy features are generated. It is a popular features of frequency domain data and shows difference in intensities for different activities (Joshua and Verghese, 2010).
7. Entropy: Entropy is frequency-domain feature (Lang and Stephen, 2004). Entropy is average rate at which information is produced by any signal emitting from device. Entropy for all three axes was calculated separately using segment of 1,000 data points.

For this study, features were extracted using MATLAB by applying iterative and loop command.

3.4.3 Selecting the Classifier

Selecting the classifier model to classify the data is crucial for authentic classification of data. For this study, machine learning (ML) techniques were applied to learn and classify the data into idle and non-idle states by using the features of labelled data. ML is a data analytical tool that learns patters of data directly from known data. Supervised classifier model was used as ML tool to characterize the data into different classes. The supervised classifier infers the function by analyzing labelled data and maps the algorithm. The algorithm then correctly determines classification of unlabeled data. (Ceamanos and Valero, 2016).

There have been various supervised classifiers used by previous researchers to classify data from accelerometer. The most common of those are k nearest neighbors, Naïve Bayes, IBL, Multilayer perceptron, and decision tree. Previous studies have tested the validity of various classifiers by many statistical measures. The paper by Ahn et al. (2013) had obtained the statistical results of different classifier model from 10 runs from 10 folds classification to identify accuracy of each model to classifying accelerometer data (Ahn et al., 2013). These classifier models included IBL, J48, multilayer perceptron, and Naïve Bayes. The statistical results of accuracies of the models showed that IBL, J48, and multilayer perception have accuracy of 93% in classifying data, however Naïve Bayes has accuracy of only 81.75% (Ahn, 2013). The paper aimed to classify the data from accelerometer mounted on excavator to show the feasibility of accelerometer to measure construction efficiency (Ahn et al, 2013). Another paper by Joshua and Varghese performed statistical analysis of different classifier models to come up with right classifier. The study investigated application of activity to automate work-recognizing process in construction. This paper also utilized 10-fold cross validation process to estimate performance of Naïve Bayes, decision tree and multilayer perceptron. The statistical analysis of accuracy of classifiers showed that multilayer perceptron performed better than other classifiers (Joshua and Varghese, 2010). Considering results and suggestions from previous accelerometer-based activity recognition studies, multiple perceptron (MLP) has been chosen for this study to map the classifier model and classify the data from accelerometer into idle and non-idle modes.

MLP is a supervised learning classifier that trains the model based on set of known input-output pairs and learn to model the correlation between those input and outputs. It is feedforward artificial neural network model consisting of an input layer, one or more hidden layers and an output layer as shown in Figure 3.7. Multilayer perceptron consists of many perceptron organized into multiple layers. Perceptron is an algorithm to adjust inputs into function to come up with desired output with minimum error.

MLP for classifying data into idle and non-idle was performed using Google Colaboratory. Google Colaboratory is notebook which is used to execute codes for data analysis and can be accessed through any browser.

3.4.4 Training and Validating the Classifier Model

MLP requires data with known outputs to train and test the model. Training MLP model involves adjusting the parameters or weights of inputs to form function that could map desired outputs with minimum errors. Testing the model helps in increasing accuracy of function for reliable classification of data into states.

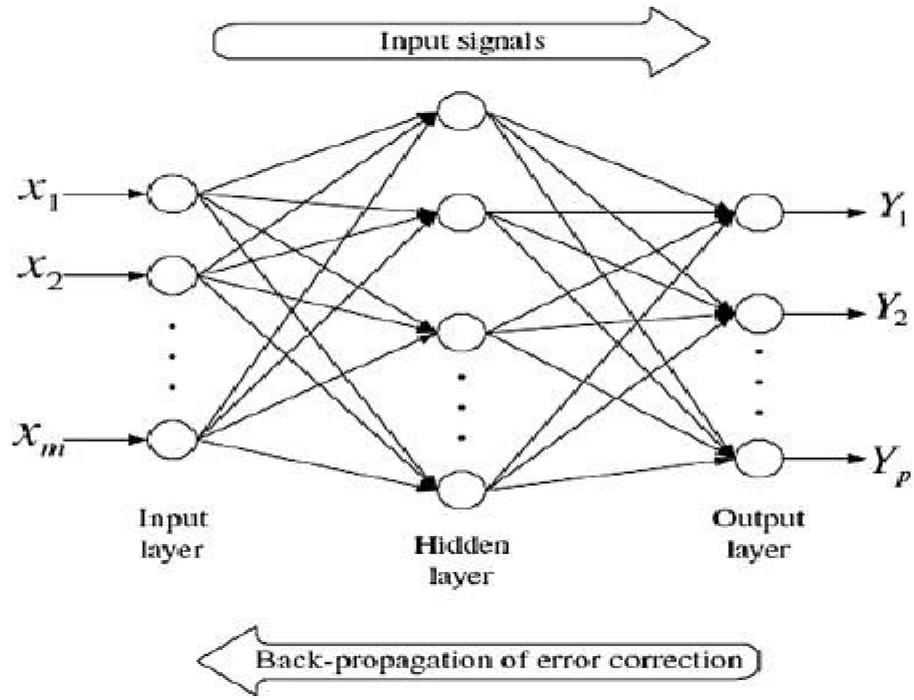

Figure 3.7: Working diagram of multilayer perceptron (Ghafari et al, 2014)

