FLEET CONFIGURATION OF HIGHWAY CONSTRUCTION USING SIMULATION-BASED OPTIMIZATION

BY

ZAID AHMAD KHALLAF

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CONSTRUCTION ENGINEERING AND MANAGEMENT

February 2022

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Zaid Ahmad Khallaf** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN CONSTRUCTION ENGINEERING AND MANAGEMENT**

Dr. Laith A Hadidi
Department Chairman

Dr. Adel Alshaibani
(Advisor)

Prof. Suliman Saleh Al-Homidan
Dean of Graduate Studies

15/3/22

Prof. Abdulaziz Bubshait
(Member)

Date

15/3/2022

Dr. Awsan Mohammed
(Member)

© Zaid Ahmad Khallaf

2022

DEDICATION

Foremost, I grant Allah praise and thanks for granting me the patience and determination to complete my M.Sc. program.

ACKNOWLEDGMENTS

My sincere gratitude goes to my master's thesis advisor, doctor Adel Alshaibani, for his remarkable comments and continual engagement throughout the learning process as well as his precious time, efforts, and appreciated support along the way.

Furthermore, I would like to extend my appreciation to the thesis committee, Dr. Abdulaziz Bubshait, and Dr. Awsan Mohammed, for their sharp remarks, which helped in enhancing and strengthening the developed model capabilities.

In addition, a special thank goes to Dr. Omar Alsawafy for all his kind gestures, patience, and valuable observations that were important in the completion of this thesis.

Moreover, my appreciation goes to the Construction Engineering and Management Department (CEM) faculty who lighted my way out to complete my master program, the chairman department Dr. Liath Hadidi as well as Prof. Ali Shash, Dr. Waleed Umer, Dr. Firas Tuffaha, Dr. Ahmed Ghaithan, Dr. Adel Aldosary. Also, it brings joy to thank the faculty of the Civil and Environmental Department, whom I learned a lot from them.

Also, I would like o to take this chance to express my deep thanks to my second family at King Fahd University of Petroleum and Minerals including but not limited to the Palestinian community, my roommate Mr. Yousef Odeh, my colleagues Mr. Wahib Saif, Mr. Mohammad Arafa, My friends Mr. Abdul Hafiz Hariri, Mr. Abed Anis.

I would like to express my gratitude to my loved ones for supporting me throughout the process by keeping me focused and assisting me in putting everything together. My father,

my mother, my brothers, and my sisters will always be remembered for being there for me anytime I needed them and for being the amazing family that they are.

TABLE OF CONTENTS

ACKNOWLEDGMENTS ..... **V**

TABLE OF CONTENTS ..... **VII**

LIST OF TABLES ..... **XI**

LIST OF FIGURES ..... **XII**

LIST OF ABBREVIATIONS ..... **XIV**

ABSTRACT ..... **XV**

ملخص الرسالة ..... **XVII**

CHAPTER 1: INTRODUCTION **1**

1.1 General Overview **1**

1.2 Problem Statement **4**

1.3 Research Objective **4**

1.4 Significance of the Study **4**

1.5 Thesis Organization **5**

CHAPTER 2: LITERATURE REVIEW **7**

2.1 Chapter Overview **7**

2.2 Onsite Construction Equipment **9**

2.3 Selection Criteria for Construction Equipment **10**

2.3.1 Socio-Economic Criteria **11**

2.3.2 Engineering Criteria **12**

2.3.3 Environmental Criteria **13**

2.4 Mathematical-Based Optimization Techniques **14**

2.4.1 Mathematical simulation Application in Construction 15
2.4.2 Mathematical simulation Application in Earthmoving operations 16
2.5 Computer-Based Optimization Techniques 18
2.5.1 System Dynamics (SD) 18
2.5.2 Agent-Based Modeling (ABS) 24
2.5.3 Hybrid Simulation Method 25
2.6 Simulation Application in Construction Management 27
2.6.1 System Dynamic Applications and Its Limitation 27
2.6.2 Agent-Based Modeling Application and Its Limitation 29
2.6.3 Hybrid System Applications and Its Limitation 30
2.7 Discrete-Event Simulation (DES) 31
2.7.1 Discrete-Event Overview 31
2.7.2 DES Major Concepts 32
2.7.3 DES Model Behavior 36
2.7.4 Discrete-Event Simulation Application in Construction 36
2.7.5 General Application of DES in Construction Management 37
2.7.6 DES Application in Road construction 42
2.7.7 DES Application in Reducing CO2 Emissions 43
2.7.8 Discrete-Event Simulation Technique Limitations 45

CHAPTER 3: RESEARCH METHODOLOGY 47

3.1 Chapter Overview 47
3.2 A procedure for Developing Mixed Integer Programming Model for EM Operations 49
3.2.1 Planning of Earthmoving Operations 50
3.2.2 Factors Affecting Earthmoving Operations 55
3.2.3 Mixed Integer Programming for Optimization Earthmoving Operations 58

3.3 A procedure for Developing DES Model for CM Applications 88
3.3.1 Step-by-Step DES Model for Construction Management Applications 89
3.3.2 DES Model for Earthmoving Operations 93
3.3.3 DES Model Resolution Steps 96
CHAPTER 4: IMPLEMENTATION 100
4.1 Chapter Overview 100
4.2 MILP Model Components 102
4.2.1 Data 102
4.2.2 Model 104
4.2.3 Model definitions 107
4.3 DES Model Components 107
4.3.1 Cut-fill sections and Entities 109
4.3.2 Working Days 110
4.3.3 Earthmoving Operations Process 111
4.4 Model Verification 111
4.4.1 Case Study One Scope Description 112
4.4.2 Case Study Two Scope Description 113
4.5 Developed Model Results and Discussion 116
4.5.1 MILP Results and Discussion 116
4.5.2 DES Model Results and Discussion 124
4.5.3 Sniping from the DES model 129
CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS 133
5.1 Research Summary and Conclusions 133
5.2 Research Limitations 134

5.3 Recommendations and Future Work 135

REFERENCES..... 136

VITAE..... 147

LIST OF TABLES

Table 2. 1: Socio-Economic Criteria for Selecting Equipment" (Waris et al., 2014)..... 11
Table 2. 2: Engineering Criteria for Selecting Equipment" (Waris et al., 2014)..... 12
Table 2. 3: Environmental Criteria for Selecting Equipment (Waris et al., 2014) 13
Table 2. 4: Denotations for Causal Loop Diagramming (Sterman 2000)..... 21
Table 2. 5: Application of SD in the Field of CM 28
Table 2. 6: ABMS Application in CM..... 30
Table 2. 7: Hybrid System Applications in CM..... 31
Table 2. 8: Elements of CYCLONE Modeling (Halpin and Riggs 1992) 38
Table 3. 1: Scraper Properties..... 94
Table 3. 2: Pusher Properties 95
Table 4. 1: Model Set Declarations and Definitions..... 103
Table 4. 2: Model Parameter Declarations and Definition 104
Table 4. 3: Model Variable Declarations..... 105
Table 4. 4: Model Equitation's Declarations and Constraints 105
Table 4. 5: Model definitions, Solve, and Display..... 107
Table 4. 6: DES Model Blocks 108
Table 4. 7: Example 1 Data..... 113
Table 4. 8: Equipment Characteristics 114
Table 4. 9: Lengths of the Haul-Road..... 114
Table 4. 10: A&M Model Output (Alshibani and Moselhi 2012) 115
Table 4. 11: MILP Output Data VS Other Models..... 117
Table 4. 12: Daily fleet configuration..... 119
Table 4. 13: Daily Moved Soil Quantities, Scrapers Trips, Cost, And Duration Between Cut-Fill Sites..... 120
Table 4. 14: Total Soil Quantities Moved from Each Cut to Fill Sites..... 121
Table 4. 15: Soil Amounts transfer Utilizing MILP Fleet Configuration..... 125
Table 4. 16: Daily Fleet2 Configuration 127
Table 4. 17: Soil Amounts Transfer Utilizing MILP Fleet Configuration..... 127

LIST OF FIGURES

Figure 1. 1: Research Methodology 6
Figure 2. 1: literature reviews 8
Figure 2. 2: Stocks and Flow Diagramming (SFD) (Alzraiee 2013). 23
Figure 2. 3: Stocks and Flow Diagramming (SFD) (Alzraiee 2013). 24
Figure 2. 4: Dominant structure of hybrid simulation (in this case, Method 2 is dominant) (Moradi et al. 2015) 27
Figure 2. 5: Integrated structure of hybrid simulation (Moradi et al. 2015) 27
Figure 2. 6: Parallel structure of hybrid simulation (McNaught 2012) 27
Figure 2. 7: Drive-Through Example Logic Flow (Ingalls 2002). 35
Figure 2. 8: System state update in DES and continuous simulation (Alzraiee 2013) 36
Figure 2. 9: Example of CYCLONE model (Zhang 2005) 38
Figure 2. 10: Historical Development of Simulation Program (Abduh 2007) 39
Figure 2. 11: Model Diagram of a Dry Batch Delivery and Concrete Placement Model in DISCO (Haung and Halpin 1994) 40
Figure 2. 12: STROBOSCOPE Network Fragment for Earthmoving Operation 41
Figure 3. 1: Methodology 48
Figure 3. 2: Dynamic Fleet Configuration 49
Figure 3. 3: Pusher-Scraper Cycle Time 50
Figure 3. 4: Pusher-Scraper One Cycle Time 1 50
Figure 3. 5: Pusher-Scraper One Cycle Time 2 51
Figure 3. 6: Pusher-Scraper One Cycle Time 3 53
Figure 3. 7: The Balance Number of Scrapers in Case 1 & 2 Pushers 54
Figure 3. 8: Scraper Load Growth Curve (Karshenas & Farid, 1988)" 68
Figure 3. 9: Scraper Optimal Loading Time (Karshenas & Farid, 1988) 68
Figure 3. 10: Performance Chart to Table Format Using WebPlotDigitize 71
Figure 3. 11: Speed Determination Using IF-Statement 72
Figure 3. 12: Cycle Time Calculation 72
Figure 3. 13: Proposed Model Resolution Steps 75
Figure 3. 14: Conceptual Framework for Developing a Successful DES Model 88
Figure 3. 15: Resolution Steps of the Developed DES Model 97
Figure 4. 1: Breakdown of the Implemented Process 101
Figure 4. 2: GAMS Organizing Style 1 102
Figure 4. 3: GAMS Organizing Style 2 102
Figure 4. 4: Cut-Fill Section and Entities 109
Figure 4. 5: Working Days Representation 110
Figure 4. 6: Earthmoving Process 111
Figure 4. 7: Example one profile view 113
Figure 4. 8: Proposed Road Plan and Profile view 115
Figure 4. 9: S1-S8 & S7-S9 haul-road layout 115
Figure 4. 10: Emissions Amount and Cost of MILP Model VS the Selected Models 118
Figure 4. 11: MILP Model Emissions Amounts and Costs Vs A&M2 121
Figure 4. 12: Daily Update of Trips and Quantities at Different Cut-Fill Sections 122
Figure 4. 13: Daily Planned Operations for Non-Interruption Crews 124

Figure 4. 14: Fleet Configuration VS Cost and Quantities 126
Figure 4. 15: DES Model Flow Logic 129
Figure 4. 16: Project Progress Chart 130
Figure 4. 17: Trips Number Between Different Cut-Fill Areas 130
Figure 4. 18: Total Cost Between Different Cut-Fill Areas 131
Figure 4. 19: Cut-Fill Section Representation 131
Figure 4. 20: Total Soil Quantity Moved Between Different Cut-Fill Areas 132
Figure 4. 21: Fleet Utilization 132

LIST OF ABBREVIATIONS

ABMS	Agent-Based Modeling and Simulation
AI	Artificial Intelligence
CLD	Causal Loop Diagram
CM	Construction Management
CYCLONE	Cyclic Operation Network
DES	Discrete-Event Simulation
DISCO	Dynamic Interface Simulation for Construction Operation
FIFO	First-In-First-Out
GUI	Graphical User Interface
KEYSTONE	Knowledge Discovery Based Simulation System
RBM	Resource-Based Modeling
SD	System Dynamics
SFD	Stocks and Flows Diagram
WBS	Work Breakdown Structure

ABSTRACT

Full Name : Zaid Ahmad Mahmoud Khallaf

Thesis Title : Fleet Configuration of Highway Construction Using Simulation-Based Optimization

Major Field : Construction Engineering Management

Date of Degree : May 2022

Earthmoving operations are the core task in most heavy construction projects (e.g., highways constructions, dams, tunnels, etc.) that involve the utilization of heavy equipment. Heavy machinery is associated with high utilization costs that significantly impact the operation's overall budget. Therefore, being able to find the optimized crew configuration that results in the least cost and/or schedule will assist contractors in successfully delivering such projects with the planned budget and schedule. Several mathematical and simulation optimization models have been developed for optimizing earthmoving operations. However, most of these optimization systems do not consider the dynamic changes of the fleet configuration as the project progresses.

This thesis presents a simulation-based optimization model for earthmoving operations through finding the optimum crew configuration that results in the least cost and/or schedules taking into consideration the dynamic change of the fleet configuration as the project progresses. The presented system integrates a mathematical model which is based on Mixed Integer Linear Programming (MILP) with a simulation model that employs Discrete Event Simulation (DES). The mathematical model provides the simulation model with the initial fleet configuration that was solved using MILP. While the DES model accounts for the uncertainties related to the cycle time, validate the mathematical model

and find the final project cost, duration, and optimum fleet configurations for different cut-fill areas. To validate the developed system, three case projects were solved. Comparing the results obtained with our model and the literature models of the selected cases, there was a significant improvement in project cost by 7.029% for the first case project, 25.44% for the second, and 65.4% for the third. As for the project's overall duration, the improvement percentage was 45.763% for the first case, 42.27% for the second case, and 20% for the third. Furthermore, the results reveal that the fleet configurations generated by the DES model are in agreement with those selected by the MILP model by 95.023%.

The generated model can assist contractors in planning earthmoving operations and achieving the least possible cost while considering (1) available resources to the contractor, (2) the dynamic fleet configuration of the multi-cut-fill sites, (3) the optimum soil quantities to be moved between different cuts and fill sites, (4) project environmental and indirect costs, (5) queues at each cut and fill areas and (6) uncertainties associated with the dynamic behavior of the earthmoving operations.

ملخص الرسالة

الاسم الكامل : زيد أحمد محمود خلاف

عنوان الرسالة : تشكيل أسطول بناء الطرق السريعة باستخدام التحسين القائم على المحاكاة

التخصص: هندسة وإدارة التشييد

تاريخ الدرجة العلمية: أيار 2022

عمليات نقل التربة هي المهمة الأساسية في معظم مشاريع البناء الثقيلة (مثل إنشاءات الطرق السريعة والسدود والأنفاق وما إلى ذلك) التي تنطوي على استخدام المعدات الثقيلة. ترتبط الآليات الثقيلة بتكاليف استخدام عالية تؤثر بشكل كبير على الميزانية الإجمالية للعملية. لذلك ، فإن القدرة على العثور على التكوين الأمثل للطاقم الذي ينتج عنه أقل تكلفة أو جدول زمني سيساعد المقاولين في تسليم مثل هذه المشاريع بنجاح بالميزانية والجدول الزمني المخططين. تم تطوير العديد من نماذج التحسين الرياضية والمحاكاة لتحسين عمليات نقل التربة. ومع ذلك ، فإن معظم أنظمة التحسين هذه لا تأخذ في الاعتبار التغييرات الديناميكية لتكوين الأسطول أثناء تقدم المشروع.

تقدم هذه الرسالة نموذجًا للتحسين القائم على المحاكاة لعمليات نقل التربة من خلال إيجاد التكوين الأمثل للطاقم الذي ينتج عنه أقل تكلفة و / أو جدول زمني يأخذ في الاعتبار التغيير الديناميكي لتكوين الأسطول مع تقدم المشروع. يدمج النظام المقدم نموذجًا رياضيًا يعتمد على البرمجة الخطية المختلطة الصحيحة (MILP) مع نموذج محاكاة يستخدم محاكاة الأحداث المنفصلة (DES). يوفر النموذج الرياضي لنموذج المحاكاة التكوين الأولي للأسطول الذي تم حله باستخدام MILP. بينما يراعي نموذج DES حالات عدم اليقين المتعلقة بزمن النقل ،يتحقق من صحة النموذج الرياضي ، ويجد التكلفة النهائية للمشروع ، والمدة ، وتكوينات الأسطول المثلى لمناطق القصوالتعبئة المختلفة. من أجل التحقق من صحة النظام المطور ، تم حل ثلاث مشاريع. بمقارنة النتائج التي تم الحصول عليها بنموذجنا والنماذج للحالات المختارة ، كان هناك تحسن كبير في تكلفة المشروع بنسبة 7.029٪ لمشروع الحالة الأولى ، و 25.44٪ للمشروع الثاني ، و 65.4٪ للثالثة. أما بالنسبة للمدة الإجمالية للمشروع ، فقد بلغت نسبة التحسن 45.763٪ للحالة الأولى ، و 42.27٪ للحالة الثانية ، و 20٪ للحالة الثالثة. علاوة على ذلك ، كشفت النتائج أن تكوينات الأسطول التي تم إنشاؤها بواسطة نموذج DES إتفاق مع تلك المحددة بواسطة نموذج MILP بنسبة 95.023٪.

يمكن أن يساعد النموذج الذي تم إنشاؤه المقاولين في تخطيط عمليات نقل التربة وتحقيق أقل تكلفة ممكنة مع مراعاة (1) الموارد المتاحة للمقاول ، (2) التكوين الديناميكي للأسطول لمواقع الردم والقص المتعددة، (3) كميات التربة المثلى ليتم نقلها بين مواقع الردم والقص المختلفة ، (4) التكاليف البيئية وغير المباشرة للمشروع ، (5) طوابير الانتظار في كل مناطق قص وردم ، و (6) أوجه عدم اليقين المرتبطة بالسلوك الديناميكي لعمليات نقل التربة

CHAPTER 1: INTRODUCTION

1.1 General Overview

Earthmoving operations are the core task in most heavy construction projects (e.g., highways constructions, dams, tunnels, etc.) that involve the utilization of heavy equipment. Heavy machinery is associated with high utilization costs that significantly impact the operation's overall budget. Therefore, being able to find the optimized crew configuration that results in the least cost and/or schedule will assist contractors in successfully delivering such projects with the planned budget and schedule. Moreover, the earthmoving process has a complex and dynamic nature. As a result, many difficulties are encountered during the project construction. These difficulties are as follows: 1) the complicated interaction between the resources involved in the process while operations are in progress, and 2) varying conditions and uncertainties arise during the executions that affect the operations. Several mathematical and simulation optimization models have been developed for optimizing earthmoving operations to assist in the decision-making process that results in cost-saving and productivity enhancement (Klingstam and Gullander 1999).

Generally, the Mixed-Integer Linear Programming (MILP) technique has the most applications in optimizing the earthmoving operations due to its effectiveness and simplicity. For the past decades, several MILP models have been utilized to optimize earthmoving operations. For instance, Hare et al. (2011) developed a mixed-integer programming model that incorporates blocks that restrict earth movements operations across the construction site. Yi and Lu (2016) proposed a mixed-integer linear

programming model that accounts for the sensitivity of the MILP optimum results while considering the variation in the input parameters. Fernandes and Espindola (2019) employed the mixed-integer programming method to minimize the total transportation cost of moving soil quantities for a Brazilian highway road (BR-316) by finding the optimal amount of soil to be transferred from each borrow pit to the dumpsites. Falcão et al. (2020) built a mixed-integer model based on a mathematical problem called the vehicle routing problem. The main objective of the developed model was minimizing the haul road of multi- fleets of dump trucks. Two case studies were implemented using the model. The findings indicated that this model is a decision-making tool for project planners.

4 However, the simulation tools imitate the real-world system by providing a holistic image of different project resources, activities (AbouRizk 2010). Generally, there have been several simulation construction systems developed within the last decades. For instance, CYCLONE, a general-purpose simulation language for planning, analyzing, and controlling the cyclic nature of construction operations, was introduced by Haplin in 1977. The introduction of CYCLONE simulation to the construction initiated the development of other simulation programs such as DISCO (Haung and Halpin 1994), STROBOSCOPE (Martinez and Ioannou 1999, Martinez 1996), SIMPHONY (Hajjar and AbouRizk 1999), Micro-CYCLONE (Halpin and Martinez 1990), CIPROS (Tommelein et al. 1994), UM-CYCLONE (Ioannaou 1989) and HSM (Sawhney and AbouRizk 1995).