For this study, two third of the labelled data was used to train the classifier model. The features of labelled data were input to the classifier to form the model that could recognize the patterns of accelerometer signals for idle and non-idle states. MLP classifier is a set of connected input/output units and each connection has weight. In this case, each feature of segmented data act as input and corresponding activity classification (idle and non-idle) acts an output. During the training phase, the classifier learns by adding weights to each input feature in a data set to come up with a model that could output the corresponding known activity class.

Validating the classifier model is one of the essential tasks to analyze classifier performance in classifying the acceleration signals. After creating the model using training data, the model was validated using a third of data as testing data. Testing data of acceleration signals with corresponding output (classifications) was fed to the model. The model was then run to output classes (idle or non-idle) of test data and matches with their corresponding labels. After that, the model outputs the quantity of results which match with labels. For validation of the model used in this study, the functions involved in the model was adjusted so that model could output all the results of test data correctly.

3.4.5 Classifying the Data

The statistical features of accelerometer data collected for 12 hours were extracted. The classification of extracted features into state of idle and non-idle was performed using the classifier model.

4.0 RESULTS AND ANALYSES

This section presents the outcomes obtained by applying procedures explained in the methodology. The section also focuses on interpretation of results in verifying conclusions.

This section has been categorized into: (i) Hourly cost of equipment, (ii) Necessary idle time of equipment, (iii) Actual idle hours and (iv) Comparison of cost and efficiency.

4.1 Hourly Cost of Equipment

Hourly cost of equipment is the sum of owning and operating hourly cost of equipment. As mentioned in the Methodology, operating and owning cost of equipment are based on actual data of equipment obtained from contractor and equipment data obtained from equipment manuals. Tables 4.1 and 4.2 show hourly owning and operating cost of equipment and factors involved in their calculations respectively. The costs were obtained by applying calculations and procedures explained in the Methodology section.

Table 4.1: Equipment Owning Costs per Hour

Equipment	Purchase price ($)	Interest per year (%)	Insurance per year ($)	Residual value	Total Owning Cost per hour ($)
Excavator II	245562	5.00	3069.53	151164.78	17.27
Excavator I	146800	5.00	1468.00	97977.82	7.27
Truck	25200	4.50	880.00	7780.67	0.62
Wheel loader	133500	5.00	1668.75	83059.83	9.47

Table 4.2: Operating Costs per Hour

Equipment	β_1	β_2	CCI	MRP ($)	Fuel consumption /h ($)	Total Operating Cost per hour ($)
Excavator II	0.006304	0.001893	1.157	284176.64	12.38	49.77
Excavator I	0.006304	0.001893	1.202	176463.74	10.17	30.22
Truck	-0.00246	0.004753	8.935	225173.98	6.78	12.26
Wheel loader	0.00881	0.002543	1.206	161042.46	6.78	26.73

Total cost per hour of equipment obtained by adding owning and operating cost is listed in Table 4.3 for each equipment involved in the activity. The cost per hour of equipment was calculated to fulfill third objective of the study “determining the effects of wasteful idle hours on cost of construction equipment”.

Table 4.3: Total Costs per Hour of Equipment

Equipment	Total Cost of equipment per hour ($$)
Excavator II	**67.04**
Excavator I	37.95
Truck	12.88
Wheel loader	36.20

From Table 4.3, the value presented in bold is the highest cost per hour of equipment among all equipment involved in the operation utilized for this study. The Excavator II has the highest cost per hour of equipment as it has highest purchase price and fuel consumption cost per hour. This means that idle time for Excavator II can have the largest impact on total equipment cost for the activity.

4.2 Necessary Idle Time of Equipment

The simulation model provides waiting time of equipment which could also be referred as necessary idle time of equipment. The snapshot of the simulation model that mimics the activity observed for this study is shown in Figure 4.1.

The model starts from queue that holds soil and that soil is excavated by Excavator I and loaded into Truck. The information shown on link between queue (soil) and combi (ldngofdirt) is capacity of the Truck to carry dirt in cubic yards. After that, Truck travels, dumps the dirt and hauls back to loading area, which are depicted by combi. After that, dumped Truck is carried by Wheel Loader, which is shown in terms of combi. The Wheel Loader then hauls, unloads the dirt and returns to start another cycle, which is shown by Normal and links. Unloaded dirt by Wheel Loader is then carried by Excavator II to back fill to foundation which are shown by combi (loading and backfilling) and normal (moving back of excavator boom).

The simulation model allows limited number of letters to name any of its elements. Therefore, sub-activities have been annotated with unique names, which are shown in Table 4.4. The results of the model after running simulation for 12 hours, which are waiting time or necessary idle of each equipment are shown in Table 4.5.

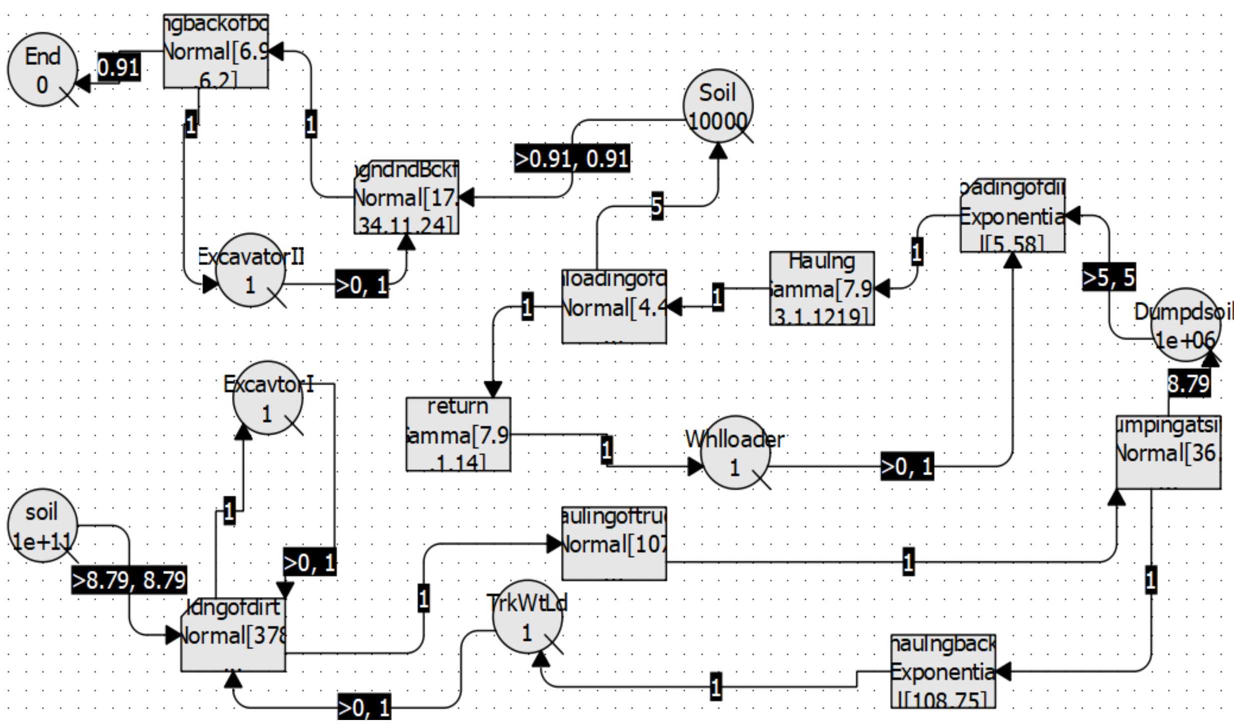

Figure 4.1: Snapshot of Simulation Model

Table 4.4: Annotation of Activities in the Simulation Model

Sub-Activity	Equipment involved	Notation in Simulation Model
Loading of dirt for excavating	Truck and excavator I	Ldngofdirt
Hauling for dumping	Truck	Hauingoftruck
Dumping at disposal site	Truck	Dumpingatsite
Haling back for filling	Truck	Haulngback
Loading of dirt for backfilling	Wheel loader	Loadingofdirt
Hauling for back filling	Wheel loader	Haulng
Unloading of dirt for back filling	Wheel loader	Unloadingofdirt
Hauling back for loading	Wheel loader	return
`Loading and Back filling	Excavator II	Ldngnd
Moving back of boom	Excavator II	mvngbackofboom

Table 4.5: Necessary Idle Time for Each Equipment

Equipment	Necessary Idle Time (hours)
Excavator II	0
Excavator I	**3.16**
Truck	0
Wheel loader	0.31

The results shown in Table 4.5 are of significance as they were obtained after attaining second objective of this study. The value highlighted in Table 4.5 is the highest necessary idle time (waiting time) of all the equipment. This is because, Excavator I is excavating the earth and filling earth in Truck, therefore it must wait while Truck dumps that earth and completes its cycle.

The results from simulation model can be altered by changing number of equipment. In order to reduce necessary idle time of Excavator I, simulation model with two Truck was developed. The simulation model was developed with same activities and resources except quantity of number of Truck was input two instead of one. Table 4.6 shows the results of simulation model with two Trucks.