5 On the other hand, various simulation techniques are utilized to optimize earthmoving operations as a model introduced by Moeslhi and Marzouk 2002, Optimization-based

simulation (Alshibani and Moselhi 2012). However, the most famous simulation techniques are System Dynamics (SD), Agent-Based Modeling, and Discrete-Event Simulation (DES).

6 DES technique has the most application in construction as it is the oldest technique introduced to the construction industry. In this thesis, the latter will be considered. DES is a powerful tool for simulating complex processes that have cyclic nature, such as construction operations. DES treats the system as a summation of individual activities that interact with each other's to generate outcome results. Activates in DES model flow through the process, seize resources, and release them after the process is finished. The aforementioned features of the DES make it the most suitable technique for the simulation of earthmoving operations.

7 The main setbacks of those models and systems individually or collectively are that (1) they do not consider the dynamic change of fleet size as the project progresses, in the case of multi-borrow pits and landfill sites, (2) they do not consider the environmental aspects, (4), they do not capture the uncertainties associated with earthmoving operations activities, and (3) some of them do not consider the time constraints, (4) all previous models consider the work a continuous process which is not the case in the real-world problem. Hence, this study aims to develop a Simulation-based Optimization model (DES-MILP) that addresses the previously mentioned limitations and be used as a planning tool for earthmoving operations.

8 The potential stakeholders of the scope of this thesis are contractors and project managers, where they can employ the developed model of this study to efficiently

optimize the cost and time of earthmoving fleet configuration. Also, the developed model enables the stakeholder to prepare bids for earthmoving projects.

1.2 Problem Statement

In common practice, planners, when planning earthmoving operations, neglect the stochastic and dynamic nature of the equipment as well as the uncertainties associated with equipment operations. Ultimately, this may contribute to poor utilization of the available fleet and resources. Particularly, this study attempts to answer the following questions:

How to select the optimum fleet configuration for a highway construction project that provides the least possible cost and duration while considering the following:

- Fleet dynamic change as the project progress
- Uncertainties associated with both project cost and time
- Available resources to the contractor
- Environmental aspects (emissions)
- Soil amount and types
- Queues at each cut and fill areas

1.3 Research Objective

This study aims to develop a simulation-based optimization model that provides the optimum fleet arrangements for highway construction projects considering the dynamic fleet change as well as the uncertainties associated with project time and cost.

1.4 Significance of the Study

The simulated model of this research will enable the stakeholders to:

- Efficiently select the fleet arrangements for highway construction that lead to the least possible cost.
- Optimum utilization of the available resources.
- Consider all uncertainties associated with the dynamic behavior of the operations during the planning stage, which helps to avoid any additional unnecessary costs.
- Prepare an accurate cost estimation for biding highway construction.

1.5 Thesis Organization

This thesis is organized into five chapters (Figure 1.1). Chapter 1 (Introduction) covers an introduction to the topic, which is divided into the following parts, 1) problem statement, 2) research objective, 3) significance of the study. Chapter 2 (literature review) presents a summary of both types of simulations, mathematical-based, and computer-based simulation. It also discusses the applications of the simulation in construction management, as well as provides an elaboration on DES and its applications. Chapter 3 (Methodology) explains the detailed steps of developing a DES model, followed by identifying the model inputs. Chapter 4 (Model Implementation) illustrates the implementation of the model following the steps elaborated in the methodology. Chapter 5 (Conclusion and recommendations) summarizes the whole work performed in this study, draws conclusions based on the outcomes of this work-at-hand, and outlines the recommendations for future development and enhancement.

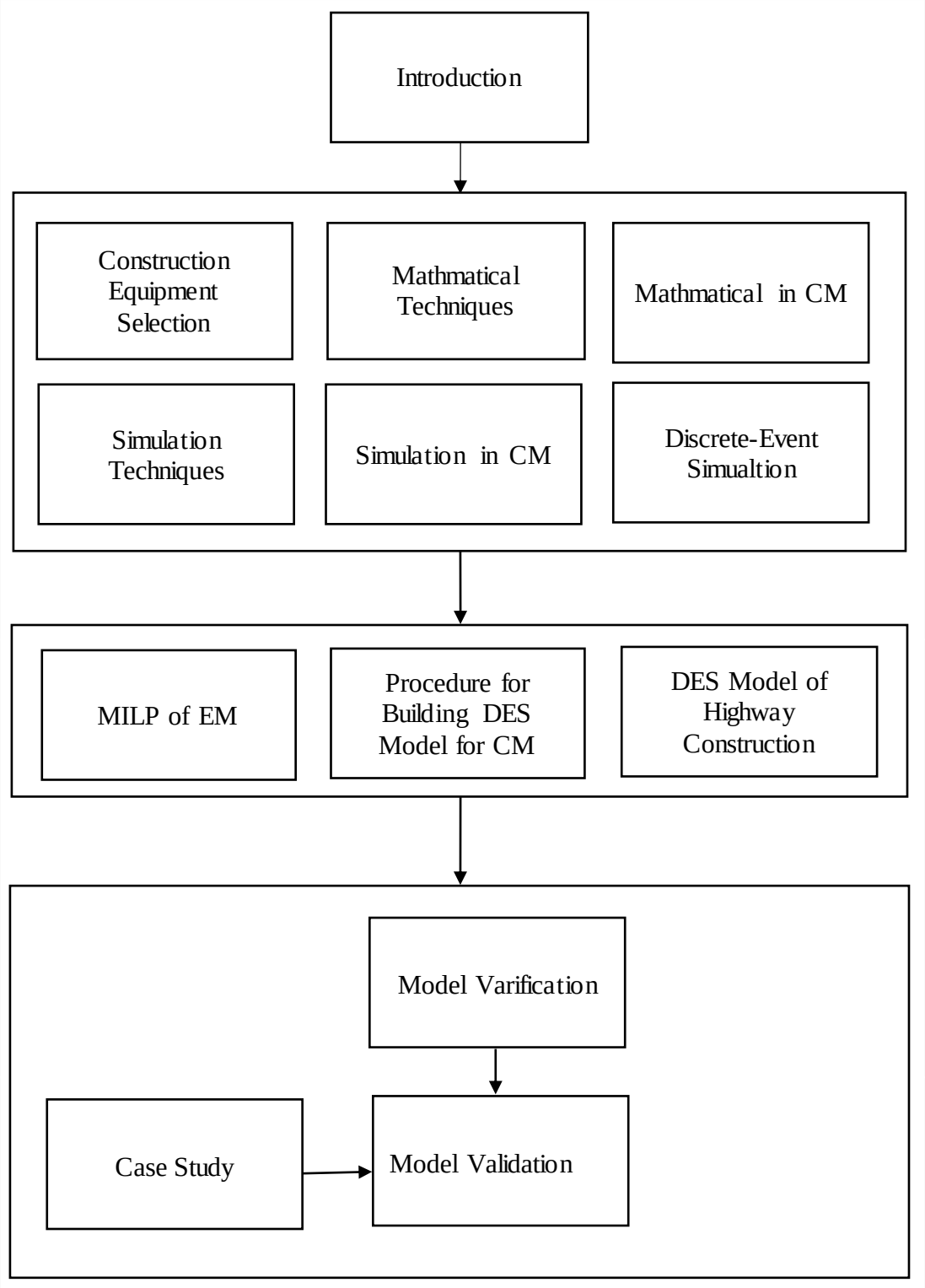


Figure 1. 1: Research Methodology

CHAPTER 2: LITERATURE REVIEW

2.1 Chapter Overview

This chapter is devoted to providing a comprehensive literature review on the current optimization and simulation practice in construction management in general and earthmoving operations in particular. It mainly highlights both mathematical optimization techniques and computer simulation techniques. Moreover, it explains in depth the mixed-integer linear programming (MILP) and discrete event simulation method (DES). Furthermore, it discusses the different criteria for selecting construction equipment. Figure 2.1 explains the various literature reviews explored prior development of the model.

Sections 2.2~2.3 provide an overview of different criteria for the selection of the construction equipment. They discuss onsite construction equipment, Socio-Economic, Engineering, Environmental Criteria for selecting construction equipment. Furthermore, Section 2.4 demonstrates the mathematical optimization for construction management in general and earthmoving operations in particular. In addition, sections 2.5~2.6 demonstrate the different computer simulation techniques and their applications and limitations in construction management. Finally, section 2.7 thoroughly explains the DES technique, its applications, and its limitations.

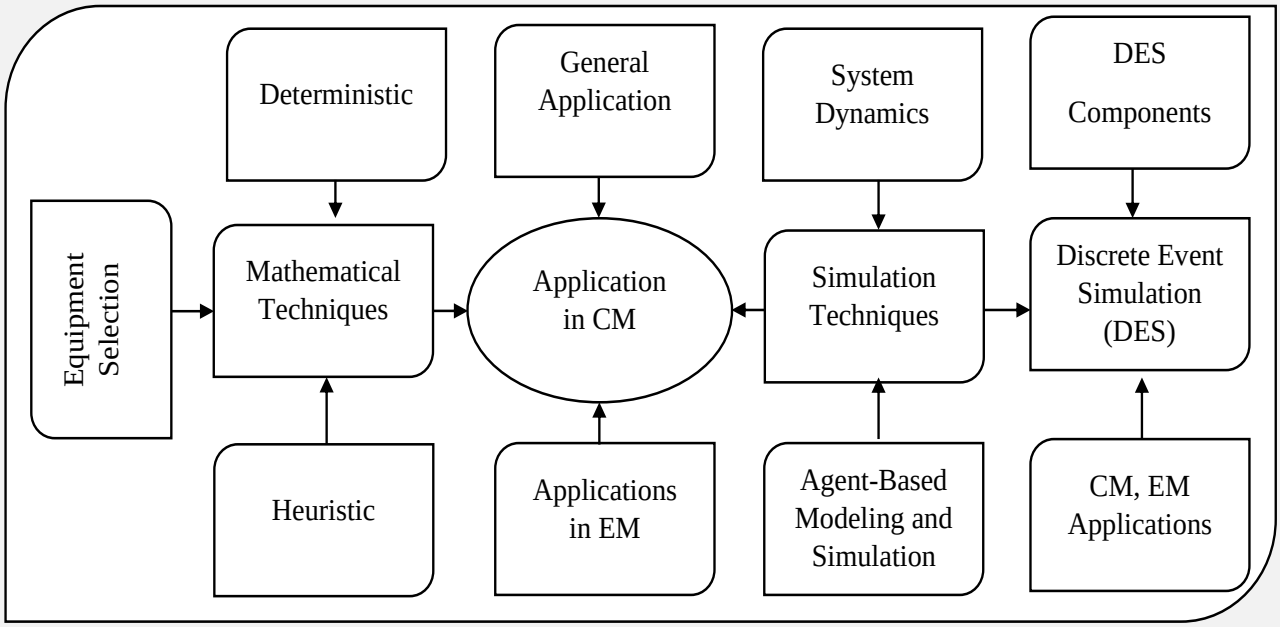


Figure 2. 1: literature reviews

2.2 Onsite Construction Equipment

In recent years, the construction sector has seen industrialization growth, resulting in the high mechanization of construction projects. Thus, construction equipment plays a vital role in delivering efficient and productive work. The selection of the right equipment during the construction phase is a challenging process. Usually, the selection process of the equipment is made by matching the task to be performed with the available equipment in the fleet. This criterion takes into consideration the production rate, cost, and capacity of the equipment (Waris et al., 2014). However, different construction projects acquire different types of equipment. For instance, low usage of equipment (e.g., hoisting, backhoe, and forklift) is required for residential projects, while heavy and industrial construction projects require intensive use of the equipment to carry out the work, such as mass excavation, pipeline, road construction, etc. (Gransberg et al., 2006).

The successful delivery of heavy construction projects, namely structural steelworks, earthwork, and others within the time and cost constraints, is mainly relying on heavy construction equipment. The acquisition of those equipment requires a significant capital investment from the construction firm. Yeo and Ning 2006 state that heavy construction equipment accounts for 36 % in terms of risk and uncertainties for the owner.

Earthmoving operations are an integral part of heavy construction projects. These operations are performed in an environment fraught with a lot of uncertainties. Planning such operations at the early stage of the project life requires great care to meet the project objectives and satisfy project and resource constraints. The complexity of such operations results from the involvement of many factors that affect the project cost and onsite productivity, where equipment type is one of them. However, earthwork is cyclic that

requires an expensive fleet combination (e.g., loader_trucks system, dozer_scrapers system, etc.) to move huge amounts of earth. Selecting the optimum fleet configuration is the key element of the successful delivery of this class of projects, which results in reducing the cost associated with the construction equipment.

2.3 Selection Criteria for Construction Equipment

As aforesaid, taking a strategical level decision to select the most appropriate construction equipment to perform the assigned task is challenging. The decision should be made such that the task to be accomplished matches the contractor's available equipment as well as considers the equipment productivity, cost, capacity, and other factors. For example, when selecting earthmoving equipment, the contractor should take into consideration the following: 1) soil type, 2) contract provision, 3) spatial association, 4) logistical issues (Gates and Scarpa 1980).

Chan et al. 2001 established a database application for selecting the most suitable backhoe and loader for earthmoving operation. Their evaluation criteria are based on the following aspects: 1) technical, 2) economic, 3) performance, 4) strategic. Haidar et al. 1999 divided the selection criteria into two aspects. First, optimization genetic algorithms in which the evaluation criteria are based on owning and operating costs, equipment manufacture characteristics including model, operating life, and number. Second, is subjective knowledge. Unlike the conventional way of selecting the construction (e.g., it is based on time, cost, quality), Waris et al., 2014 categorized the selection of the construction equipment based on sustainability into three categories: 1) socio-economic, 2) engineering, 3) Environmental.

2.3.1 Socio-Economic Criteria

Previous studies showed that construction equipment is the main cause of injuries and accidents on job sites (Idoro, 2011), as the safety and health practices concerning the operators during project execution are the lowest on the list (Mbuya and Lema, 1996). Therefore, there is a need to consider such factors during the equipment selection phase. On the other hand, economic aspects are a critical factor in selecting the equipment. The contractor has three methods to procure equipment, namely Buying (100% ownership), a pre-defined fixed monthly fee for renting or leasing the equipment. The selection of the appropriate method is made based on the contractor's financial capability. For instance, large companies prefer owning the equipment, while small ones cannot afford the owing choice (Gransberg et al., 2006). Table 2.1 depicts the socio-economic criteria that should be considered for selecting construction equipment.

Table 2. 1: Socio-Economic Criteria for Selecting Equipment (Waris et al., 2014)

Socio-Economic Criteria	Author
Ownership cost	Peurifoy et al., 2006
Operational cost	Grasberg et al., 2006
Availability of local skilled operator	Zaki et al., 1996
Operator health	Kittusamy and Buchholz, 2004
Operators view and comfort	Caterpillar, 2011
Safety features	Arslan et al., 2004
Operator proficiency	Alkass et al., 1993
Training needs for operator	Mackenzie et al,. 2000
Relationship with dealer/supplier	"Prasertrungruang and Hadikusumo, 2009

2.3.2 Engineering Criteria

Engineering criteria are known to be the spine of designing the equipment. They are mainly a barometer for measuring production rate, performance, operation ability. Including those factors in the selection process will greatly reflect its smart acquisition practices (Tatum et al., 2006). Aside from this, engineering characteristics assist in lowering the maintenance and repair costs and provide higher operational efficiency (Tavakoli et al., 1989). Engineering criteria are depicted in the Table 2.2

Table 2. 2: Engineering Criteria for Selecting Equipment" (Waris et al., 2014)

Engineering Criteria	Author
Equipment age	Goldenberg and Shapira, 2007
Equipment capacity	Alkass et al., 1993
Equipment reliability	Arslan et al., 2004
Equipment efficiency	Prasertrungruang and Hadikusumo, 2009
Equipment operating life	Valli and Jeyasehar, 2012
Equipment productivity	Eldin and Mayfield, 2005
Fuel efficiency	Caterpillar, 2011
Implement system	Tatum et al., 2006
Traction system	Tatum et al., 2006
Structure and suspension system	Tatum et al., 2006
Power train system	Tatum et al., 2006
Control and information system	Tatum et al., 2006
Compliance with site operating conditions	Alkass et al. 1993, O'Brien and Zilly, 1971
Spare parts availability	Prasertrungruang and Hadikusumo, 2009

Engineering Criteria	Author
Meet job/operational requirements	Haidar et al., 1999
Meet haul road condition	Eldin and Mayfield, 2005
Versatility of equipment	Jrade and Markiz, 2012
Easy repair and maintenance	Valli and Jeyasehar, 2012
Machine/equipment standardization	Avakoli, et al. 1989

2.3.3 Environmental Criteria

All non-road construction vehicles and machinery are powered by a diesel engine, which contributes to greenhouse emissions and air pollution. Thus, the environmental aspects have become the concern of all parties involved in the contract (Guggemos and Horvath, 2006). The implementation of emissions reduction strategies becomes legislation need ((Lewis et al., 2009). Table 2.3 depicts the environmental criteria that should be considered for selecting construction equipment.

Table 2. 3: Environmental Criteria for Selecting Equipment (Waris et al., 2014)

Environmental Criteria	Author
Greenhouse gas emissions	"Yan et al., 2009"
Fossil fuel consumption	"Sharrard et al., 2007"
Energy saving	"Kim et al., 2012"
Noise control	"Koo and Ariaratnam, 2008"
Vibration control	"Koo and Ariaratnam, 2008"
Quantity of particulate matter	"Hajji, 2013"

Environmental Criteria	Author
Oil/lube leakage control	USEPA, 2007
Use of sustainable fuels	Lewis et al., 2009
Use of biodegradable lubricants and hydraulic oil	Boyde, 2002
Environmental statutory compliance	USEPA, 2007

2.4 Mathematical-Based Optimization Techniques

Due to the complex nature of the construction operations, there has been limited attention paid to the mathematical optimization process approach. Generally, better awareness of these techniques can be beneficial to all decision-makers in the construction industry, specifically to project managers. Mathematical optimization methods are used to solve various engineering problems. Even though these techniques are derived from various fields, they surprisingly can be expressed in the following way (Venkrbec et al. 2018):

$$Minimize\ or\ maximize\ \boldsymbol{f}(\boldsymbol{x}),$$

$$subject\ to: \boldsymbol{h}(\boldsymbol{x}) = 0,\ \ \boldsymbol{g}(\boldsymbol{x}) \leq 0\ or\ \ \boldsymbol{g}(\boldsymbol{x}) \geq 0\ where\ x^{lo} \leq \boldsymbol{x}\ \leq x^{up}$$

$$\boldsymbol{lo}\ indicates\ lower\ boundry, while\ \boldsymbol{up}\ indicates\ upper\ boundry$$

The objective function f***(x)*** defines the criterion for selecting the optimum solution, while the constraints describe the boundaries that delimit the space of all feasible solutions. As regards, to obtain valuable results, an appropriate method should be selected. This can be done through the analysis of the problem from its function standpoint, constrain, and decision variables. Overall, there are two solution approaches for a single criteria

optimisation problem, namely heuristic, and mathematical programming methods (Venkrbec et al. 2018).

Heuristic techniques are suitable for solving optimization problems in civil engineering as they converge fast and provide approximately optimal solutions. The most frequent heuristic techniques used in the field of CM are the following: 1) ***genetic algorithm*** *(GA),* 2) ***simulated annealing (SA),*** 3) ***direct search (DS)***, 4) ***neural networks (NN),*** and others. Similarly, mathematical programming techniques are utilized for solving optimisation problems in civil engineering. Differently, they provide exact solutions but require more time and coverage slowly in the case of optimizing discrete, nonlinear, highly combinatorial, and particularly nonconvex problems. The most famous used techniques of the latter are ***linear programming (LP)***, ***mixed-integer nonlinear programming (MILP), mixed-integer nonlinear programming (MINLP),*** and ***nonlinear programming (NLP)*** (Venkrbec et al. 2018).

2.4.1 Mathematical simulation Application in Construction

As explained earlier, Construction operations are complex and cyclic in their nature, as is the case for earthmoving operations. As a result, it is difficult to utilize one mathematical optimization technique to solve CM problems. Generally, the applications of the latter, but are not limited to, the following areas: 1) Assignment problem (AP), which deals with answering the question of how to minimize the total project cost while assigning a given number of tasks to a given number of agents (Kuhn 1955), 2) Project scheduling problem (PSP), that concerns minimizing the total project cost and it can be used for minimizing both time and cost, also it is known as time-cost trade-off problem (TC TO) (Icmeli et al. 1993), 3) Vehicle routing problem (VRP), which seeks the optimal route to

route an identical fleet of vehicles from a central point to supply destinations taking in consideration vehicle capacity as a constrain (Dantzig and Ramser 1959).