Table 4.6: Results of Simulation Model with Two Trucks

Equipment	Necessary Idle Time (hours)
Excavator II	0
Excavator I	0
Truck	7.46
Wheel loader	0.31

After putting two Trucks in the simulation model instead of one, necessary idle time for Excavator I reduced to zero. This is because Excavator I can load one Truck while other Truck completes its cycle of hauling and dumping and do not need to wait. However, necessary idle time for Truck increases from 0 hour to 7.46 cumulative hours of necessary idle time of the two trucks. The increase in time is because of waiting of Truck while Excavator I is filling other Truck.

4.3 Actual Idle hours of equipment

Accelerometer data from each equipment was analyzed as explained in the methodology. Each state of equipment produces distinguish patterns of acceleration, which assures the reliability of accelerometer in measuring efficiency of equipment. The graphs in Figures 4.2 to 4.5 show acceleration patters of equipment involved in the operation while they are idle and non-idle. The units of accelerometer is in meter per second squared or G-forces. Single “g” of accelerometer is equivalent to 9.8 m/s^2. The results of analyzing accelerometer data of each equipment into idle and non-idle states using MLP are shown in Table 4.7. Table 4.7 shows results of applying the steps mentioned in the section “Accelerometer Data Classification and Processing” of Methodology. The results shown in table 4.7 are from first objective of the study.

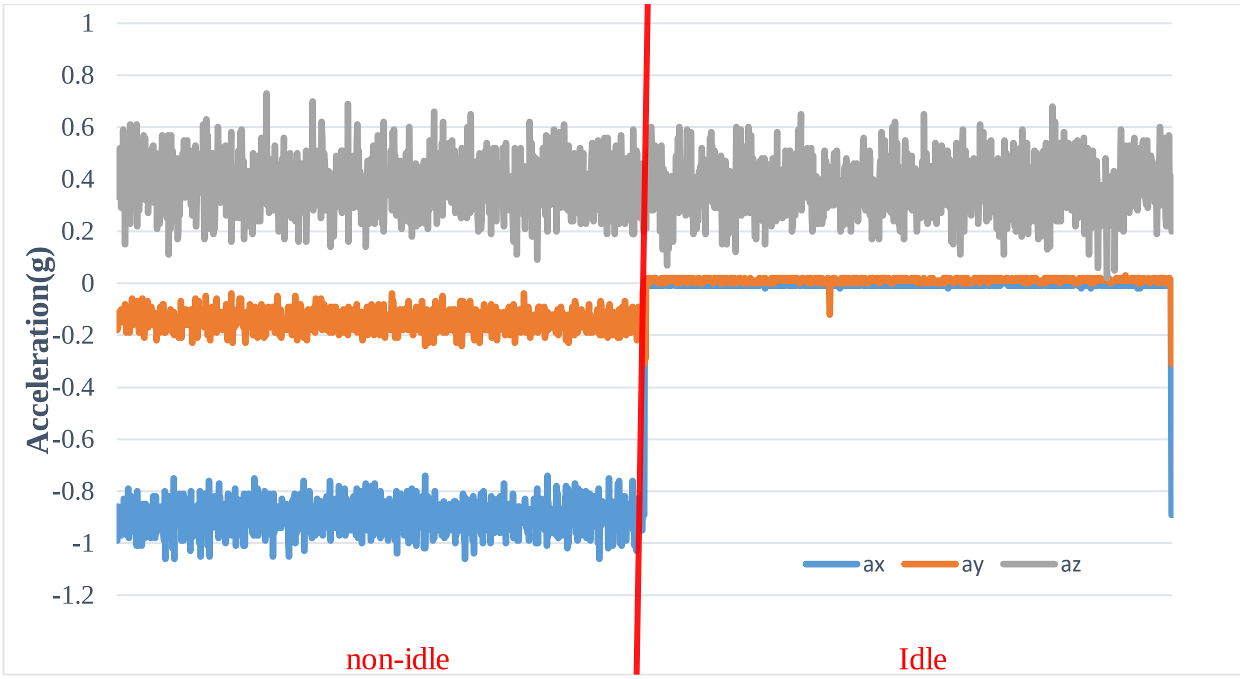

Figure 4.2: Acceleration Pattern of non-idle and idle Truck

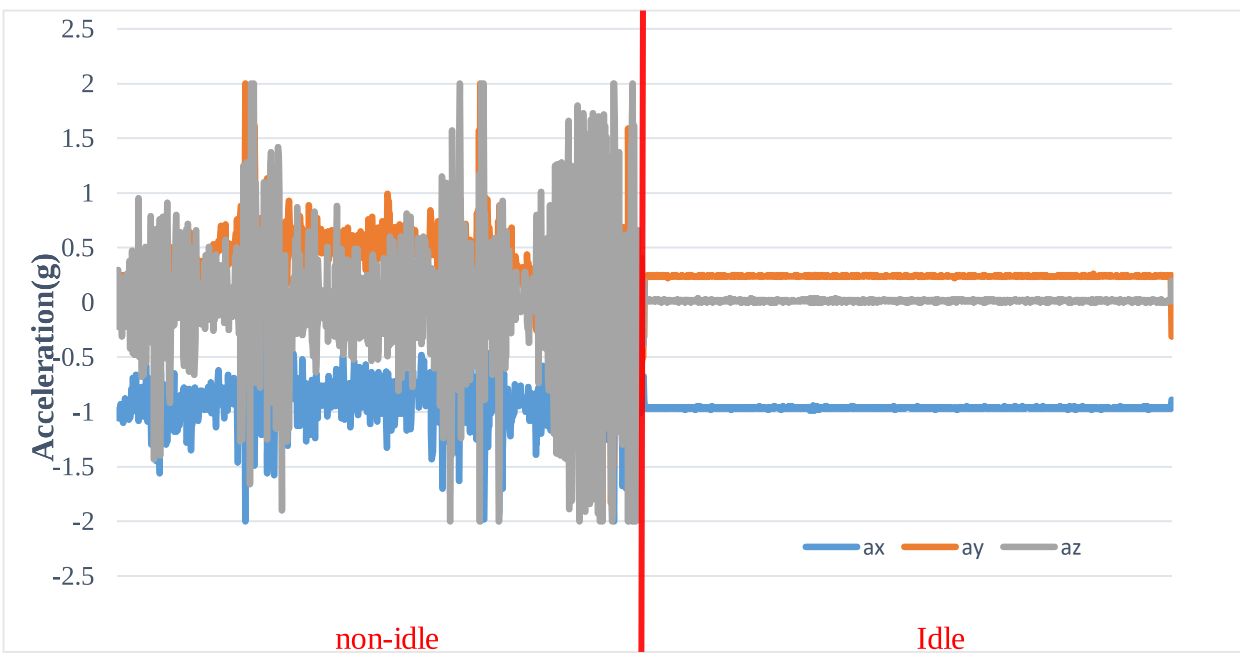

Figure 4.3: Acceleration Pattern of non-idle and idle Excavator I

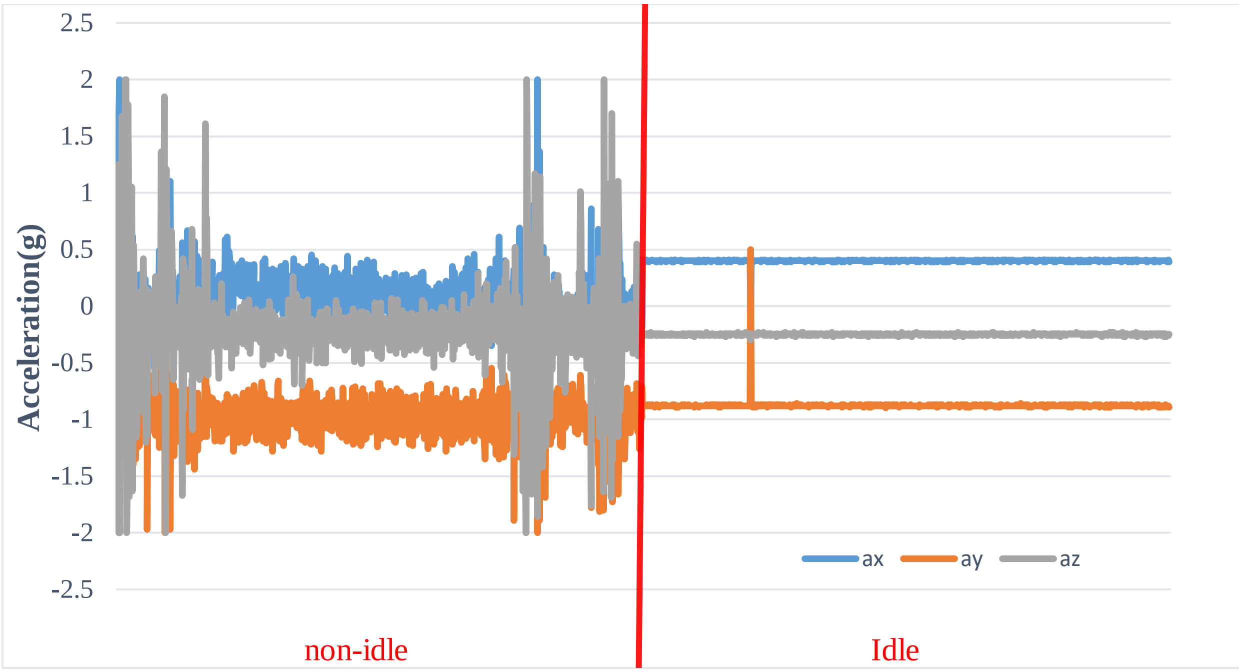

Figure 4.4: Acceleration Pattern of non-idle and idle Excavator II

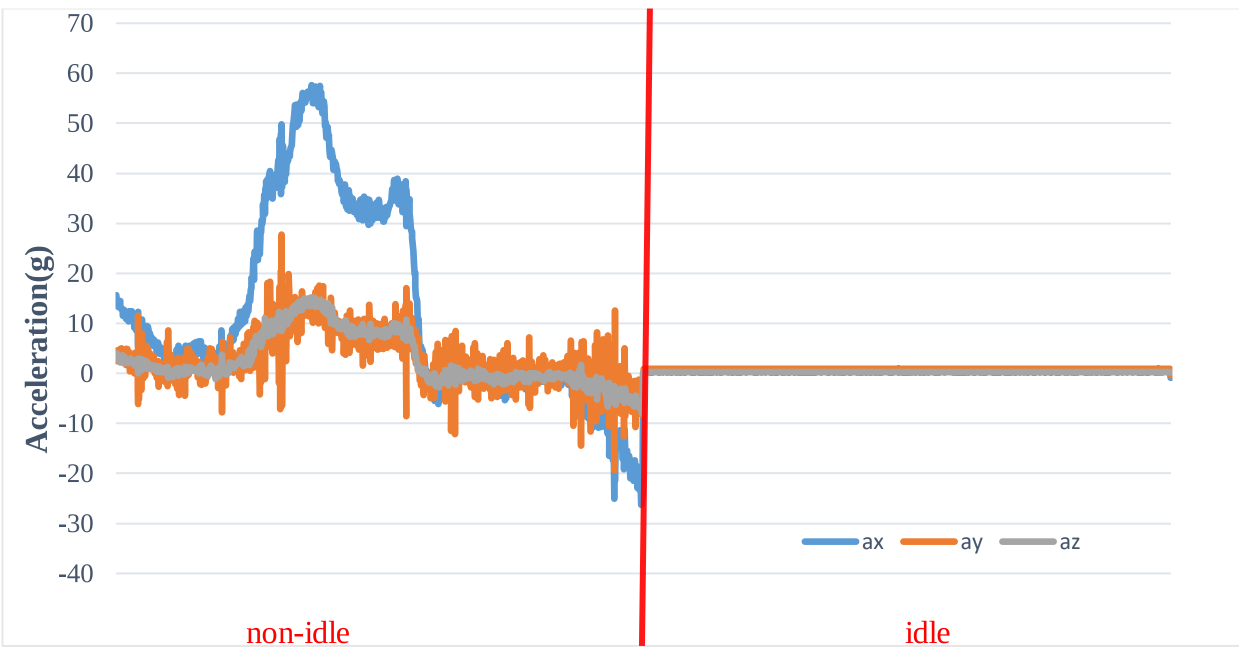

Figure 4.5: Acceleration Pattern of non-idle and idle Wheel loader

Table 4.7: Classification of Accelerometer Signals

Equipment	Idle hours	Non-idle hours	Total hours
Excavator II	1.81	10.19	12
Excavator I	6.41	5.59	12
Truck	3.03	8.97	12
Wheel loader	3.22	8.78	12

Graphs shown in Figures 4.2, 4.3, 4.4 and 4.5 explain accuracy of accelerometer in transmitting distinguish signals for different states of equipment. Therefore, it is feasible to collect data regarding idle and non-idle modes of construction activities using accelerometer. In Figure 4.5, the peak acceleration value for Wheel Loader is approximately 58 g which is too high for on road construction equipment. For avoiding such errors, the accelerometers were checked to make sure they are functioning properly. However, this data does not affect the conclusions. The graph is solely plotted to show the difference in pattern of idle and non-idle acceleration and rest of other data has low values of acceleration for Wheel Loader.

Idle hours for excavator I shown in Table 4.7 are more than half of total data collection hours. This means, Excavator I is not contributing to overall productivity of operation for more than 6 hours. Besides this, results also show that Truck and Wheel

Loader do not contribute to overall productivity of the operation for more than 3 hours of total 12 hours.

4.4 Comparison of Cost and Efficiency

This study aims to compare idle time of construction equipment from simulation and field data to obtain wasteful operational hours of an equipment. Besides this, finding effects of wasteful hours on cost is also one of objectives of this study. Table 4.8 shows calculation of difference in idle time and their effect on cost of equipment.