2.4.2 Mathematical simulation Application in Earthmoving operations

Ji et al. 2010 provided a linear programming model to find the most cost-efficient cut to fill assignments. The idea behind this model is to divide the large road project into several linear construction sections and then try to find the minimal earth movement between them. In relation, De Lima 2021 developed an optimization model to plan the distribution of materials in earthmoving operations. The developed model considered the interference between the cut and fill section, such as vegetation, topographical features, and rivers. This model aims to minimize the total earthmoving cost while taking into consideration project duration, volume balance, and time for the release of traffic as constraints. Excel was used for data analysis, while IBM CPLEX was used as an optimizer.

On the other hand, Moselhi and Alshibani 2007 employed a genetic algorithm with an integration with the global positioning system (GPS) to select near-optimum crew formulation. The integrated model allows real-time monitoring and tracking the crew productivity. This helps keep fleet configuration optimal at any time during construction. Also, Alshibani 2009 combined genetic algorithms and linear programming models to obtain a near-optimum crew that provides a least-cost operational plan.

Hare et al. (2011) developed a mixed-integer programming model that incorporates blocks that restrict earth movements operations across the construction site. The model was considered an extension of the classical models of optimizing earthmoving construction project costs. Their model provided a significant saving. However, the

computational model time was impractical as the number of road sections increased. As a result, they provided an algorithm to reduce the model resolution time. Yi and Lu (2016) proposed a mixed-integer linear programming model that accounts for the sensitivity of the MILP optimum results while considering the variation in the input parameters. The model categorized the parameter into three main classes, namely (1) operational class concerns the fleet characteristics, such as capacity, number of trucks, and hourly production rates, (2) haul job class (quantity and path), (3) haul road class (layout of the haul road). As the MILP reached the optimal solution, the sensitivity analysis investigated the operational class provided the haul road class (control class) remained unchanged while the objective function changes fell within the acceptable range.

Fernandes and Espindola (2019) employed the mixed-integer programming method to minimize the total transportation cost of moving soil quantities for a Brazilian highway road (BR-316) by finding the optimal amount of soil to be transferred from each borrow pit to the dumpsites. Transferred material volume was used as a decision variable while a 5 km maximum distance, the availability of the material, and its quality were used as constraints. CPLEX optimizer was used to solve the model. The results showed a reduction of 18% of the original budget. Falcão et al. (2020) built a mixed-integer model based on a mathematical problem called the vehicle routing problem. The main objective of the developed model was minimizing the haul road of multi- fleets of dump trucks. Two case studies were implemented using the model. The findings indicated that this model is a decision-making tool for project planners.

2.5 Computer-Based Optimization Techniques

2.5.1 System Dynamics (SD)

System dynamics also was known as Industrial Dynamics (Dangerfield 2014), was introduced for the first time in 1961 by Jay Forrester in his book “industrial dynamics” (Forrester 1961, Sterman 2000). It is defined as a method of modeling and testing a complex nonlinear dynamic social system (Alzraiee 2013). SD system is a famous type of continuous simulation, where a set of differential equations formulated in a conceptual model representing the abstract level of the system is governing the change. The complexity of the SD model is derived from the complexity of the differential equations used to develop the model. SD simulation model parameters change continuously over time. Thus, the system state changes continuously as well, as is the case in a continuous simulation model. (Alzraiee 2013 and Jabri 2014).

The idea behind the SD model is addressing issues by considering the aggregate of products, people, etc., and not as the case in the agent-based system considers individual agents or as the situation in discrete event simulation considers individual entities (Dangerfield 2014). To further illustrate, it considers the whole system rather than the summation of individual elements. In other words, the overall behavior of the system is determined by its structure. For instance, SD has successfully modeled systems that require holistic consideration as well as feedback loops (Alzraiee 2013). SD is used as a modeling and planning tool in the industrial system to solve complex problems related to social systems. Also, it is used in many disciplines, particularly those related to engineering, economics, social, management, as well as environmental problems (Wolstenholme 1990). According to researchers, SD is primarily an approach used to solve problems at top

management levels and constitutes elaboration on a continuous simulation that addresses the complexity of the systems and nonlinearity of feedback processes (Sterman2000, Lyneis 2001).

For a successful SD model implementation, Sterman (2000) identified a systematic procedure of five steps illustrated as follows. The first important step is system understanding. This step is crucial for the successful implementation of the model. Hence, the modeler needs to comprehend the problem deeply, identify all key variables, time horizons, and clearly understand the historical behaviors of the variables. This can be done by breaking down the problem into small components without violating SD holistic concept. The second stage is conceptualization. At this stage, the feedback loops and the theories concerning the behavior of the variables are identified. The third stage is the model formulation. It is a logical step where the structure specification, parameter estimation, behavior relationships are identified. The fourth stage is model testing for verification. The last stage represents policy design and evaluation. It is concerned with the environmental condition and new decision rules.

Three important in a better understanding of how SD works. These include the Stocks and Flows Diagram (SFDs), which represent the rate and the movement of the entities from the start to the end of the model. Causal Loops Diagrams (CLDs), and Model Boundary, which are responsible for capturing the conceptual relationships of system variables. An explanation of each term is shown below.

Model Boundary:

In the SD model, the behavior of the system is generated within a close boundary of the feedback process. To be able to define the SD model boundary, it is necessary to identify the behavior of the interest that can be obtained from the purpose of the model. The scope of the model is summarized by selecting the key variables, which can be classified as exogenous, endogenous, and excluded (Jabri 2014).

Exogenous variables, such as planned project productivity and duration, are external variables that are not involved in the model. Also, they are not explained by the feedback structure of the model. However, they are involved in the casual-effect structure. Furthermore, The Exogenous variable's value does not depend on the state of other variables. The external variables to the system determine their values. To put it in another way, exogenous variables will not influence by the internal interaction of the system.

On the other hand, endogenous variables are considered the most important variables in an SD system. These variables portray the dynamic inherent in the system. On a similar note, the endogenous variables are involved in a causal-effect structure of the SD model. In contrast, exogenous variables are dependent on the state of other variables in the system. Fatigue, overtime required, quality, and error are an example of endogenous variables. Finally, the excluded variables are variables beyond the scope of the model. Excluding these variables are necessary, as including them complicates the model and makes it difficult to be developed (Alzraiee 2013).

Causal Loops Diagrams (CLD)

Sterman 2000 states that the dynamic behavior in the SD system is mainly caused by its feedback loops. According to Richardson 1986, CLDs conceptualize the feedback system's structure as understood by the modeler. Sterman 2000 classifies CLDs into two

main categories based on the influence of the outputs on the inputs of the system. The first category is called open CLD, where the system outputs have no influence on the inputs but are responsive towards their inputs. On the other hand, the second classification is called close CLD, where the outputs both influence and respond to their inputs. Furthermore, he classifies CLDs as either positive or negative. Positive loops are a form of causal relationships that signify a self-reinforcing process. Basically, they are responsible for destabilization or stabilization of the operation, whereas the negative loops direct the operation toward a specified goal value (Alzraiee 2013). Table 2.4 illustrates how two variables, say 'A' and 'B' contained in a causal link

Table 2. 4: Denotations for Causal Loop Diagramming (Sterman 2000)

Causal Link	Description	Mathematical Formulation
	All else remaining equal, if variable 'A' increases (decreases) then 'B' increases (decreases) in variable above (below)	$\partial B/\partial A > 0$ in this case of accumulations, $B = \int_{t0}^{t}(A + \cdots)ds + B_{t0}$ (2.1)
	All else remaining equal, if variable 'A' increases (decreases) then 'B' decreases (increases) in variable below (above)	$\partial B/\partial A < 0$ in this case of accumulations, $B = \int_{t0}^{t}(-A + \cdots)ds + B_{t0}$ (2.2)
	Significant time delay is involved in implementing the causal relationship between the variables 'A' and 'B'	

LCD can be either positive or negative. As shown in the first row, the increase in the value of variable ‘A’ leads to an increase in the value of variable ‘B’, plus the decrease in the value of the variable ‘A’ leads to a decrease in the value of the variable ‘B’. In this case, a positive sign appears at the end of the arrow indicating that variable ‘A’ has a positive impact on variable 'B'. The second row shows that increasing the value of variable ‘A’ results in the decreasing of the value of variable ‘B’ and decreasing the value of variable ‘A’ results in the increase of the value of variable ‘B’. In this case, a negative sign is shown at the end of the arrows indicating that variable ‘A’ has a negative impact on variable ‘B’. This can help in mathematical computing of the change in the variables by integrating the variable's rate of change. The third row represents the most important concept in SD, namely delay. According to Sterman 2000, delays are crucial sources of system dynamic behavior and need to be controlled to avoid any instability arising in the system. Delays define as the process outputs that lag their inputs. Two parallel arrows are placed on the causal link between the variable ‘A’ and ‘B’ to represent the delay.

Stocks and Diagrams (SFDs)

While CLDs are deemed to be useful in the representation of the interdependencies and the feedback process, they fail to capture the stock and flows diagram (SFDs) of the system (Sterman 2000, Binder et al. 2004), Thus the need for Stocks and Flows Diagrams (SFDs) arises. Generally, SFDs are produced from CLDs and are responsible for the dynamic behavior of SD models (Sterman 2000). SFDs are used as integration with CLDs in the SD model to enhance the clarity of the model schema (Alzraiee 2013).

Figures 2.2 shows the typical three elements of an SFD. The rectangles represent the stocks, while the pipes with the valves pointing at the stocks represent the flows. Finally, the clouds represent the sources of inflow to or outflow from the model (Alzraiee 2013).

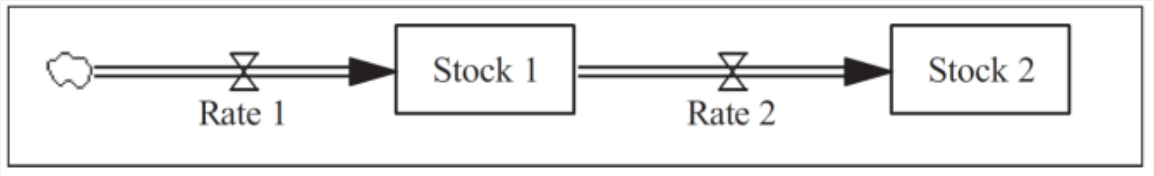


Figure 2. 2: Stocks and Flow Diagramming (SFD) (Alzraiee 2013).

In the SD model, stocks are accumulation characterization of the state of the system that generates information, which is considered the basis of decisions and actions. Stocks are used to accumulating the difference between inflows and outflows going into and leaving the stock. This is how the delay is formed in the system. However, flows are responsible for the level of accumulation at stocks and reflect the disequilibrium source in the model (Alzraiee 2013).

The hydronic principle was used to originate the SFD convention in the SD model. The principle is based on that the amount of water accumulated in a reservoir at any given period of time is equal to the difference between the water quantity flowing into the reservoir and the water quantity flowing out of the reservoir. Coping this principle to SFDs, the net flow into stock will equal the change rate of the same stock (Forrester 1961). To show how this principle applies to SFDs, mathematical equations are used to describe the model as follows 1) each stock will be assigned an initial value, which updated during the model run, 2) the updated stock and flows will be constantly observed to monitor the system's performance through decision-makers. Figure 2.3 clearly shows a representation of SFDs by mathematical equations. As can be seen from the graph, the simulation time is

divided into two small equal time intervals. At T1(time interval 1), the system state is at S1(State 1). After running the model, the state of the system is updated to S2,

which is the sum of S1 and S2, and the net flow between T2 and T1. The same is applied to S3.

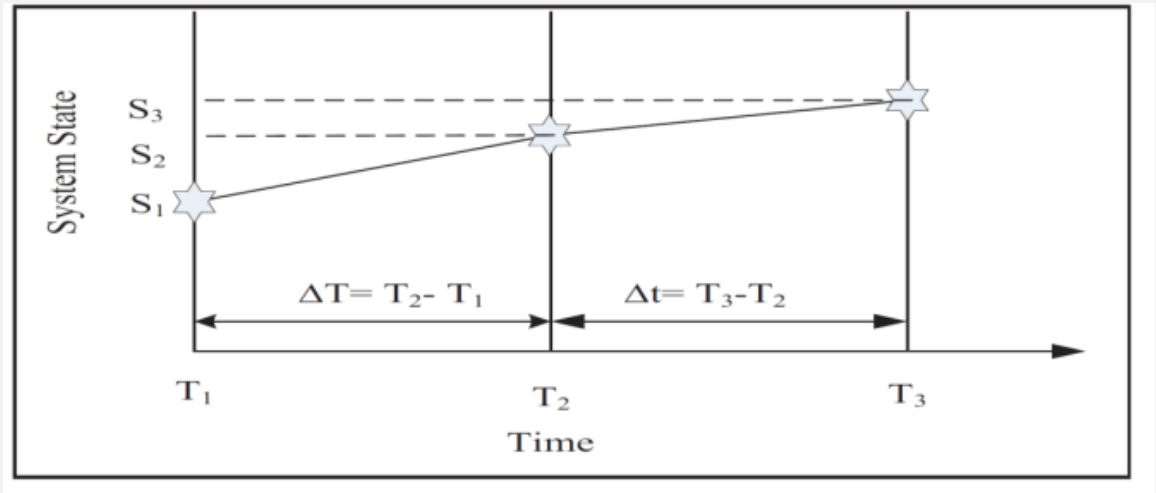


Figure 2. 3: Stocks and Flow Diagramming (SFD) (Alzraiee 2013).

2.5.2 Agent-Based Modeling (ABS)

Agent-Based Simulation, also known as Agent-Based Modeling (ABM), Agent-Based Modeling and Simulation (ABMS), Multi-Agent Simulation (MAS), etc., is defined as a "class of computational models for simulating the actions and interactions of autonomous agents, both individual or collective entities such as organizations or groups, to assess their effects on the system as a whole." (Grimm and Railsback 2013). ABS is different than DES and SD in which a bottom-up approach is used to build the model elements before studying the whole process. This allows the investigation of the model dynamics fundamentals that provides a realistic conclusion (Jabri 2014).

There is no agreement between the researchers on the precise definition of the term agent. However, the majority agree with Wooldridge 1995 that an agent can be an object,

program, computer system if meets the following properties: 1) Autonomy, which means that the agent should have the power over its behavior and function without human interface, 2) Social ability, in which it can communicate with other agent and/or human operator, 3) Reactivity: the agent should have the ability to detect and respond to any changes in its environment, 4) pro-activeness: the agent should have the ability to reason and learn from experience.

The basic principle behind every AB model is to generate behavior as a result of the interaction between other agents. This behavior is also referred to as emergence or emergent behavior in the AB terminology. The emergence of behavior can be seen in various existing AB models, from the simple to the most sophisticated one. However, Mecal and North 2010 address the question of emergence in AB models by demonstrating that the bottom-up approach to construct AB models interaction by interaction and agent by agent results in a state of self-organization. In other words, behaviors, patterns, and structures appear from the AB model without being directly programmed into the AB model. Unlike DES and SD, ABMS focuses on the representation of the heterogeneity of agents through their population and the development of self-organization.

2.5.3 Hybrid Simulation Method

As aforesaid, construction projects have a dynamic and complex nature. Further, they involve uncertainties, dependencies, and complicated behaviors. Hence, using basic simulation methods might be insufficient to model the construction projects appropriately; there is a need for hybrid approaches. The latter is defined as combinations of basic methods (DES, SD, and ABMS), or pairing other techniques, such as neural networks (NNs) and fussy logic (FL)(Bokor et al. 2019).

Hybrid model has the advantage of utilizing the benefits of each method and balancing its shortcomings. Therefore, for better representation of the reality, the selection of the most suitable approach for each model component should be done, based on the question to be answered (Borshchev 2013, Borshchev and Filippov 2004). In the lectures, there are different existing names for the combined approaches, including "multi-paradigm", "hybrid", and "multi-method" simulations (Mustafee et al., 2015).

DES focuses on the process and handles the operational level issues, whereas DS deals with the strategic level. Thus, compounding them creates more efficient, realistic, and improved hybrid models that can be used for increasing productivity through coordinating the managerial and operational decisions (Alvanchi et al. 2011, Peña-Mora et al. 2008). Furthermore, the combination of the DES-SD approach can be used to obtain more accurate project duration data (Alzraiee et al. 2015). On the other hand, DES and SD models are combined with other models to achieve different purposes. As an example, a combination of DES-ABM can be useful in operational research (Siebers et al. 2010). The positive features of combining SD-ABM are useful to compare the result of each approach (Lättilä et al. 2010). Also, the combination of the three approaches, namely DES, SD, and ABM is possible (Borshchev 2013).

Moradi et al. 2015 defined three different ways of linking the DES and SD models. First, is the hierarchical format, where the operational DES and the strategic SD vertically interact. In this format, one of the two models will be dominant (Figure 2. 4). Second, phase-to-phase format. In this scenario, the two models run separately. Third, integrated format, where constant bidirectional interactions are existing between the models (Figure 2.5). Swinerd and McNaught 2012 provided

A method of combining the SD-ABM models (Figure 2.6).

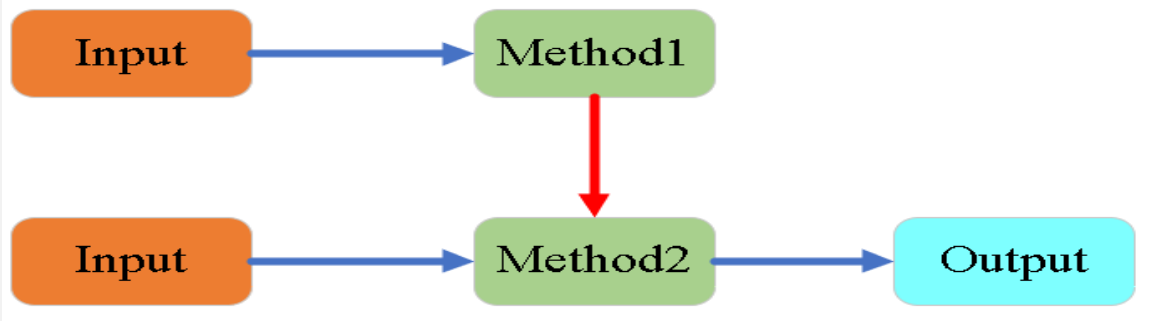


Figure 2. 4: Dominant structure of hybrid simulation (in this case, Method 2 is dominant) (Moradi et al. 2015)

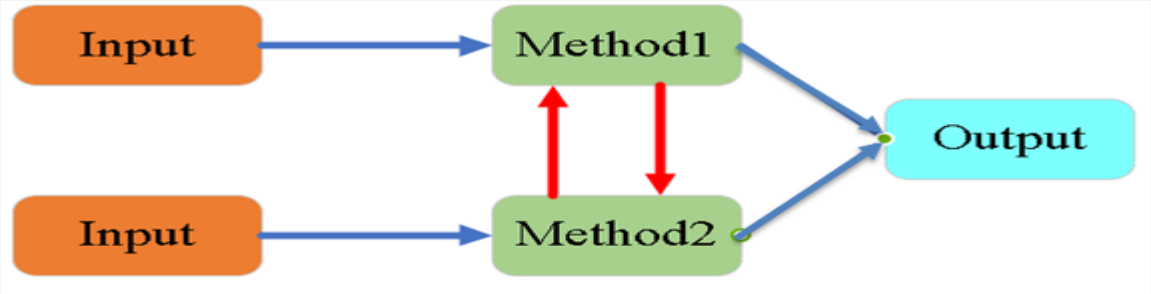


Figure 2. 5: Integrated structure of hybrid simulation (Moradi et al. 2015)

Figure 2. 6: Parallel structure of hybrid simulation (McNaught 2012)

2.6 Simulation Application in Construction Management

This section discusses the application of computer-based simulation techniques in the construction field and its limitations.

2.6.1 System Dynamic Applications and Its Limitation

Work To Do' SD model, developed by Robert in 1974, was the first-time introducing SD modeling application in the field of construction management. The latter

was applied to address issues that have dynamic inherent such as productivity, resources, actual progress, and perceived progress (Alzraiee 2013). Additionally, SD models have been applied to explore the interaction of factors and feedback in construction activities. However, the application of SD models can be seen in various fields of construction management, namely 1) project planning and control, 2) performance and effectiveness, 3) sustainability, 4) organization and stakeholder management, 5) knowledge management, 6) site and resources management, 7) strategic management, 8) risk analysis and management. Table 2.5 depicts the application of SD in the field of CM and the corresponding authors.