Table 4.8. Comparison of Idle Time and their Effect on Cost of Equipment

Equipment	Necessary Idle Time (hours)	Actual Idle Time (hours)	Wasteful Time (hours)	Cost per hour ($)	Total Cost ($)	Cost Difference ($)	% Cost Difference (%)
Excavator II	0	1.81	1.81	67.04	804.48	188.38	23.42
Excavator I	3.16	6.41	3.25	37.95	455.40	278.04	61.06
Truck	0	3.03	3.03	12.88	154.56	51.90	33.58
Wheel loader	0.314	3.22	2.906	36.2	434.40	152.45	35.09

The results shown in Table 4.8 are obtained by attaining third objective of the study. Necessary idle time shows the idle time required for equipment to complete its cycle which was obtained by running the simulation model. Actual idle time of each equipment is obtained from field data while its utilization in the activity. Wasteful idle hours are obtained by subtracting necessary idle time from actual idle time. Wasteful idle hours are caused due to constraints on site and poor planning of utilization of equipment. Unlike, necessary idle hours, wasteful idle hours can be avoided by removing constraints on the site. Constraints causing wasteful idle time for the activity utilized in this study were bottleneck on site, breaks for equipment operator, and grade of road of the site. Breaks of equipment were because of engagement of wheel loader operator in grading the foundation using grader.

After that, total cost is obtained by multiplying cost per hour of equipment by 12 hours (total hours of data collection). Cost of wasteful hours in Table 4.8 shows proportion of cost of total 12 hours of equipment that is wasted. Cost of wasteful hours is calculated as the difference of actual idle hours from field data and necessary idle hours. Percentage of cost wasted shows percentage of total of cost of equipment for 12 hours that does not contribute to overall operation of the activity. As shown in Table 4.8, percentage cost difference for Excavator I is more than 50% of total 12 hours cost which is because of high value of wasteful hours of Excavator I.

4.5 Comparison of Necessary Idle Time for different number of equipment and their Cost

In order to present the suggestion for the contractor, total cost of equipment due to necessary idle time for one truck and two truck is compared. It would allow the contractor to choose the alternative between one and two trucks based on total cost of all equipment.

Table 4.9: Comparison of Cost of Necessary Idle Time for Different Alternatives

Equipment	Cost due to One Truck	Cost due to Two Trucks
Excavator II	0	0
Excavator I	119.8	0
Truck	0	96.0
Wheel Loader	11.3	11.3
	Total cost 131.2	**Total cost 107.3**

In Table 4.9, cost due one Truck represents cost utilized due to necessary idle time of each equipment when simulation model involves only one Truck. Cost due to two Trucks shows cost due to necessary idle time of each equipment when two Trucks are input into the simulation model. It is shown in Table 4.9, total cost utilized due to necessary idle for all equipment for one Truck scenario is less than that of two Trucks scenario. Therefore, in order to reduce overall cost of the activity, trucks are feasible to use than one Truck.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This section explains conclusions drawn from interpretation of the results and highlights importance of results in achieving each objective. The section also focuses on constraints on the research design and suggestions for contractors to improve construction processes.

5.1 Revisiting of Objectives

For this study, literature was reviewed deeply to recognize the gaps in the knowledge and shortcomings in existing research regarding efficiency and cost of construction operations. As most of construction processes and activities involve utilization of construction equipment, therefore its efficiency and cost play an important role in successful completion of an activity. The literature review helped in understanding current methodologies and studies on cost and efficiency of construction equipment. The goal of this research is to integrate cost of construction equipment with efficiency of construction equipment and identify effects of equipment idle time on its cost. The research provides methodology to the researchers and contractors with framework to relate construction equipment efficiency with its hourly cost. To achieve the goal of the research, three objectives were set.

The study started with focusing on first objective by choosing methodology to collect data regarding efficiency of construction equipment. For that, literature was reviewed to identify the methods that have been proven successful in collecting construction efficiency data. Besides this, selection of project and activity to collect data were also crucial tasks as construction equipment abundant activity was required for data collection. Therefore, focus was laid to collect data for earthmoving activities because of their nature of involvement of equipment. Due to impactful and accurate results of accelerometer in previous studies for classifying states of equipment as idle and non-idle, this study utilizes accelerometer for calculating efficiency of equipment.

Second objective of the study, “developing simulation to determine the necessary idle time of the equipment” was achieved by using jStrobe. The software helped to build the model to mimic real-world construction activity and obtain waiting time of equipment, which is necessary idle time. The simulation model requires viable data for its results to be reliable. For this purpose, the activity was videotaped to obtain data regarding sequence of operation and time required for each equipment to perform sub-activity. Material carrying capacity of each equipment required for modelling simulation was obtained using the CAT manuals.

Achieving third objective, “determining the effects of wasteful idle hours on cost of construction equipment” required calculating hourly cost of construction equipment. Hourly cost of construction equipment was calculated by summing hourly operating and owning cost of equipment. Hourly owning and operating costs were calculated using formulas and tables from literature review and actual cost of equipment which were according to information provided by contractor owning the equipment. The following conclusion are drawn by achieving third objective of the study.

- Excavator I is responsible for wasting most of cost comparing to other equipment involved in the operation. One of the possible reasons of this is Excavator I waits for Truck to complete its cycle. After watching videotape of the activity, it could also be concluded that, the hauling path of truck had bottleneck effect due to presence of other equipment in its path. This caused truck to take more time to complete its cycles.

- Looking at Table 4.7, it can be concluded that Wheel Loader is wasting 35% of its 12 hours period cost which does not contribute to overall operation. Looking at videotape, one of the possible explanations could be idling of Wheel Loader due to unavailability of its operator. The engine of Wheel Loader was kept on while its operator was performing grading which led to more idling time of Wheel Loader than necessary idling time.

Fourth objective of presenting suggestions regarding reducing wasteful idle time of construction equipment was fulfilled by interpreting results of the study.

5.2 Limitations

The main purpose of the study is to present the methodology that could integrate cost and efficiency of construction and identify effects of efficiency on cost of construction equipment. This study is empirical research and can further be improved in the future work for more viable results. Following are limitation of this study which need to be overcome in future studies.

5.2.1 Constraints in the Simulation Model

The simulation model presented in this methodology does not incorporate constraints that were observed by watching videotape. Incorporating breaks between the cycles in the simulation model due to bottleneck on the site would increase reliability of the model.

Due to limitation of the software, constraints could not be incorporated in any one of the cycles in the simulation model of the operation. jStrobe has capability to incorporate repeated constraints that would affect every cycle in the simulation but cannot include constraints in selected number of cycles in the operation. Those constraints include but are not limited to disturbances in hauling path of equipment, equipment operator's breaks and bottleneck on construction site.

5.2.2 Choosing Most Appropriate Distribution of Time Instance of Activity

For this study, time instance to complete each cycle of sub-activity by equipment was fitted into statistical distributions for modelling simulation of activity. For most viable results, distribution with maximum p-value should be chosen. But, the software utilized for simulation for this study does not offer all types of distributions to incorporate into the model. Therefore, for some activities' distribution with second maximum p-value was chosen.

5.2.3 Variable Fuel Usage of Construction Equipment

The fuel consumption per hour of construction equipment is different for idle and non-idle equipment due to change in load of engine. CAT 45th manual used for this study to obtain fuel consumption per hour of equipment only provides fuel consumption when equipment is on and working (non-idle). Therefore, for this study same fuel consumption per hour is used for idle equipment to calculate operating cost per hour. However, fuel consumption per hour of idle and non-idle equipment should be different due to change in engine load.

5.2.4 Including Labor Cost

This study mainly focuses on cost and efficiency of construction equipment, therefore does not include labor cost of equipment operator. For the contractors, in order to measure overall efficiency of construction activity, equipment operator costs need to be incorporated in addition to equipment cost.

5.3 Suggestions

This section contains the recommendations for the contractors and practitioners that would help them in maximizing operational efficiency of equipment and reducing cost of the activity. Increasing operational efficiency of equipment would also result in decreased overall cost of activity.

5.3.1 Adding optimal number of equipment

Choosing optimal number of construction equipment that could maximize efficiency and minimize cost is crucial task for success of project. Number of construction equipment involved in any activity plays an important role in achieving required efficiency of overall project. The results of the study show that Excavator I has the highest idle time of all equipment from both actual field data and simulation model. This is because, Excavator I spends much of its time during operation waiting for Truck to complete its cycle. Therefore, contractors should focus on allocating right number of equipment for each activity. One way to do this is to use simulation model. Simulation can be used by running the model number of times with different number of equipment each time and choosing number of equipment that could maximize overall efficiency of operation.

5.3.2 Allocating adequate number of resources

The results of field data analysis show that Truck and Wheel Loader have much higher idle time than obtained from simulation model. One of the reasons that caused higher idle time of the Truck is constraints in the hauling path of Truck. The hauling path of the Truck had bottleneck, which caused it to wait for other equipment to pass and be idle for few seconds during most of its cycles. Wheel Loader also has higher idle time because operator of Wheel Loader was performing grading besides operating Wheel Loader. After back filling of foundation by Excavator II, Wheel Loader operator was letting Wheel Loader be idle while its engine was on for few minutes and started grading.

Therefore, proper planning of allocation of resources of activity and choosing right number of construction equipment in activity are required to maximize efficiency of activity. For this, tracking efficiency of equipment on regular basis is necessary. Monitoring efficiency by accelerometer and comparing that with required efficiency from simulation would help contractors to track their performance. Besides, integrating efficiency with cost will make contractors aware of importance of efficiency in reducing cost of activity.

5.3.3 Utilizing simulation model to allocate optimum number of equipment

The activity utilized for this study involved only one Truck. After running simulation model with two Trucks and all other same conditions as observed in the activity, the cost wasted due to necessary idle time of all equipment decreased. This interprets that utilizing two Trucks in the activity instead of one would decrease the cost of the all equipment involved in the activity and so the cost of the activity. Therefore, running simulation model for different number of equipment and calculating cost of idle hours of all equipment can help contractors in deciding number of equipment with the least cost of all equipment.

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