Table 2. 5: Application of SD in the Field of CM

Field	Type of investigation	Author
Sustainability	waste and demolition management	Yuan et al. 2011
Project Planning and Control	cost/ schedule control and change management	Sing et al. 2016
Performance and Effectiveness	Project performance enhancement by optimizing management plan and changes and policymaking	Moonseo & PeñaMora 2003
Strategic Management	systematic understanding of the strategic issues involved in CM	Rodrigues et al. 1996
Site and Resource Management	safety and resource management	Park, 2005

Field	Type of investigation	Author
Risk Analysis and Management	Analyzing the risk factors that involve complex casual-loop relationships	Wang et al. 2016
Knowledge Management	strategic learning in a dynamic environment	Chen & Fong, 2013
Organization and Stakeholder Management	organizational capabilities and excellence	Terouhid & Ries, 2016

Limitation of the Systemic Dynamic (SD)

Jabri 2014 states that the limitations of SD arise from its nature method. That makes the SD model unable to show a detailed view of the quantitative operational aspect of the system. On the other hand, randomness is another drawback of SD since it relies on deterministic mathematical differential equations. Finally, to develop and validate an SD model, huge, detailed sets of data are required. Also, it requires specialized modeling skills, thus using the SD model is a time-consuming procedure (Alzraiee 2013).

2.6.2 Agent-Based Modeling Application and Its Limitation

The majority of the previous studies regarding the application of ABMS in the field of the construction sector are concentrated on the following areas: 1) construction claims, which involves sharing, discussion of vital information and works task organization, 2) infrastructure management seeking for the performance enhancement, 3) supply change management that involves sharing the necessary information about the schedule, stocks,

and cost to assure the successful implementation of supply change operation (Jabri 2014). Table 2.6 provides a brief explanation of ABMS application related to the aforementioned fields

Table 2. 6: ABMS Application in CM

Field	Type of investigation	Author
Supply chain	Investigating the significance of real-time information sharing in the construction	Min & Bjornsson, 2008
Construction claim management	Enhancing the negotiation power as well as convergences between the project's parties	ElAdaway & Kandil, 2009
infrastructure management	Decision-making and budget allocation of infrastructure projects	Sanford & McNeil, 2008

2.6.3 Hybrid System Applications and Its Limitation

According to Alzraiee 2013, there is a need to integrate both DES and SD into one hybrid simulation model as construction operations' nature is neither fully discrete nor continuous. Moreover, a hybrid simulation model helps to overcome the drawbacks of each model separately. For instance, SD fails to represent the detailed operational level of construction projects.

However, there are a few available lecturers regarding the application of the DES-SD hybrid system in the construction industry. Some applications of utilizing the hybrid system in CM are depicted in Figure 2.7.

Table 2. 7: Hybrid System Applications in CM

Type of investigation	Author
Analyzing the operation and strategic aspects of CM	Peña-Mora et al. 2008
Optimisation of construction site layout	Zhou et al. 2009
integrating safety behavior into construction planning	Goh et al. 2016

Limitation of the Hybrid model

Eldabi et al. state that the hybrid simulation technique is a comparatively new method in the field of the construction industry. Yet, it requires more research to validate its capability. Moreover, there is a lack of documenting the hybridized process. All these factors are limit the adoption of the DES-SD model in the construction industry.

On the other hand, Alzraiee 2013, listed some of the limitations of DES-SD as follows. 1) there are some restrictions regarding the integration of DES and SD, 2) SD conceptual model relies heavily on the available data, and the simulation process is time-consuming 3) for a modeler to develop a hybrid model, a knowledge of DES, and SD is required.

2.7 Discrete-Event Simulation (DES)

2.7.1 Discrete-Event Overview

Discrete-event simulation is defined as a top-down architectural model (Yin and Mckay 2018) consisting of a series of logically separated processes (events) that are automatically updated through time. The idea behind the DSE model is addressing issues by considering the individual entities (Brailsford and Hilton 2001). To further illustrate, it

treats the system as a summation of individual elements that interact with each other to generate outcomes. In other words, the overall behavior of the system is determined by its individual elements, where the state of the system changes only when the events occur. DSE utilizes the numerical method for solving dynamic complex problems. Overall, it is used in many disciplines, particularly those related to engineering, economics, social, management, services, as well as environmental problems (Babulak 2008).

2.7.2 DES Major Concepts

To better understand the behavior of the DSE model, it is necessary to understand its components. Ingalls 2002, and Bank et al. 1984, described the following concepts. *1)* ***System***, a collection of entities that interact with each other's to achieve a specific goal. ***2) System state***, a group of variables that contain the necessary to describe the system at any given time. ***3) Model***, a conceptual representation of the system that contains logical, structural, or mathematical relationship that describes the system in terms of entities with their attributes, process, sets, activities, events, and delays. ***4) attributes*** (e.g., awaiting customer priority), are essential to understand the performance and function of entities in the simulation. Attributes are a unique characteristic of a given entity. ***5) List*** (e.g., all customers waiting in the line at the current time ordered by priority), permanent or temporary collection of associated entities organized within a logical fashion. ***6) Events*** and Activities (e.g., service time), a period of time with a specified length. The interaction of entities with activities creates events. Activities contain three elements, namely, delays, queues, and logic. Delay occurs whenever the entity paused for an ascertained time, which is unknown until it ends. Queues occur where the entities wait for an indefinite ascertained time in a simulation place. Lastly, logic activities in a simple way permit the entities to

change the state of the system through the manipulation of decision logic or state variables. ***7) Calendar (***Event list), a group of events that will occur in the future. 8***) Event notice,*** a record of events type and time along with the data necessary for event execution. ***9) Clock*** is a variable that represents the simulated time. For instance, assume the current simulation time is Clock =10 min, and the inspection is started after 5 min, then event time will be (10+5=15 min), ***10) Queue*** is used to store the entities for a length of time and release them when the resources are become idle, ***11) lastly, the Entity*** (e.g., People, product, machine), System component, or object that needs a precise representation in the model. The change of the state of the system is caused by entities. Besides, the stopping condition of the simulation is linked to the entity's availability. There are some rules are used to order the entities on the list, such as First in-First out (FIFO), Last in-First out (LIFO), or based on the attributes, such as due date. It should be noted that different simulation packages use different terminologies of the same concept. For instance, Set, or chain is used instead of a list (Banks 1984).

Borshchev and Filippov 2004, described how the entities travel through the DES flowchart as follows, entity seizes the required resources to perform the needed tasks. The seized resources will not be released until the task is completed. As soon as the entity reals the source, the simulation clock will record the time. Sometimes, the resources are not available or busy at the time when the entity acquires them. In this situation, the entity will be stuck in a queue until the required recourses are free again. Eventually, all information will be stored in a chronological list based on the occurrence order.

Taking fast food restaurant’s drive-through window as an illustration example of the purpose of fully comprehending the DES major components. Figure 2.7 shows the

flow logic. As the car leaves the street and enters the restaurant area, the driver has two options to choose from either to get in or not to get in line. If he considers leaving the line, he leaves as a dissatisfied customer. In the situation where he considers getting in the line, the following two things will occur simultaneously. First, if there is an available room, he moves forward to order. In case no room is available, he requires to wait at the menu board until a new room is available. As soon as the room becomes available, he proceeds so the next customer can order. Second, the driver's order is received in the kitchen, where the order preparation is begun as soon as there is an available cook. At the time the driver arrives at the pickup window, he pays and picks the order if it is ready. Otherwise, he has to wait until the preparation is completed (Ingalls 2002).

From the aforementioned example, the following concepts can be extracted. The car enters the restaurant, and order placing are two ***entities***. The time of the day, where the car enters the restaurant, and the order value are ***attributes***. Waiting at the menu board, waiting for the order preparation, and waiting to pick up the order are ***delays***. The part of the line waiting at the menu board waiting for a room to be available, the order waiting in the kitchen to be prepared, the part of the line waiting to pick the window are ***Queues***. The menu board, kitchen, order pick-up window are ***resources.***

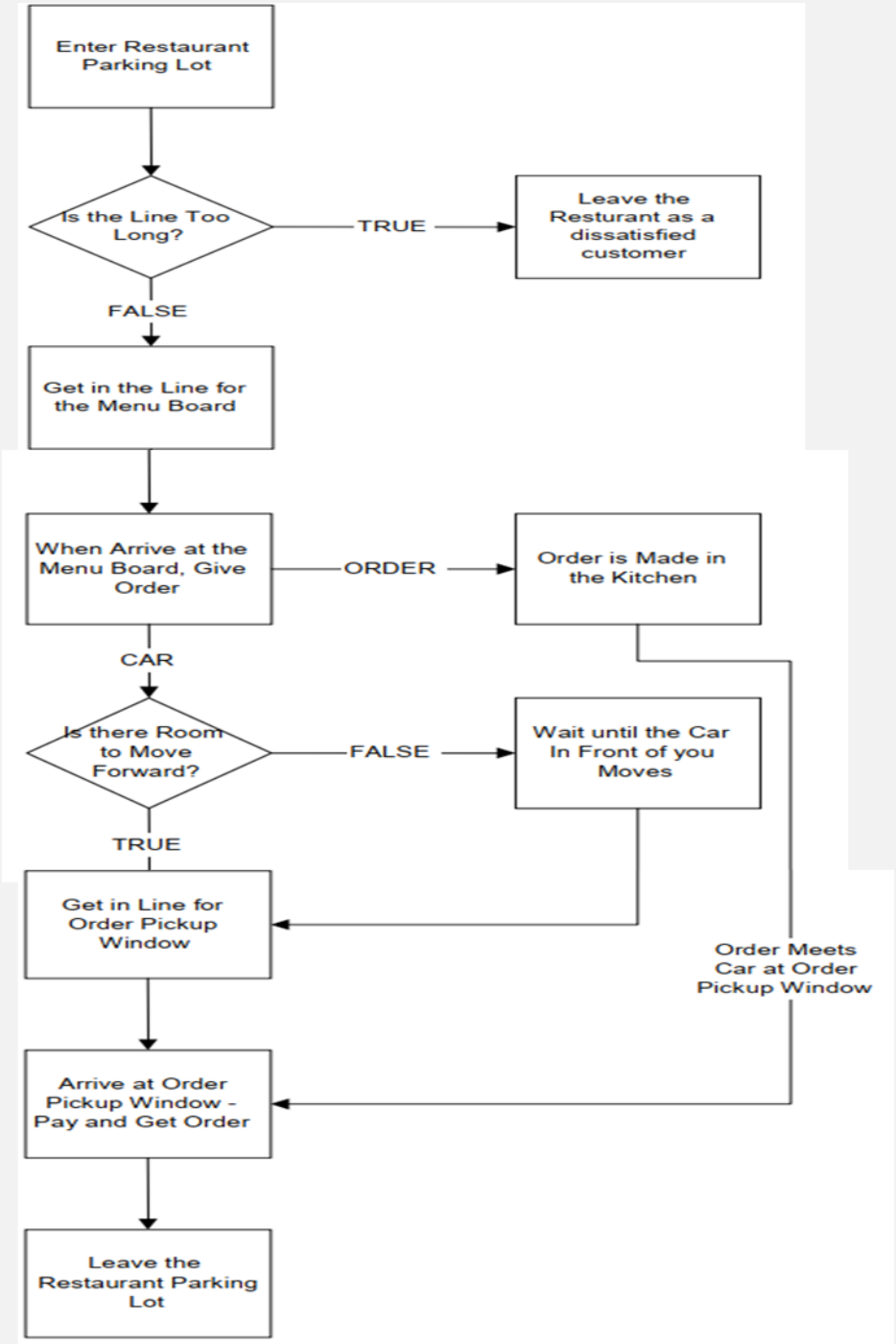


Figure 2. 7: Drive-Through Example Logic Flow (Ingalls 2002).

2.7.3 DES Model Behavior

Figure 2.8 depicts the simulation behavior of the DES model. As seen from the figure, three consecutive events (E1, E2, E3) that take place at three-time sets. At the initial state, the simulation clock records the time as T0 and the system's state as S0. The occurrence of event E1 will change the state of the system from S0 (system state at T0) to S1 (system state at T1). Hence, the simulation clock records the system state as S1 and T1. The same concepts apply to the cases of S2, S3, T2, T3, when the events E2, E3 occur. The zero-slope line (A) represents the behavior of the DES model, where the system state between consecutive events (T0 and T1) and (T1 and T2) will not be updated until the next scheduled event occurred. Finally, the curved line (B) represents the expected actual state of the system when considering the state between events.

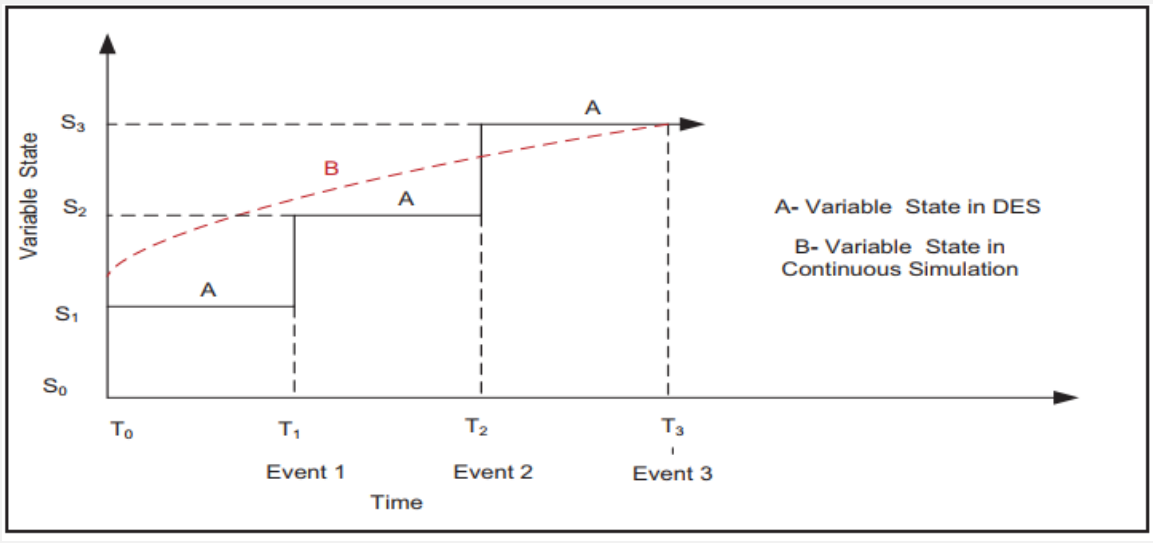


Figure 2. 8: System state update in DES and continuous simulation (Alzraiee 2013)

2.7.4 Discrete-Event Simulation Application in Construction

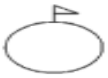
Discrete event simulation has a variety of applications in the construction industry. This is DSE is the oldest simulation technique introduced to this field (Jabri 2014). Also,

DSE is a powerful tool supporting cyclic nature activities, as is the case in the construction. The application of DSE is not limited to, Project scheduling and planning, road construction and pavement, transportation, earthmoving operation. Recently, many efforts have been introduced to the use of DSE in estimating Co2 emissions from off-site construction equipment. The following paragraphs discuss the remarkable efforts of the researchers in using DES in various aspects of the construction field.

2.7.5 General Application of DES in Construction Management

Halpin 1997 initiated the beginning of the simulation in construction by introducing the CYclic Construction Operation Network (CYCLONE), a general-purpose simulation language that provides the ability of planning, analyzing, and controlling the cyclic nature construction operation. CYCLONE is applicable for both simple and very complex operations such as earthmoving, highway projects, crane operation, concrete pouring, and pipe laying. CYCLONE has a generic nature language, which gives the advantage of modeling cyclic systems outside of the construction as the case in projects' scheduling. Table 2.8 provides an overview of CYCLONE Modeling elements. Figure 2.9 represents an example of the CYCLONE model.

Table 2. 8: Elements of CYCLONE Modeling (Halpin and Riggs 1992)

Name	Symbol	Function
Normal activity		Units arriving at Normal will be processed right away without delaying.
Combination (COMBI) activity		Units arriving at COMBI will be processed if units are available in all preceding Queue node.
Queue node		Queue provides position that allows units are delayed pending COMBI activities.
Consolidate function node		Consolidate function node performs the consolidate marking.
Counter		Counter measures the modeled system's production rate.
Arcs		Arcs show the logic that units flow from element to element.

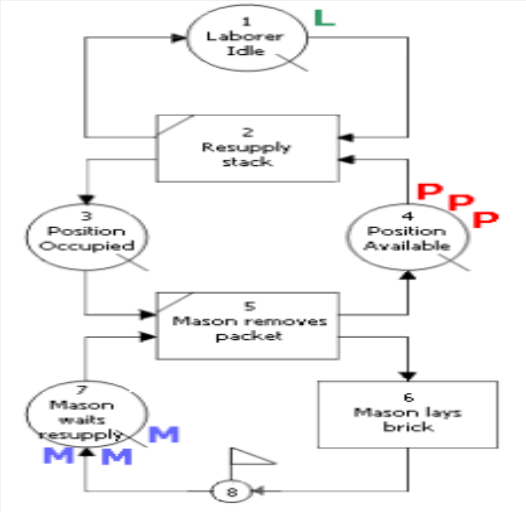


Figure 2. 9: Example of CYCLONE model (Zhang 2005)

The introduction of CYCLONE simulation to the construction marked the spark for developing other simulation programs such as DISCO (Haung and Halpin 1994), STROBOSCOPE (Martinez and Ioannou 1999, Martinez 1996), SIMPHONY (Hajjar and AbouRizk 1999), Micro-CYCLONE (Halpin and Martinez 1990), CIPROS (Tommelein et al. 1994), UM-CYCLONE (Ioannaou 1989) and HSM (Sawhney and AbouRizk 1995).

Figure 2.10 depicts the historical development of the simulation program from 1970 to 2007.

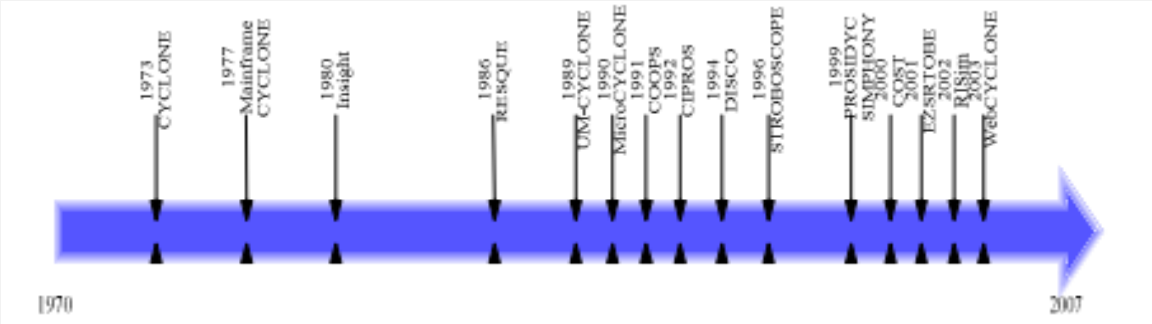


Figure 2. 10: Historical Development of Simulation Program (Abduh 2007)

Oloufa 1993 introduced a new simulation tool for modeling and simulation of construction operation called MODSIM. This tool is based on two programming languages, namely object-oriented and procedural. MODSIM aims to simplify the physical building process of a simulated model by replacing the programming code with a graphical user interface. MODSIM help in representing the construction operation entities and resources by creating objects of different classes.

Haung and Halpin 1994 followed the same track as Oloufa in adopting the graphical user interface rather than extensive code writing by introducing DISCO (Dynamic Interface Simulation for Construction Operation). The idea behind DISCO is to demonstrate the dynamics of the construction operations during the simulation run by employing a schematic modeling diagram. Running DISCO will dynamically report graphical and tabular format on each node of the static model diagram. A DISCO format of a dry batch delivery and concrete placement model diagram is shown in Figure 2.11. Tommelin et al. 1994 provided another based object-oriented system tool for simulation of construction

operation by integrating resources available in a library of construction methods with data from specification, design drawing, and construction plan.

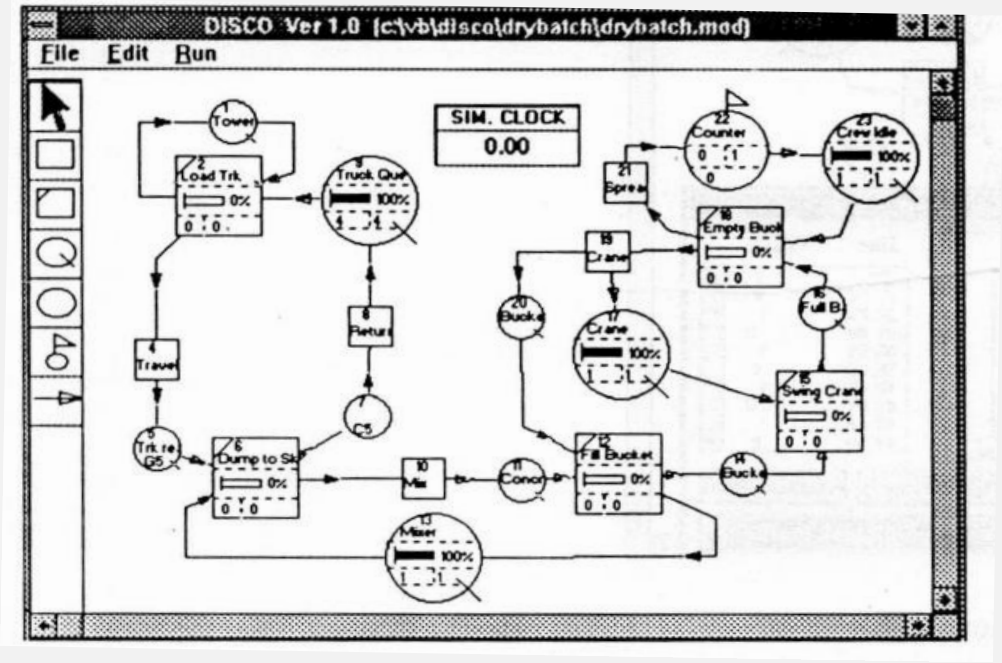


Figure 2. 11: Model Diagram of a Dry Batch Delivery and Concrete Placement Model in DISCO (Haung and Halpin 1994)

Martinez 1996, as a part of his Ph.D. research, develop a general-purpose simulation program for simulation of complex construction operation called STROBOSCOPE (STate- and ResOurce-Based Simulation of COnstruction ProcEsses). STROBOSCOPE is based on C programming language where the user writes a code to develop a model or can use the graphical network-based available in EZstobe. STROBOSCOPE can make complex dynamic decisions according to the system characteristic, attributes, and resources state. This makes STROBOSCOPE a distinguished tool for modeling complex construction operations such as earthmoving and road construction. In 1998, Martinez provided another special-purpose simulation program

called Earthmover for simulation of earthmoving operation. Figure 2.12 depicts a STROBOSCOPE network fragment for earthmoving operation.

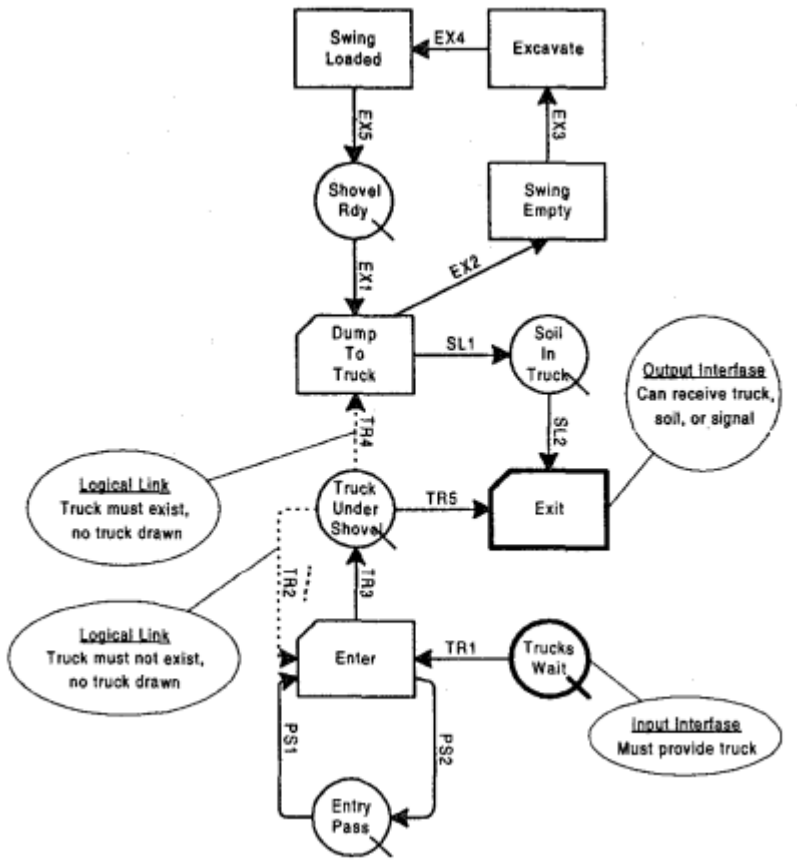


Figure 2. 12: STROBOSCOPE Network Fragment for Earthmoving Operation

Shi and AboRizk 1997 used an object-oriented system to develop a tool called Resource-based Modeling (RBM) for simulation of the construction operation. RBM is used to define and store the process of active resources as an atomic model in a model library. The user can use the stored atoms as a base for the project, then select the required resources and project site conditions from the library. This is an efficient tool as no professional programming skills are required.

Sawheny and AboRizk 1995 used the concept of work breakdown structure (WBS) and simulation process to overcome the limitation of CPM (the traditional approach for

planning construction projects) by developing a Hierarchical Simulation Modeling (HSM). HSM allows the modular to develop the project plan using a symbol-based graphical format.

Hajjar and AbouRizk 1999 integrated three special-purpose simulation tools namely, 1) AP2-Earth (Hajjar and AbouRizk 1997, a tool for earthmoving operation), 2|) CRUISER (Hajjar and AbouRizk 1998, a tool for aggregate production plants), 3) CSD (Hajjar et al. 1998, optimization tool for construction dewatering operation) to develop a special-purpose simulation (SPS) tool called SIMPHONY. SIMPHONY allows the user to create an SPS model by using a predefined template or by creating a new modeling element to meet project requirements.

2.7.6 DES Application in Road construction

SDESA (Lu 2003) is a new Simplified Discrete-Event Simulation Approach used to overcome the limitations arising from using the traditional CPM for planning cyclic, linear, and asphalt paving construction systems. SDESA is based on the extraction of constructive features from activity/event-based simulation. This tool has been used for two road construction projects in Hong Kong. However, SDESA can be used as a general-purpose simulation method for planning complex construction. It can offer the DES capability in handling the looping process, dynamic queuing as well as the tracking of individual resources. Also, it can be used as an SPS tool for complex construction of practical size as the case in “the single-plant-multiple-site ready-mixed-concrete batch, truck-mixing travel, and site place system”.

Labban et al. 2013 investigated the possibility of building an asphalt paving simulator that is accessible to users without simulation expertise. The idea behind this proposed model is to produce a typical DES of the process being modeled as the following steps. 1) collection of the required data for carrying product processing as well as environmental information. 2) developing an algorithm to prepare the collected data for the simulation. 3) processing the input data by using a self-replication generic DES engine. On the other hand, Aziz et al. 2017 investigated the possibility of increasing the production rate of highway construction and minimizing road closure time by integrating DES with Value Stream Mapping (VSM).

2.7.7 DES Application in Reducing CO2 Emissions

Construction sustainability has become the concern of all parties involved in the construction industry, especially the problem of green gases emissions. However, many researchers utilized DES in minimizing not only project cost but also Co2 emissions. LI and Lel 2010, created a DES model that accurately provides a micro-level realistic quantification of Co2 emissions. Similarly, Zhang 2015 introduced a DES model to evaluate the non-road construction emission-reduction plans. The developed model accounts for the randomness, dynamic interaction as well as uncertainties in construction. This model is assumed to provide stakeholders with an alternative way to identify the crucial activities and the emission-related operation to develop an emission-reduction plan. Ahn et al. 2010 as well presented a DES method to enhance the estimation of emission in construction operation.

DES Application in Optimization of Construction Operations

The complexity of the modern construction operation necessitates the development of a new simulation technique to reduce the uncertainty and meet the project specification. As regards, Elwaki 2011, as part of his Ph.D. research, created a simulation language called KEYSTONE (Knowledge Discovery Based Simulation System) that accounts for missing data, outliers in the input data, and fuzziness. KEYSTONE models qualitative variables using Fuzzy clustering. KEYSTONE has an optimization engine that can be used for selecting the optimum combination of resources.

On a similar note, DES has been acknowledged as a powerful optimization simulation technique of complex construction operations, especially earthmoving, mining, and road construction operations., Botín et al. 2015 provided a management optimization tool for the real-time face allocation of operation and equipment performance. This tool aims to minimize the duration of pre-production development in block-cave projects and reduce the high-risk level. Furthermore, it can assist the management decisions in equipment dispatching and short-term planning system. The application of this tool in the Chuquicamata Underground Project in Chile proved its ability by bringing forward the start-up date by 420 days.

Rodrigues et al. 2018 introduced a decision-making tool called Colored Petri Net (CPN) aiming to reduce the operational cost and planning time in earthmoving operation through considering the motor grader. The model is used to identify the duration of the service and the related operational cost. Correspondingly, Montaser et al. 2012 provided a tool for estimating the productivity of earthmoving operations in near-real-time by integrating the Global Position System (GPS) with commercial software. This tool support

project managers in taking quick corrective action in case of dispersion between actual and planned performance.

Regarding the use of DES in optimizing fleet selection in the earthmoving process, Alshibani and Moeselhi 2012 presented a near-optimum fleet selection model that helps the contractor to assist the risk associated with fleet reconfiguration cost. Also, the developed model accounts for the uncertainties concerning the activity during the construction as well as project cost (direct and indirect), and contractor available resources. The proposed model integrates the optimization technique into the simulation analysis, in addition to using GPS to collect near-time data of the hauling units. Moreover, Lu and Yi 2018 presented a Simulation-based Earthmoving Fleet Optimization Platform (SEFOP) to help decision-makers automatically select and allocate the optimum fleet for earthmoving operation in an efficient and user-friendly manner. Particularly, SEFOP is created to maximize the profit resource planning.

2.7.8 Discrete-Event Simulation Technique Limitations

Even though DES has been acknowledged and has given added value to the construction operation, DES has its limitations as any other simulation technique. To begin with, DES is a computer-based simulation technique, which means both the limitation of the developed model and the DES are involved. Second, according to the researcher, one significant drawback of DES is that the external factors influencing the operation being modeled cannot be completely captured (Jabri 2014).

On the other hand, DES is still unable to assess the model system's stability in the surrounding environment. Therefore, the surrounding environment could derive the system

performance in a non-linear hidden causal relationship (Helal 2008). Zulch et al. 2002 explain the reason behind this problem is that the strategic level variables are continuous and qualitative in their nature. This creates a challenge when using DES to model this level.

On a similar note, the advancement mechanism of DES derives many difficulties when accounting for the overall operation being modeled (Martin and Raffo 2001). However, even on the operational level, DES is unable to provide a complete overview of consecutive events and time steps (Alzraiee 2013). The aforementioned DES limitations are related to the behavior techniques themselves; these delimit the full comprehension of the interaction between the system's entities and parameters in the actual state of the system in the modeling process.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Chapter Overview

This chapter is devoted to providing a comprehensive description of the research methodology. The key idea of the proposed model is integrating the Mixed Integer Programming optimization technique with Discrete Event Simulation (DES) to obtain the least cost of a highway construction project by considering the dynamic change of the fleet as the project progress at each borrow pit and landfill. This model is unique since it is the only model that considers the fleet dynamic configuration, as depicted in figure 3.2. The proposed model will be implemented using both mathematical optimization and automated simulation tools. For the sake of achieving this goal, a detailed approach for creating Mixed Integer Programming (MIP) model for earthmoving operations is presented in section 3.2. Section 3.4 is dedicated to providing a comprehensive DES model for a highway construction project, including a detailed outline of each entity, resources, events, and their attributes. On a similar note, the flow logic of the entities in the model is explained in this section. A breakdown of the methodology is demonstrated in Figure 3.1 below.

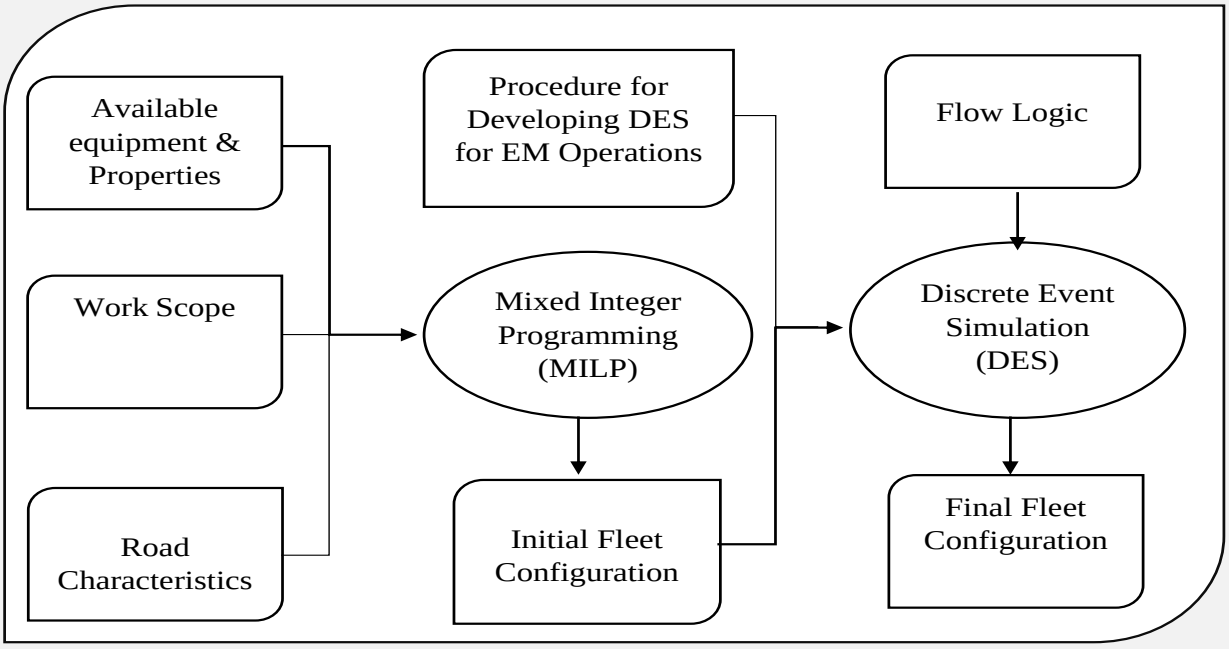


Figure 3. 1: Methodology

Dynamic Fleet Configuration

The definition of the dynamic configuration term indicates that each crew's equipment (e.g., scrapers-pushers system, trucks-loaders system) differs per shift based on the remaining material quantities in each borrow pit. For instance, assume that crew number one operates between borrow pit one and landfill one, and it consists of eight scrapers and two pushers on the first working day. On the second working day, the number of scrapers and pushers of crew one will be different from the previous day if the remaining soil materials in the borrow pit do not require that number of equipment on the first day. Figure 3.2 Portraits the term dynamic configuration when the line of balance is used to plan the earthmoving operations. Hence, the fleet has to be re-arranged so that the least cost is maintained

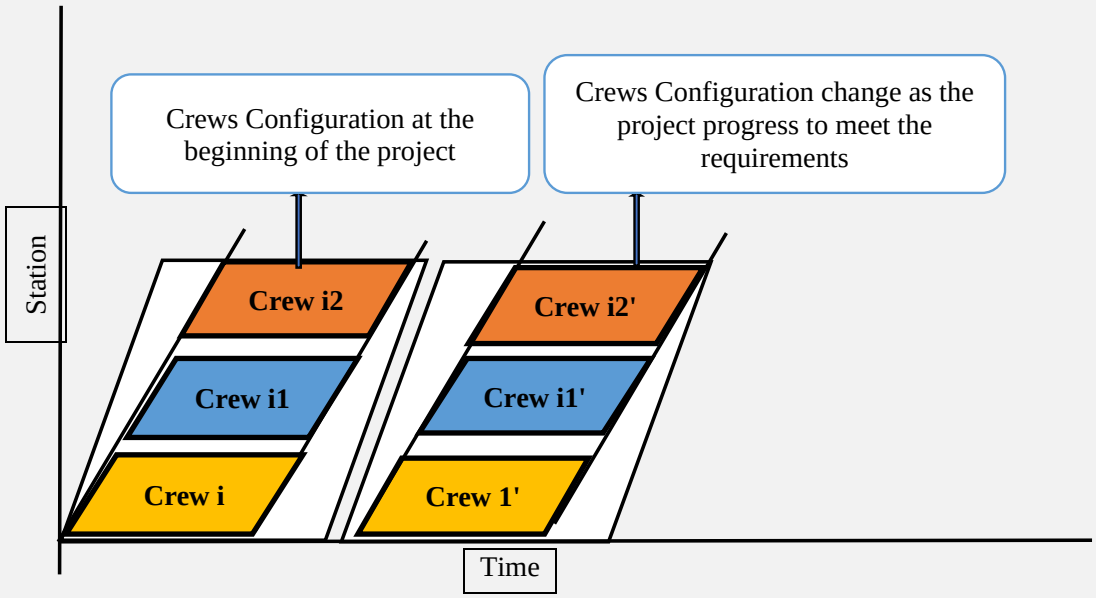


Figure 3. 2: Dynamic Fleet Configuration

3.2 A procedure for Developing Mixed Integer Programming Model for EM Operations

As mentioned in section 2.3, the two mathematical solution approaches for an optimization problem are heuristic and mathematical programming. For achieving the purpose of this study, the latter will be considered to obtain the least possible cost of a highway construction project. However, it is important to understand the planning and the cyclic nature of earthmoving operations before the model development. In general, the four main distinguished tasks of each cycle are Loading, hauling, dumping, and return (Figure 3.3). The time required to complete each cycle is varied according to several factors like road characteristics, weather conditions, etc.

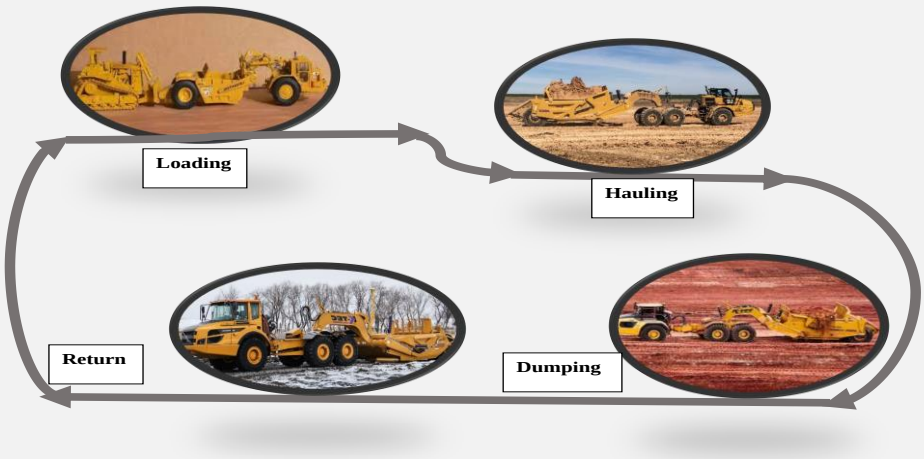


Figure 3. 3: Pusher-Scraper Cycle Time

3.2.1 Planning of Earthmoving Operations

To develop a comprehensive understanding of the developed model, the following demonstrative example regarding planning the earthmoving operations is provided.

Considering the following bar chart for one cycle (Figure 3.4), the expected productivity, idle time of one pusher, and one scraper in the crew are as follows:

The bar chart indicates that the Pusher Cycle Time = 3 min, Scraper Cycle Time= 10 min, Pusher Idle Time = 7 min. Hence the utilization rate of each can be calculated as follow:

Time (min)		1	2	3	4	5	6	7	8	9	10
Equipment Type	Pusher	Loading			Pusher Idel Time						
	Scraper	Loading			Hauling				Dumping	Return	

Figure 3. 4: Pusher-Scraper One Cycle Time 1

$$Pusher\ Utilization\ (U_p) = \left(\frac{3}{10}\right) X\ 100 = 30\%$$

$$Scraper\ Utilization\ (U_s) = \left(\frac{10}{10}\right) X\ 100 = 100\%$$

Since the utilization rate of the scraper is 100%, crew productivity is calculated based on its productivity. Assuming the scraper capacity = 15 m^3, the whole productivity of the fleet is:

$$Crew\ productivity = \frac{\#\ of\ scraper\ x\ scraper\ capcity}{scraper\ cycle\ time} = \frac{1\ x\ 15}{10} x\ 60 \frac{min}{hr} = 90 \frac{m^3}{hr}$$

The calculated productivity is not the optimum as the pusher remains idle for 7 min, which will result in a cost with no production. Let's add an extra scraper to the fleet to see how the productivity of the fleet alters. The new bar chart representation will be as follow (Figure 3.5):

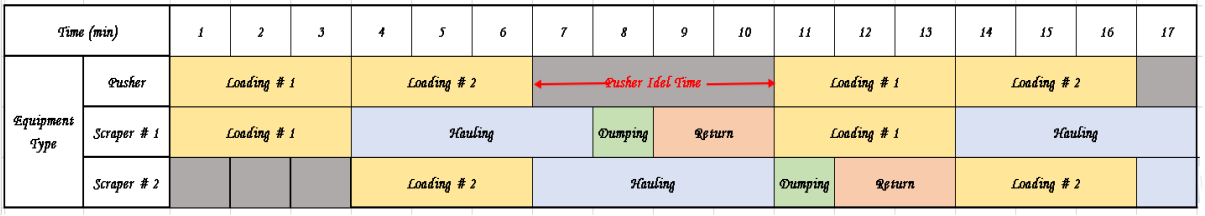


Figure 3. 5: Pusher-Scraper One Cycle Time 2

In the second case, the bar chart shows that the Pusher Cycle Time = 6 min, Scraper Cycle Time= 10 min, Pusher Idle Time = 4 min. Hence, the new utilization rate of each can be calculated as follow:

$$Pusher\ Utilization\ (U_p) = \left(\frac{6}{10}\right) X\ 100 = 60\%$$

$$Scraper\ Utilization\ (U_s) = \left(\frac{10}{10}\right) X\ 100 = 100\%$$

Scrapers are controlling the operation as their utilization rate is 100%. In this scenario the new crew productivity is:

$$Crew\ productivity = \frac{\#\ of\ scraper\ x\ scraper\ capcity}{scraper\ cycle\ time} = \frac{2\ x\ 15}{10} x\ 60 \frac{min}{hr} = 180 \frac{m^3}{hr}$$

It can be seen that scrapers still control the operation cycle, and the pusher still has an idle time of 3 minutes. For the operation efficiency to be improved, more scrapers should be used. If an additional scraper is used, the following is found:

Pusher Cycle Time = 9 min, Scraper Cycle Time= 10 min, Pusher Idle Time = 1 min.

$$Pusher\ Utilization\ (U_p) = \left(\frac{9}{10}\right) X\ 100 = 90\%$$

$$Scraper\ Utilization\ (U_s) = \left(\frac{10}{10}\right) X\ 100 = 100\%$$

Again, scrapers are controlling the operation as their utilization rate is 100%. In this case the new crew productivity is:

$$Crew\ productivity = \frac{\#\ of\ scraper\ x\ scraper\ capcity}{scraper\ cycle\ time} = \frac{3\ x\ 15}{10} x\ 60 \frac{min}{hr} = 270 \frac{m^3}{hr}$$

Now, the operation can be considered as efficient U_s = 100 % & U_p= 90%. However, the pusher is not fully utilized and if one more scraper is used (# scraper = 4), the following will result (Figure 3.6):

Figure 3. 6: Pusher-Scraper One Cycle Time 3

As it can be seen from the above bar chart, the pusher is fully utilized. However, the scrapers are having an idle time of 2 minutes.

Pusher Cycle Time = 12 min, Scraper Cycle Time= 10 min, Scraper Idle Time = 2 min.

$$Pusher\ Utilization\ (U_p) = \left(\frac{12}{12}\right) X\ 100 = 100\%$$

$$Scraper\ Utilization\ (U_s) = \left(\frac{10}{12}\right) X\ 100 = 83.33\ \%$$

This time, Pusher is controlling the operation cycle as their utilization rate is 100%. In this case the new crew productivity is:

$$Crew\ productivity = \frac{\#\ of\ scraper\ x\ scraper\ capcity}{pusher\ cycle\ time} = \frac{4\ x\ 15}{12}\ x\ 60\ \frac{min}{hr}$$

$$= 300\ \frac{m^3}{hr}$$

Note that any additional scraper to the system will not make a difference. However, an additional pusher can be added to the system, and we can study its impact on the operation efficiency as done above. This process can continue until an optimum solution

is reached that satisfies all the constraints and the variables involved in the system. The above example is rather a straight operational planning problem with no constraints provided. In fact, it can be easily solved with a simple mathematical expression as follows:

$$\#\ of\ scrapers = \frac{Pusher\ production\ rate}{Scraper\ production\ rate} = \frac{PR_p}{PR_s}$$

Taking the last case as an example:

$$\#\ of\ scrapers = \frac{PR_p}{PR_s} = \frac{300}{90} = 3.33\ \cong 4\ scrapers$$

This can be further represented using the following simple graph (Figure 3.7):

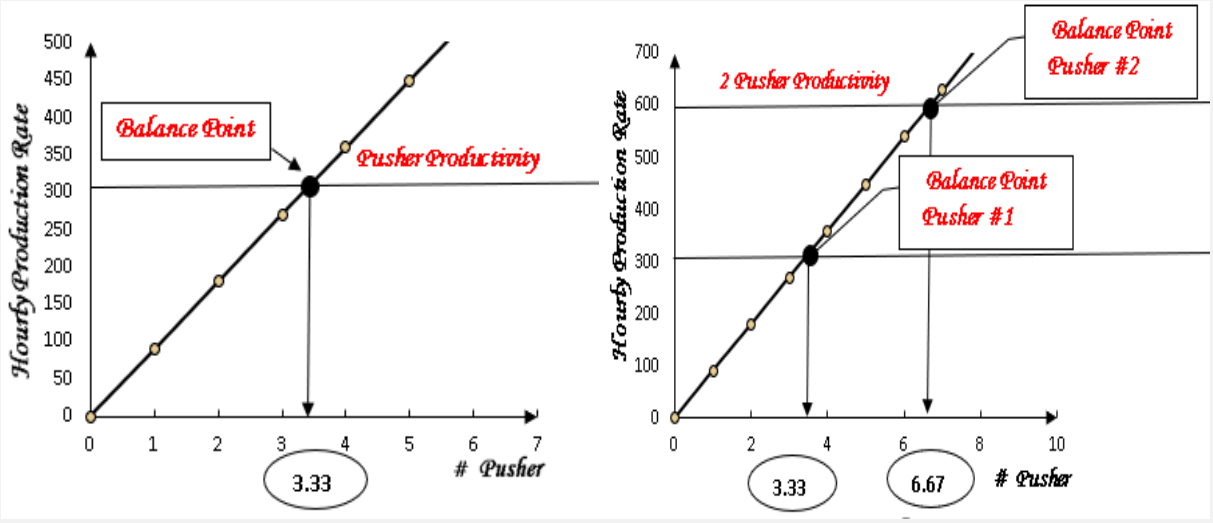


Figure 3. 7: The Balance Number of Scrapers in Case 1 & 2 Pushers

The previously demonstrated example discussed a humble rather straightforward planning problem with no constraints provided. However, in real-world problems planning an earthmoving operation involves many constraints and variables affecting earthmoving activities that must be considered. Besides, earthmoving operations usually have more than

one barrow pit and landfill site. In such cases, traditional planning using bar charts and graphs will not yield good results. Therefore, optimization models are absolutely recommended to be used for planning complicated systems.

3.2.2 Factors Affecting Earthmoving Operations

As discussed earlier, in real-world earthmoving planning, many variables and constraints affecting the operations have to be considered. In this scenario, the model consists of certain user-defined constraints, like the available fleet, road topography such as grade and rolling resistance, work scope (amount of soil available, needed at each source, landfill), etc. Therefore, It is necessary to study the factor affecting the earthmoving process before presenting the detailed step-by-step of developing the MIP model. After the deep screening of the aforementioned lecturer regarding the factors affecting planning the earthmoving operations, the below-mentioned factors will be considered in developing the optimization model.

- **Project Completion Time**

  Project completion date varies from one construction project to another. For instance, a heavy construction project requires more time compared to an ordinary one. In some situations, the project completion date is more important than the project cost as there are legal consequences for the late delivery. However, project duration is very crucial when it comes to earthmoving projects as they are equipment intensive. An unnecessary delay could result in high costs. Besides, sometimes project duration could be a constraint as well.

- **Project Total Cost**

Project budget is the concern of any contractor, as he aims to achieve the maximum possible profit. Usually, the contractor tries to minimize the expenses as much as possible, especially the unnecessary costs. However, the project budget is agreed on and specified in the contract, and it can be treated as another constraint that restricts the operation. Besides, it can be considered as an objective function that needs to be minimized or set to a specific value.

- **Quantity of Material and its Properties**

  It is the amount of material that needs to be excavated, loaded, and hauled from one or more borrow pits to one or more landfill sites (the amount of work that needs to be fulfilled). On the other hand, the soil type alerts the equipment productivity. For instance, the performance of scraper in excavating loose soil will be higher than rocky soil.

- **Equipment Hourly Cost**

  The hourly cost of each piece of equipment is the key factor that directly impacts the total cost of the project. Therefore, the generated model needs to select the right equipment in terms of cost. Hourly cost consists of direct cost, which is the operating cost of the equipment, and the indirect "overhead" and the owning cost.

- **Job site Conditions**

  Equipment performance is highly affected by the road and site physical condition such as site geology and topography characteristics. For instance, the excavating rate of the loose material might be different from the rocky

soil. Also, the available space for maneuvering to load and dump could affect equipment cycle time. On the other hand, road condition such as grade resistance affects the equipment performance. These resistances must be considered for the model to select the best hauling routes.

- **Environmental Conditions**

  Environmental conditions such as weather conditions can dramatically alter the site job condition, especially soil condition. For instance, rain makes the soil muddy. Therefore, the rolling resistance decrease. This affects the movement of the hauling unit. On the other hand, the emission (CO_2, N_2O, CH_4) from the construction equipment has become the concern of all parties involved in the contract. As the number of heavy equipment (pusher, scraper) increases, the amount of emission emits into the atmosphere increases. This emission is associated with a taxation cost. Therefore, it has to be minimized as much as possible. This cost will further be explained in more detail in the "Cost Representation" section.

- **Contractor's Available Resources**

  The contractor's available resources are a crucial element in delivering the construction project on time and within the budget. The shortage of resources will make the project unprofitable. Therefore, the contractor needs to maximize the utilization of the recourse to avoid any additional cost such as leasing, as well as a legal consequence resulting from the delay.

- **Equipment Characteristics**

Equipment characteristics are a vital factor in achieving the required job. Despite several available types of construction equipment to perform the same job, they have different specification that contributes to productivity, safety, and other factors. As a result, it is important to select appropriate equipment that meets the requirements.

- **Working hours**

  Working during the day will provide more production work than the night shift, as a wider vision area is available during the day. Also, increasing the working hours per day aid in the earlier completion of the project.

- **Operator's Skills**

  The role of the operator is to use the equipment in an effective manner maximizing the equipment outcomes. However, the unskilled operators could damage the mechanical parts of the equipment. Aside from this, the operator skills can be classified into three categories, namely skilled, average skilled, and unskilled.

3.2.3 Mixed Integer Programming for Optimization Earthmoving Operations

- Problem Discerption

In general, the highway construction projects consist of multi-borrow pits and landfill sites. However, the most common practice in the construction of such projects is to start the excavation from the first borrow pit until no soil quantities rema, then they move to the second borrow pits, etc. This process continues until the required road profile is reached. Overall, the latter process does not provide the maximum utilization of the available fleet. Hence, utilizing the MIP technique is beneficial to overcome the

aforementioned issue. Above all, the MIP method is a deterministic technique which means the model cannot capture the stochastic activity such as waiting time at loading and dumping queues thus, the MIP output is used as a starting point for the DES model where the latter issue can be solved. Moreover, reaching an optimum solution using the DES model is considered a lengthy process. Therefore, considering the optimum results from the MIP model shorten the process and guarantee accurate results as explained in the DES model development section.

- **MIP Model Assumptions**

The mathematical model can't imitate the actual situation in the real-world problem; adding more variables and constraints increases its complexity and computational time and makes it impractical. Moreover, the earthmoving process is fraught with a lot of uncertainty which restricts the capability of the mathematical model to capture all the randomness. Hence, the following assumptions are made for developing the model:

1. Maximum utilization of the fleet per day.
2. No queues at loading and dumping sites.
3. The first working day is reserved for moving the equipment to the site.
4. The same type of hauling and loading units are used for the entire project.
6. The equipment shifting is made after the end of the working day

- **Equipment Hourly Cost (Owning & Operating)** ($/**hr**)

To calculate the unit cycle cost of the equipment, hourly direct costs (operating & owning costs) are used, which are incurred while the equipment is operating (operating costs). Whereas Owning costs are incurred irrespective of the equipment is in or not in use. Besides, other costs are called overhead costs. A detailed explanation of owning and operating costs based on the Caterpillar method is presented below.

Owning Cost

This is a fixed cost associated with owning the equipment. It consists of the following:

a) Insurance

It is an annual premium that the contractor paid to the insurance company to protect his equipment against theft, fire, etc. This cost is calculated as a percentage of the book value in the current year. The following equation for calculating the insurance cost is provided by the Cat Company handbook.

$$\frac{\left[\frac{P\ (N+1)+S(N-1)}{2N}\right] X\ Simple\ Insurance\ rate\ \%}{Hours/years}$$

b) Interest

It is the cost paid annually on the money invested in the acquisition of the equipment ownership. The following formula is used to calculate the interest cost as per the Cat handbook.

$$\frac{\left[\frac{P\ (N+1)+S(N-1)}{2N}\right] X\ Simple\ interst\ rate\ \%}{Hours/years}$$

c) Storage

This cost is associated with keeping the construction equipment in the storage area without being involved in any project. As a result, there will be cost for maintenance, rental, and security wages. Usually, this costs around 0.5 to 1.5 % of the equipment book value.

d) Depreciation

Depreciation is defined as the decline in the market value of the asset due to wear, age, and obsolescence. Double-declining balance, straight-line, and sum-of-years-digits methods are among the common methods for calculating the depreciation of the construction equipment (S.W. Nunnally).

$$straight - line\ depreciation\ D_n = \frac{IC - S - TC}{N}$$

$$sum - of - years - digits\ \ depreciation\ D_n = \frac{(year\ n\ digit)(IC - S - TC)}{1 + 2 + 3 - .. + N}$$

$$Double - decline\ balance\ depreciation\ D_n = \frac{2}{N}(BV_{n-1} - TC)$$

Where,

D_n : $Depreciation\ in\ year\ n$

IC : $Ienitial\ Cost$ \$

S : $Salvage\ value$ \$

TC : $Tire, track\ cost$ \$

N : $Numbers\ of\ years\ of\ use\ \ (years)$

BV_{n-1} : $Equipment\ book\ value\ at\ the\ end\ of\ previous\ year, BV_{n-1} \geq S$ \$

After calculating each element of the ownership costs, the hourly ownership cost can be obtained by dividing the calculated annual cost by the number of operating hours per year. The average rates for the investment costs from the literature are provided in the below table.

Average Rates for Investment Costs

Item	Average Value (%)
Interest	3–9
Tax	2–5
Insurance	1–3
Storage	0.5–1.5

Table 3. 1: Average Rates for the Investment Costs (Douglas D, 2006)

The following is an illustrative example of calculating the hourly ownership cost for the second operation year of a 465 hp twin-engine scraper working 8 hr/day and 250 days/year provided by Douglas D, 2006:

- $Initial\ cost$: 18,6000 \$
- $Tire\ cost$: 14,000 \$
- $Estimated\ life$: 5 $years$
- $Salavge\ value$: 22,000 \$
- $Insurance$: 1.5 %
- $Interest$: 8 %
- $Taxes$: 3 %
- $Storage$: 0.5 %

$$Second\ year\ depreciation\ D_2 = \frac{\frac{(4)(186000 - 22000 - 14000)}{15}}{2000} = 20\ \$/hr$$

$$\frac{\left[\frac{P\ (N+1)+S(N-1)}{2N}\right]}{Hours/years}=\frac{\frac{186000x5+22000x4}{10}}{2000}=50.9\ \$/hr$$

$$Insurance+Interset+\ Taxes=8+1.5+3=12.5\rightarrow 0.125\ x\ 50.9$$

$$=6.3625\ \$/hr$$

$$Storage=\frac{0.005x\ 101800}{2000}=0.456\ \$/hr$$

$$Total\ Ownership\ Cost=\ 20+\ 6.3625\ +\ 0.456=26.82\ \$/hr$$

Operating Cost

This cost is incurred when the equipment is operating. Hence, the operating cost increases as the operation period increases. Besides, this cost is altered by the site condition, equipment type, etc. Operating cost can be classified into the following.

a) Tires

The equipment pneumatic tires wear out due to the usage. Therefore, there will be costs associated with replacing them at the end of the expected life. Also, even during their useful life, tires need to be repaired when required. The tire cost can be obtained from the equipment dealer as well as from the local shop. The repair cost can be estimated based on records or as a percentage of the tire depreciation cost. According to Caterpillar Performance Handbook 2018, the cost and repair of the tires are as follows:

$$Tire\ cost=\frac{Replacement\ Cost\ \$}{Estimated\ life\ in\ hours}$$

$$Tire\ repair\ cost=\frac{Factor\ x\ \ deleivered\ price\ less\ tire\ \$}{Estimated\ annual\ use\ in\ hourss}$$

Where,

$Factor: Can\ be\ obtianed\ from\ Caterpillar\ Performance\ Handbook$

b) Filters, Oil, Gears (FOG)

Filters, grease oil, and lubricating oil are changed frequently to maintain a good operating condition of the equipment. The quantity of FOG and the period between changes differ according to the working conditions, hours, engine characteristics. The FOG is determent from records.

c) Repair and Maintenance

This cost accounts for a significant portion of the total operating cost. It is defined as the cost for repairing and maintaining the construction equipment due to wear and tear resulting from the regular operation. Scheduled maintenance helps in reducing the cost. However, the repair and maintenance costs increase with the equipment age. In general, this cost is calculated as a percentage of the equipment annual depreciation.

d) Special Items

Bucket teeth, drill bits, blades, cutting edge, etc are classified as high wear items as their life is shorter than the equipment service life. The costs of these items can be estimated from manufacturing guidelines or records.

e) Operators' Wages

The operator v includes the base wages plus incitive, namely fringe benefits, bonus, etc. This cost varies with projects. Usually, it is calculated as a separate cost and then added to the operating cost.

f) Fuel

Fuel is used to provide power to the equipment as a result of internal combustion. The fuel consumption rate of the construction equipment is a function of the engine type and the nature of the working condition. Hence, the cost can be estimated based on the consumption records of similar jobs in the past. When this record is not available, the consumption guideline by the manufacturing can be used. For this study, the Caterpillar handbook is used for calculating the equipment hourly consumption rate.

g) Environmental

The buildup of CO2 in addition to other greenhouse gasses (GHG) in Earth's atmosphere result in serious environmental issues due to their ability to trap heat within Earth's atmosphere. This phenomenon results in climate change that has serious environmental effects on Earth as a planet. For this reason, many countries have stated various regulations and laws that restrict different industries regarding their GHG emissions.

Earthmoving operations are associated with heavy equipment that emits large amounts of GHG into the Earth's atmosphere. Some countries have already started charging taxation costs on heavy construction projects. This study will investigate the methods applied by researchers to quantify the amount of GHG emitted for different types

of earthmoving equipment. After quantifying the hourly emission of GHG, it will be used to find the hourly cost attributed to the GHG emission

The GHG emissions are highly correlated to diesel fuel usage. There are many researchers developed different formulas to estimate the GHG emissions from the construction equipment. The following formula from the Construction Equipment Management for Engineers Estimators and Owners written by Douglas D, Jorge A 2020, will be adopted for calculating the GHG emissions.

$$CF_i = E_{CO2i} + E_{CH4i}\, X\, 28 + E_{N2Oi} X\, 265$$

$$FCF = \sum_{i}^{n} CF_i$$

The emission amounts of CH4, CO2, N2O by pusher and scrapers can be estimated as follow.

Pusher

$$E_{CO2i} = 10210\ g/gal * Fuel\ (gal)$$

$$E_{CH4i} = 0.57\ g/gal * Fuel\ (gal)$$

$$E_{N2Oi} = 0.26\ g/gal * Fuel\ (gal)$$

Scraper

$$E_{CO2i} = 10210\ g/gal * Fuel\ (gal)$$

$$E_{CH4i} = 0.57\ g/gal * Fuel\ (gal)$$

$$E_{N2Oi} = 0.26\ g/gal * Fuel\ (gal)$$

The above factors can be obtained from table 9.4 (Douglas D, Jorge A 2020).

Where,

CF_i : $The\ carbon\ footprint\ for\ equipment\ i$

E_{CO2i} : $The\ CO2\ emission\ form\ equipment\ i$

E_{CH4i} : $The\ CH4\ emission\ form\ equipment\ i$

E_{N2Oi} : $The\ N2O\ emission\ form\ equipment\ i$

FCF : $The\ total\ carbon\ footprint\ for\ the\ whole\ fleet$

According to the data found in the environmental defense fund (EDF) website and the congressional research service (CRS, 2019), the current estimate of the environmental cost of carbon dioxide is around $50 per metric ton in today's dollars. This cost will be used to represent the environmental cost in the model formulation.

Having calculated each component of the owning & operating costs, the equipment hourly cost will be the summation of both costs.

- **Equipment Cycle Time (Hr)**

The time to complete one cycle is dependent on several factors, namely road characteristics (grade and rolling resistance) and the equipment weight. As discussed in section 3.2, the cycle time is a summation of four main components. These components are described below.

a) Loading Time

The loading time of the scraper in the earthmoving operation can be described by graphical representation of the increase in the payload (load growth curve Figure 3.8) as the contacting time with the pusher increases. However, increasing the loading time indicates neither maximum production rate nor minimum cost; this is the fact that the quantity of material inters the bowl has to force its way through the loaded material (Carmichael 1987). The studies showed that the optimum loading time of the scraper is 0.85 min, which implies a 90% scraper payload. Figure 3.9 depicts the optimum loading for the scraper.

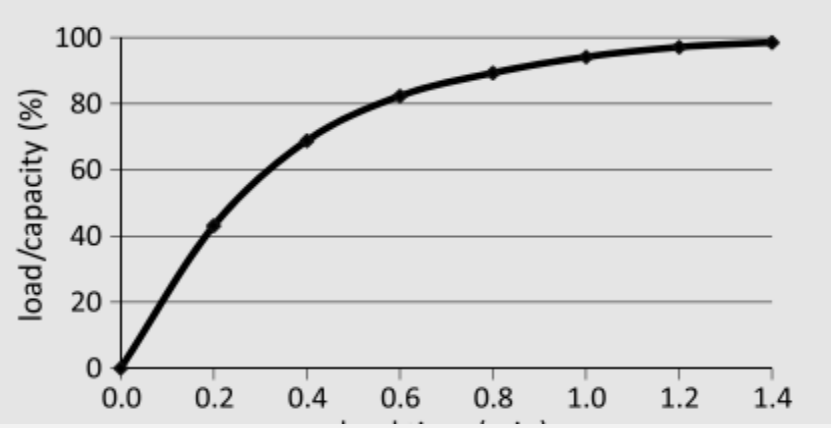


Figure 3. 8: Scraper Load Growth Curve (Karshenas & Farid, 1988)

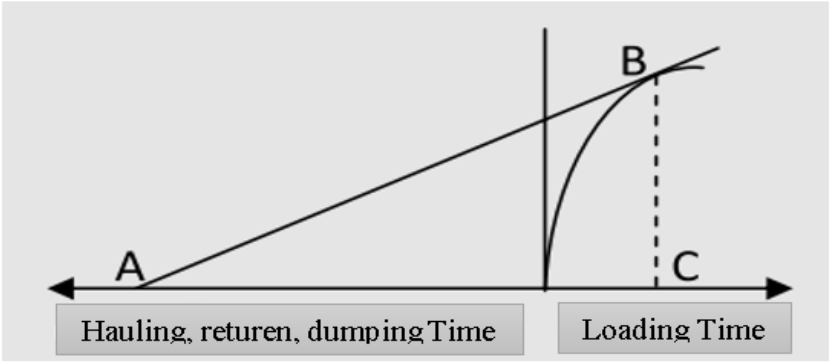


Figure 3. 9: Scraper Optimal Loading Time (Karshenas & Farid, 1988)

b) Hauling Time

The hauling time represents the period of time that takes the scraper to transfer the soil from the borrow pit to the landfill. Generally, the time equals the travel distance over the vehicle speed. However, the hauling time increases or decreases as the road characteristics (grade and rolling) resistance change. Usually, the speed of the scraper is obtained from performance charts designed for each type. These charts consider the road total resistance, the empty and the loaded weights of the scraper. For this study, CAT performance charts are considered for calculating the speed of the equipment. After picking up the speed from the chart, the hauling time would be the distance between each borrow pit and landfill over the hauling speed.

Returning Time

Return time is a period of time that takes the scraper to move back from the landfill to the borrow pit. The same method used to obtain the hauling speed is performed for obtaining the returning time.

Dumping Time

The time takes for the scraper to dump the load varies according to the dumping area condition. Generally, it follows a uniform distribution. For this study, the dumping time is assumed to be 2 min.

Regarding the pusher cycle time, it is varying according to the loading method. For instance, for back-track loading the cycle time (P_{cti}) would be

$$P_{cti} = 0.25 + 1.4\ x\ T_l$$

In the chain or shuttle push loading method the cycle time is as follows

$$P_{cti} = F_p \; x \; T_l$$

Where

P_{cti} : $Pusher\ cycle\ time$

F_p : $Factor\ form\ Nunnally$ 1977

T_l : $Pusher\ loading\ time$

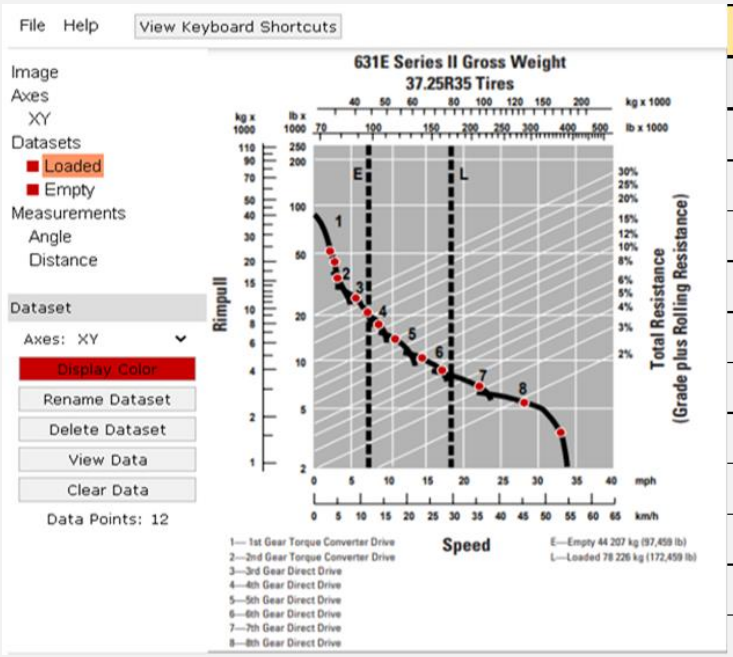
- **An automated way for calculating Fleet Hourly Cost and Cycle Time**

Cycle Time Calculation

Regarding cycle time calculation and the case of hauling roads consisting of several segments of varying characteristics, the average speed of each segment is determent. Then the summation of the average speed of all segments is considered. However, for each hauling unit, the performance charts provided by the manufacturing company (e.g., Caterpillar) are converted to digital format using the WebPlotDigitizer website (Figure 3.10) (a website created by Ankit Rohatgi to extract data from plots). Each digital chart consists of two columns (e.g., the first column represents the total resistance, the second column reflects the average speed value). Moreover, If-statement is utilized to direct the forecasting function to look up the total resistance value from either the rimpull or the retarder table to pick up its adjacent average hauling/returning speed value (Figure 3.11). On the other hand, If the total resistance is not found in the table, the speed value is obtained using interpolation. Having the average speed of each segment of the haling and returning between each cut-fill site calculated, their time is determined using the formula: $Time = Segement\ lenght/Averge\ speed$

Finally, the summation of the four-cycle times activities (e.g., loading, hauling, dumping, and returning time) provides the hauler average cycle time to perform one trip between each cut-fill area. As for the excavating unit, if the pusher is used, its cycle time is calculated using (Caterpillar handbook 2001) as follows, $Pusher\ cycle\ Time\ (min) = 1.4\ x\ loading\ time\ (min) + 0.25\ min$. For loader, the summation of the fixed and variable time is considered.

All previous equations are predefined in excel worksheet to automatically calculate the cycle time where the user is only required to enter the length of each road segment, hauling grade, rolling resistance, maximum allowed speed, dumping, and loading time (Figure 3.12).



CAT 631E Scraper + Loaded	
TR (%)	Speed (Km/hr)
0	53.7
2	53.6
3	45.7
4	36
5	27.8
6	23.5
8	17.7
10	14.1
12	11.7
15	9.1
20	5.1

Figure 3. 10: Performance Chart to Table Format Using WebPlotDigitize

```
=IF(M23>0,FORECAST(M23,OFFSET($AZ$20:$AZ$32,MATCH(M23,$AY$20:$AY$32,1)-1,0,2),OFFSET($AY$20:$AY$32,MATCH(
M23,$AY$20:$AY$32,1)-1,0,2)),FORECAST(M23,OFFSET($BC$20:$BC$32,MATCH(M23,$BB$20:$BB$32,1)-1,0,2),OFFSET($BB$20:
$BB$32,MATCH(M23,$BB$20:$BB$32,1)-1,0,2)))
```

Figure 3. 11: Speed Determination Using IF-Statement

Loading Time	0.7	Dumping Time	0.3	Max Speed	40	
Cycle Time between Cut Section #n and Fill Section #m(Min)						
	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	
D(km)	0.09144	0.1524	1.316	0.36576	0.09144	0	
GRH (%)	0	10	-2.5	-4	0	0	
RR (%)	2.5	2.5	2.5	2.5	7.5	0	
GRR (%)	0	-10	2.5	4	0	0	
TRH (%)	2.5	12.5	0	-1.5	7.5	0	
TRR(%)	2.5	-7.5	5	6.5	7.5	0	
HS(Km/hr)	50	11	54	54	19	54	
RS(Km/hr)	55	42	50	30	28	55	
HSL(Km/hr)	40	11	40	40	19	40	
RSL(Km/hr)	40	40	40	30	28	30	
HT (Min)	0.14	0.83	1.97	0.55	0.29	0.00	
RT (Min)	0.14	0.23	1.97	0.73	0.20	0.00	
TT (Min)	0.28	1.06	3.94	1.28	0.49	0.00	**8.050**

Figure 3. 12: Cycle Time Calculation

Hourly Cost Representation

Three Predefined excel worksheets (e.g., database, environmental costs, and hourly costs worksheets) containing formulas adopted from the Caterpillar handbook are used to calculate the hourly cost of hauling and excavating units. In particular, the main objective of using such formulas is to calculate both owning and operating costs, namely insurance, interest, storage, depreciation, tires, FOG, repair and maintenance, special items, operator wages, fuel cost.

The description of the hourly cost using the worksheets is as follows:

The first worksheet presents a database that hosts a group of scrapers, pushers, and their characteristics.

2. The second worksheet is used for calculating the emissions costs, as explained in the environmental cost calculation section.

3. The above worksheets are input for the third worksheet where the Caterpillar formulas were defined, and the VLOOKUP function is used to look up the selected equipment from the database to calculate its hourly cost. Overall, this worksheet is designed for the user where equipment can be selected. It should be noted that the user can add and define any equipment characteristics to the database while it will be automatically added to the third worksheet.

- **MIP Model Mathematical Formulation**

This section presents a mixed programming model that will be used to optimize earthmoving operations involving more than one borrow pit and landfill site. In addition to equipping the contractor with a tool for planning, scheduling, and biding preparation of the earthmoving operations. Moreover, the study will investigate the environmental impact attributed to (CO2, NO2, CH4) emissions from the generated crew. The developed model will take into consideration this impact as an additional cost that certainly affects the optimization process. The model output covers the optimized earthwork quantities that must be hauled from several borrow pits to different landfill sites, in addition to the optimum crew configuration utilized to perform the earthwork at hand that yields the least costs. Later, this output will be used as input of a DES model to obtain the fleet dynamic

configuration as the project progress. However, it is crucial to calculate the equipment hourly cost and the cycle time prior to the MIP model development.

Based on the previously demonstrated factors, combinations of the variable and constraints are formulated in a MIP model that covers three different scenarios. Each scenario's objective function and constraints are demonstrated in detail below. Figure 3.13 portrayed the resolution steps of the developed model.

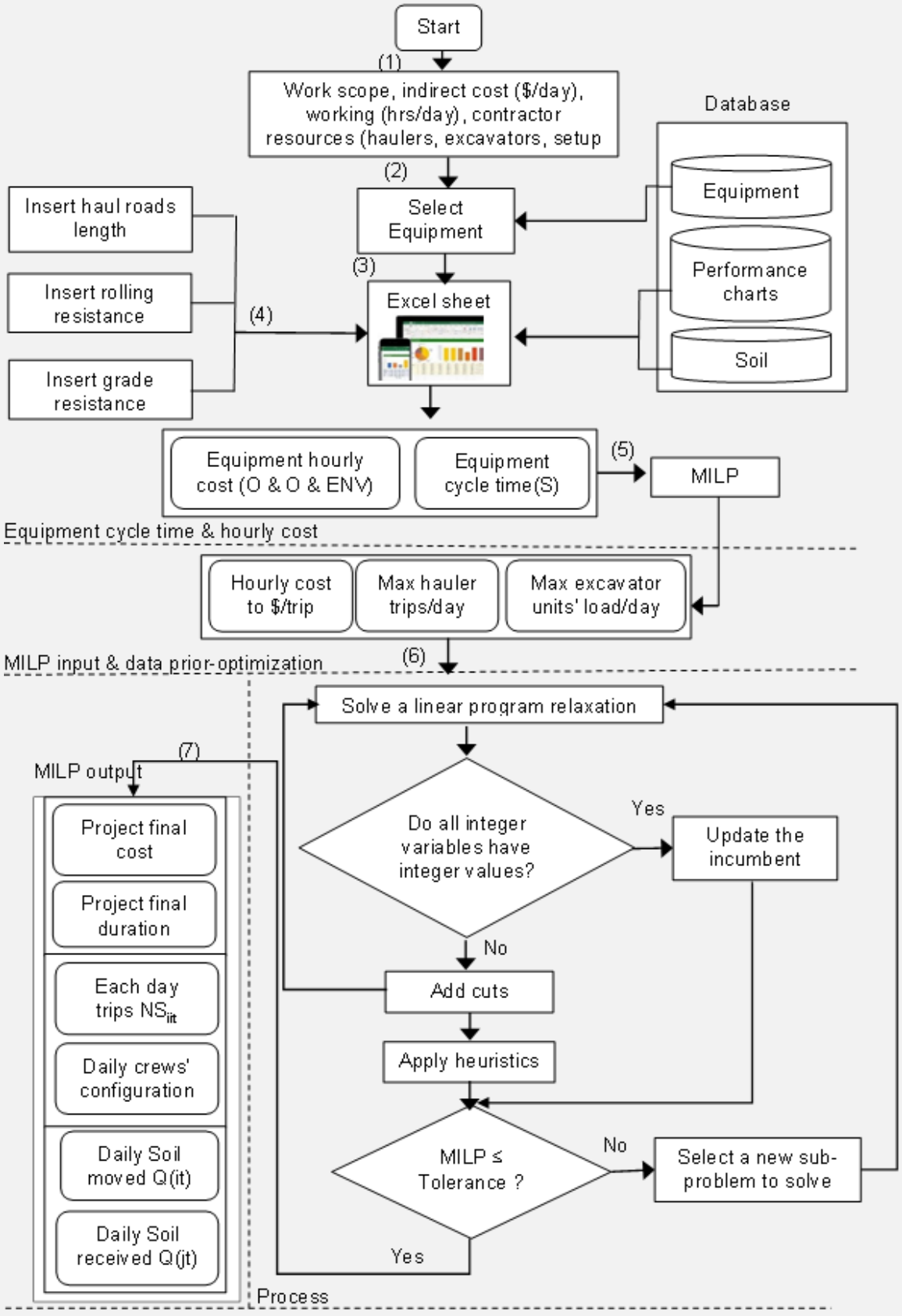


Figure 3. 13: Proposed Model Resolution Steps

According to Figure 3.10 the resolution steps of the proposed model are the following.

1. Prior to the utilization of the MIP model (steps from 1 to 16), The cycle time and the hourly cost of the fleet between each borrow pit and landfill sites are calculated using an excel sheet (a detailed explanation of the fleet hourly costs and cycle time calculations is depicted in the following sections) The input for excel sheet is as follows.

a. The length, rolling, and grade resistance of hauling road segments between each borrow pit and landfill site.

b. Equipment characteristics.

The calculated cycle time and hourly costs from the excel sheet, in addition to the following input, are required for the MIP model.

2. The number of borrow pits and landfill sites, the amount of soil available at each borrow pit, the demand at each landfill site, the cycle time between each borrow pit and landfill, the project hourly cost of the hauling and loading unit, the daily indirect cost, the hourly cost of emissions of each equipment, the available number of hauling and excavating machines, the setup cost of each landfill and borrow pit, and the maximum allowed project duration.

3. The MIP model runs utilizing a CPLEX solver.

4. The model output screen shows the optimized results, namely project total final cost, and duration, 2) daily optimum soil quantities to be moved and trips between different borrow pit and landfill sites, 3) the daily fleet configuration, 3) daily soil quantities

remaining at each borrow pit, 4) new daily soil quantities at each landfill site. As the model is executed, the hourly costs of the hauling units are converted to the cost per trip and cost per cycle time, respectively. Moreover, the model calculates the maximum trips that the hauling unit can perform between each borrow pit and landfill site and the maximum number of hauling units that one loading unit can load per day in different borrow pits and landfill sites.

- ***Scenario A: Generating an optimum daily fleet configuration of each crew at each source and destination from the available resources to the contractor***

The model innovative aspect presents the borrow pit capacity and the required amount of soil to the landfill in terms of the number of visits of the hauling unit (Scraper). In other words, each scarper visiting the borrow pit will be charged with an amount of excess equal to its capacity. For instance, if the borrow pit has a soil amount of 100 m3 to be hauled and the scraper capacity is 20 m3, this will be 5 visits to move all materials (e.g., 20 * 5 =100). In particular, this guarantees the solution's feasibility as the soil amount at the borrow pit is enough to load the scrapers at full capacity each time visiting the borrow pit. In other words, if the remaining soil amount at the borrow pit is not enough to fully load the scraper, the solution will be infeasible as the model assume an integer value (one scraper no portion of a scraper.). Based on the above-mentioned assumptions, the model is formulated as the following.

Notations:

$\boldsymbol{i}$: $source$ $(cut\ sections, borrow\ pits\ ), i = 1,2, \dots, n$

$\boldsymbol{j}$: $destination$ $(fill\ sections, landfill\ sites\ \ ),\ j = 1,2, \dots, m$

$\boldsymbol{t}$: $day,\qquad t = 1,2, \dots, k$

$\boldsymbol{Q_i}$: $Available\ soil\ in\ source\ i\ (in\ term\ of\ scraper\ capacity)\ \ (m^3)$

$\boldsymbol{Q_j}$: $Soil\ demand\ \ at\ destination\ j\ \ (in\ term\ of\ scraper\ capacity)(m^3)$

$\boldsymbol{Ic}$: $Initial\ setup\ cost\ of\ each\ cut\ and\ fill\ section$ ($)

Z: $Project\ total\ cost\ including(operating, owning, overhead, environmental\ costs)$ ($)

1- Scrapers

$\boldsymbol{S}$: $Capacity\ of\ Scraper\ \ (m^3)$

$\boldsymbol{nsa}$: $Contractor\ avaliable\ Scarpers$

C: $Hourly$ operating $cost\ of\ \ Scraper\ \ (\$/Hour)$

$\boldsymbol{Hcs}$: $Hourly$ holding $\ cost\ of\ \ Scraper\ \ (\$/Hour)$

$\boldsymbol{Sc_{ij}}$: $One\ trip\ (cycle) cost\ of\ scraper\ \ between\ each\ source\ and\ destination\ \ (\$)$

$\boldsymbol{CT_{ij}}$: $Scraper\ \ cycle\ time\ from\ source\ i\ to\ destination\ j\ (min)$

$\boldsymbol{NT_{ij}}$: $Number\ of\ trips\ that\ can\ be\ done\ by\ one\ scraper\ each\ day$

2- Pusher

$\boldsymbol{Phc}$: $Hourly$ operating $cost\ of\ \ pusher\ \ (\$/Hour)$

$\boldsymbol{Hcp}$: $Hourly$ holding $\ cost\ of\ \ pusher\ \ (\$/Hour)$

Pc: $Pusher\ cost\ for\ each\ time\ load\ a\ scraper$ $

$\boldsymbol{NPL}$: $Number\ of\ scrapers\ that\ one\ pusher\ can\ load\ per\ day$

$\boldsymbol{Pcy}$: $Pusher\ cycle\ time\ (Minute\ )$

Decision Variables:

$\boldsymbol{Ns_{ijt}}$: $Number\ of\ scrapers\ transported\ from\ \ source\ i\ to\ destination\ j\ at\ day\ t,$

$integer\ variable$

$\boldsymbol{N's_{ijt}}$: $Number\ of\ scrapers\ assigned\ to\ source\ i\ to\ serve\ destination\ j\ at\ day\ t\ ,$

$integer\ variable$

$\boldsymbol{Np_{it}}$: $Number\ of\ Pusher\ assigned\ to\ source\ i\ \ at\ day\ t\ , integer\ variable$

Updating Variables:

$\boldsymbol{Q_{it}}: \ The\ remaining\ quantity\ (m3) of\ earth\ at\ borrow\ pit\ (i) at\ day\ t$

$\boldsymbol{Q_{jt}}: \ The\ new\ quantity\ (m3) of\ earth\ at\ fill\ site\ (j) at\ day\ t$

Objective Function:

$Min\ Z$

$$= \sum_{t=1}^{k}\sum_{j=1}^{m}\sum_{i=1}^{n}\left(Sc_{ij} + Pc\right).NS_{ijt} + \sum_{t=1}^{k} BD_t * oh$$

$$+ \sum_{t=1}^{k}\sum_{j=1}^{m}\sum_{i=1}^{n}(ENVCS + ENVCp).Ns_{ijt} + \sum_{i=1}^{n} Ncut$$

$$+ \sum_{j=1}^{m} Nfill \qquad (1a)$$

Subject to:

Supply

$$\sum_{t=1}^{k}\sum_{j=1}^{m} Ns_{ijt} \leq Q_i \quad \forall i = 1, 2, \dots, n \qquad (2)$$

Demand

$$\sum_{t=1}^{k}\sum_{i=1}^{n} Ns_{ijt} \geq Q_j \quad \forall j = 1, 2, .0.., m \qquad (3)$$

Demand and Supply at day t

$$Q_{i1} = Q_i \qquad \forall i = 1\ \&\ \forall t = 1 \qquad (4a)$$

$$Q_{it} = Q_{i(t-1)} - \sum_{j=1}^{m} Ns_{ijt} \quad \forall i = 1, .., n, \forall t = 2, .., k \qquad (4b)$$

$$Q_{j1} = 0 \qquad \forall i = 1\ \&\ \forall t = 1 \qquad (5a)$$

$$Q_{jt} = Q_{j(t-1)} + \sum_{i=1}^{n} Ns_{ijt} \quad \forall j = 1, 2, \dots, m \; \forall t = 2, .., k \qquad (5b)$$

Number of trips per day from source i to destination j

$$Ns_{ij1} = 0 \qquad \forall i = 1 \;\&\; \forall j = 1 \;\&\; t = 1 \qquad (6a)$$

$$Ns_{ijt} \leq NT_{ij}.N's_{ijt} \quad \forall i = 1, 2, \dots, n \;\&\; \forall j = 1, 2, \dots, m \;\&\; \forall t = 2, 3, \dots, k \qquad (6b)$$

$$\sum_{j=1}^{m} Ns_{ijt} \leq \text{NPL}.Np_{it} \quad \forall i = 1, 2, .., n \quad \forall t = 1, 2, .., k \qquad (7)$$

Resource Restriction

$$\sum_{i=1}^{n} Np_{it} \leq Npa \quad \forall t = 1, 2, .., k \qquad (8)$$

$$\sum_{j=1}^{m} \sum_{i=1}^{n} Ns'_{ijt} \leq Nsa \quad \forall t = 1, 2, .., k \qquad (9)$$

Nonzero variable

$$Ns_{ijt}, \qquad Np_{it}, \qquad N's_{it} \geq 0 \qquad (10)$$

Fleet productivity restriction

$$Np_{it} \leq \sum_{j=1}^{m} ((Ns_{ijt} \; /NPL) + 1) \; \forall i = 1, 2, .., n \quad \forall t = 1, 2, .., k \qquad (11)$$

$$N's_{ijt} \leq Ns_{ijt} \; \forall i = 1, 2, .., n \quad \forall t = 1, 2, .., k \quad \forall j = 1, 2, .., m \qquad (12)$$

Duration Calculation

$$BD_t \leq \sum_{j=1}^{m} \sum_{i=1}^{n} Ns'_{ijt} \qquad (13)$$

$$Ns'_{ijt} \leq Ns'_{ijt} * M \qquad (14)$$

$$BD_{t+1} \leq BD_t \qquad (15)$$

The formulation of the MIP consists of two classes, namely 1) objective function, 2) constraints.

Model Objective Function

The objective indicates the minimization of the operational costs of earthmoving projects (e.g., transportation costs). It should be noted that the model presents the unit cost in terms of the cycle time of the scrapers and pushers. To illustrate, assume a 24 m^3 scraper costs 100$ per hour, and it takes 10 minutes to perform one cycle time (loading, hauling, dumping, return). This implies that each scraper trip costs 100/10= 10$ per trip or 10$ per trip/ 24 m^3= 0.417 $ per one unit (m^3). Similarly, the pusher is required to load the scraper for each trip. Hence, the pusher cost will be the pusher hourly cost/pusher cycle time. In summary, the objective function imposed the minimization of the total cost through minimizing the direct costs (the summation of the total cost of each trip of scrapers and the pushers of each day), the overhead costs, the environmental costs (the summation of the total emission costs results from each scrapers trip and the pushers cycle time of each day) respectively.

Model Constraints

Concerning the constraints, Constraints 2 and 3 are defined as the number of trips between the borrow pits and the landfill sites. Those constraints accounted for the soil quantities available at the borrow pits and needed the landfill sites.

Generally, At the end of each day, the quantities at each source reduce by an amount equal to the number of trips (scraper loads) hauled from that source to different destinations. Similarly, each destination increases by a quantity equal to the quantities

received on the previous day plus the amount hauled on the same day. These updating constraints are covered by equations 4 & 5. However, an assumption is made that the first day is reserved to distribute the equipment between the sources, which means no quantities to be hauled on that day, as shown in equations 4a, 5a, 6a. Another point is that the number of trips to be made between the sources and destinations must be less than the total number of trips that can be performed by the assigned equipment to that source as indicated by constraints 6b & 7. On the other hand, it is necessary to restrict the utilized equipment to the contractor's available resources. This is shown by constraints 8 & 9. However, it is unreasonable for the scrapers and pushers to be negative. Hence, constraint 10 restricts the value of the pushers and scrapers to integer nonzero. It is known that the project completion time is based on the equipment that has minimum productivity, thus constraints 11 and 12 is reserved to determine the minimum production rate of the scrapers and pushers. The set of constraints 13, 14, and 15 are preserved for calculating the project duration. In this model, the duration is represented by a binary variable BD (Binary Day). The working day has a value one, while the off day has zero value. However, constraint 15 forces the model to finish the project within a minimum duration at a sequential day. The constraint implies that if the previous day is a working day, the following day must be a working day and vice versa.

- ***Scenario B: Generating an optimum fleet configuration for the whole project then using this fleet for generating daily fleet configuration of each crew at each source and destination through the dynamic shifting of the equipment between different sources and destinations***

Beyond minimizing the project's total cost by selecting the optimum fleet configuration for each source and destination that leads to the least cost, further cost reduction is possible by introducing the fleet shifting between different sources and destinations, as it leads to the maximum utilization of the resources. Considering scenario B, the adjustment of the objective function, and the new constraints will be as follow:

Objective Function:

$$\boldsymbol{Equation\ 1a} + \sum_{t=1}^{k}\sum_{j=1}^{m}\sum_{j\prime=1}^{m}\sum_{i=1}^{n}\sum_{i\prime=1}^{n}(Shs_{ij}.N''s_{ii'jj't}) + \sum_{i=1}^{n}\sum_{i\prime=1}^{n}\left(Shp_{ij}.N'p_{ii't}\right) \quad (1b)$$

Subject to:

Number of Scrapers at source i at day t

$$N's_{it} = N's_{ij(t-1)} + \sum_{j\prime}^{m}\sum_{i'=1}^{n} N''s_{i'ij'jt} - \sum_{j'}^{m}\sum_{i'=1}^{n} N''s_{ii'jj't} \quad \forall i = 1,2,\dots,n+1\ and\ \forall j$$

$$= 1,2,\dots,m\ \ and\ \ \vee t = 2,3,\dots,k \quad (16)$$

Number of Pusher at source i at day t

$$Np_{it} = Np_{i(t-1)} + \sum_{i'=1}^{n} Np_{i'it} - \sum_{i'=1}^{n} Np_{ii't} \quad \forall i = 1,2,\dots,n\ and\ \vee t = 2,3,\dots,k \quad (17)$$

Nonzero integer variable

$$N''s_{ii't} \geq 0, \quad N'p_{ii't} \geq 0 \quad (18)$$

Shifted equipment Restriction

$$\sum_{j'=1}^{m}\sum_{i'=1}^{n} N''s_{ii'jj't} \leq N's_{ij(t-1)} \ \forall i = 1,2,\dots,n\ and\ \forall t = 2,3,\dots,k \quad (19)$$

$$\sum_{i'=1}^{n} Np_{ii't} \leq Np_{i(t-1)}\ \forall i = 1,2,\dots,n\ and\ \vee t = 1,2,\dots,k \quad (20)$$

Where

$\boldsymbol{i' = i}$

$\boldsymbol{j' = j}$

$\boldsymbol{Shs_{ij}}$: $Shifting\ \ cost\ of\ \ Scraper\ \ from\ one\ source\ to\ another$ ($)

$\boldsymbol{Shp_{ij}}$: $Shifting\ \ cost\ of\ \ pusher\ from\ one\ source\ to\ another$ ($)

$\boldsymbol{N''s_{ii'jj't}}$: $Number\ of\ scrapers\ shifted\ from\ source\ i\ \ to\ sourse\ i1\ and\ \ from\ destination\ \ to\ destination\ j1\ at\ day\ t\ , integer\ variable$

$\boldsymbol{N'p_{ii't}}$: $Number\ of\ Pusher\ shifted\ from\ source\ i\ to\ sourse\ i1\ \ \ at\ day\ t\ integer\ variable$

The new scenario consists of two parts. The first part indicates the shifting cost of the scrapers between one source and different destinations and between the other sources. Whereas the second part concerns the shifting of the pusher between sources as it is only operating at the sources to load the scrapers. Hence, this requires updating constraints to fit the new objective function. The constraints adjustment is as follows. Constraint 16 denotes the daily number of scrapers operating at each source and destination, which equals the number of scrapers that exists at the source plus the number shifted from other sources to that source minus the number of scrapers moved from the source to other sources at the same day. In like manner, Constraint 17 represents the daily number of pushers, which is equal to the existing number at that source, plus the number shifted from other sources minus the pushers moved to other sources. However, the number of shifted equipment must not exceed the assigned number for that source which is clearly explained in constraints 19 & 20. Also, the number of equipment cannot be negative as it represents a piece of

equipment. Hence, an additional constraint is needed to reflect this issue, as shown in constraint 18.

- ***Scenario C: Generating an optimum daily fleet configuration of each crew at each source and destination based on the minimum of selection from the Wearhouse and dynamic shifting of the equipment***

In this case, the model achieves the minimum cost by comparing the cost of shifting the equipment between different sources, destinations and the cost of transferring the equipment from the warehouse to find the best daily crew combination of scraper and pusher. In other words, if the shifting rate is higher than moving the equipment from the store, the model tries to formulate the crews based on the selection from the warehouse. Otherwise, resources selection is made base done based on the shifting. The new model is an expansion of scenario B, where the following addition is included.

Objective Function:

$$\boldsymbol{Equation\ 1a + Equation\ 1b}$$

$$+\sum_{t=1}^{k}\sum_{j=1}^{m}\sum_{j\prime=1}^{m}\sum_{i=1}^{n}\sum_{i\prime=1}^{n}\sum_{s}^{l}\left(Shss_{sij}.NDIS_{ijt}\right)\sum_{i=1}^{n}\sum_{i\prime=1}^{n}\sum_{s}^{l}\left(Shsp_{sij}.NDIP_{it}\right) \qquad (1c)$$

Subject to:

Number of Scrapers at source i at day t

$$N's_{it}$$

$$= N's_{ij(t-1)} + \sum_{j'}^{m}\sum_{i'=1}^{n} N''s_{i'ij'jt} - \sum_{j'}^{m}\sum_{i'=1}^{n} N''s_{ii'jj't} + NDIS_{ijt} - NDOS_{ijt} \quad \forall i$$

$$= 1, 2, \dots, n \; and \; \forall j = 1, 2, \dots, m$$

$$= 2, 3, \dots, k \qquad (16)$$

Number of Pusher at source i at day t

$$Np_{it} = Np_{i(t-1)} + \sum_{i'=1}^{n} Np_{i'it} - \sum_{i'=1}^{n} Np_{ii't} + NDIP_{it} - NDOP_{it} \quad \forall i$$

$$= 1, 2, \dots, n \; and \; \vee t = 2, 3, \dots, k \qquad (17)$$

Where

$\boldsymbol{Shss_{sij}}$: $Shifting\ cost\ of\ one\ scraper\ from\ the\ store\ to\ the\ source\ i\ and\ destination\ j$ (\$)

$\boldsymbol{Shsp_{si}}$: $Shifting\ \ cost\ of\ \ pusher\ from\ the\ store\ to\ the\ source\ i$ (\$)

$\boldsymbol{NDIS_{ijt}}$: $Number\ of\ scrapers\ Selceted\ \ from\ the\ store\ and\ assigned\ to\ serve$

$source\ i\ and\ destination\ j\ at\ day\ t\ , integer\ variable$

$\boldsymbol{NDOS_{ijt}}$: $Number\ of\ scrapers\ returned\ to\ the\ \ store\ at\ day\ t\ , integer\ variablen$

$\boldsymbol{NDIP_{it}}$: $Number\ of\ pusher\ Selceted\ \ from\ the\ store\ and\ assigned\ \ to\ \ source\ \ i\ at\ day\ t$

$\boldsymbol{NDOP_{it}}$: $Number\ of\ pusher\ returned\ to\ \ the\ store\ at\ day\ t$

- ***Scenario D: Generalization the model by including the cost of working extra hours as well the number of equipment to rent/buy in case of the resource's shortage***

Scenario (D) considered as a combination of the above-discus scenarios. in addition, it is expanded to include the cost of working extra hours per day. Moreover, in case of the shortage in the available resources to the contractor which hold the completion

of the project within the time limit, the model will provide the required extra equipment to meet the project deadline. Based on this scenario, the general form of the objective function is as follows.

Objective Function:

$$\sum_{t=1}^{k}\sum_{j=1}^{m}\sum_{i=1}^{n}\left(Sce_{ij}+Scd_{ij}+Pc+Pce\right).NS_{ijt}$$

$$+\sum_{t=1}^{k}\sum_{j=1}^{m}\sum_{i=1}^{n}Hcs.nsa'+\sum_{t=1}^{k}\sum_{i=1}^{n}Hcp.npa'$$

$$+\sum_{t=1}^{k}\sum_{j=1}^{m}\sum_{j\prime=1}^{m}\sum_{i=1}^{n}\sum_{i\prime=1}^{n}\sum_{s}^{l}\left(Shss_{sij}.NDIS_{ijt}\right)+\sum_{i=1}^{n}\sum_{i\prime=1}^{n}\sum_{s}^{l}\left(Shsp_{sij}.NDIP_{it}\right)$$

$$+\sum_{t=1}^{k}\sum_{j=1}^{m}\sum_{j\prime=1}^{m}\sum_{i=1}^{n}\sum_{i\prime=1}^{n}\left(Shs_{ij}.N''s_{ii'jj't}\right)$$

$$+\sum_{i=1}^{n}\sum_{i\prime=1}^{n}\left(Shp_{ij}.N'p_{ii't}\right) \qquad (1c)$$

Resources to Rent/Buy

$$Scrapers:\ \ nsa'-nsa \qquad (21)$$

$$Pusher:\ \ npa'-npa \qquad (22)$$

Where

$\boldsymbol{Sce_{ij}}$: $Scraper\ extra\ cost\ of\ one\ trip(cycle)\ between\ each\ source\ and\ destination$ ($)

$\boldsymbol{Pce}$: $Pusher\ extra\ cost\ for\ each\ time\ load\ a\ scraper$ $

$\boldsymbol{nsa'}$: $Extra\ scraper\ number\ to\ rent/buy$

$\boldsymbol{npa'}$: $Extra\ pusher\ number\ to\ rent/buy$

3.3 A procedure for Developing DES Model for CM Applications

The conceptual framework for developing a successful DES model shown in Figure 3.14 was developed based on the extensive review of the previous literature on the application of DES in the construction industry as mentioned in subsection 2.5.2.

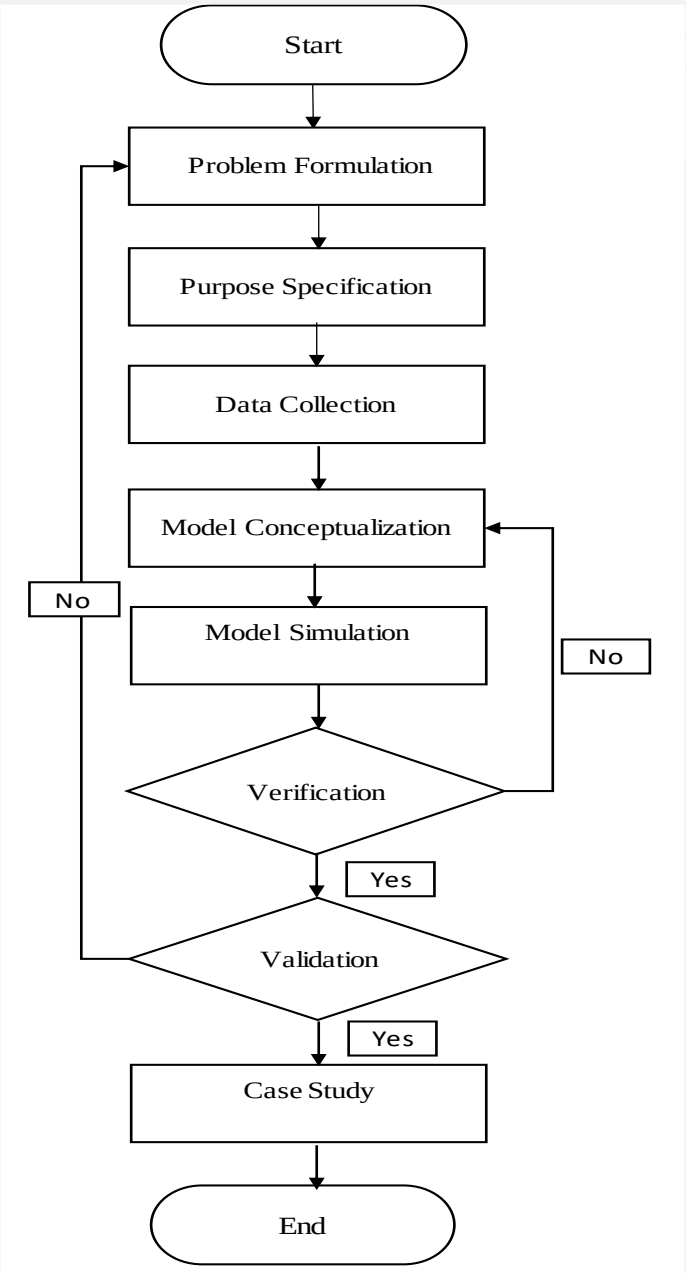


Figure 3. 14: Conceptual Framework for Developing a Successful DES Model

3.3.1 **Step-by-Step DES Model for Construction Management Applications**

As depicted in Figure 3.8, the following nine steps should be followed to guide each activity to successfully develop the proposed DES model.

Problem Formulation

For each real-world problem, a clear problem statement should be identified, and the expected research outcome should be agreed upon. As an illustration, if the policymaker provided the problem statement, the analyst should be able to understand the described problem. In the same situation, if the analyst provided the problem statement, the policymaker needs to understand and agree with the formulation. On some occasions, the problem statement is reformulated as the study progresses. For this study, a DES model will be developed to overcome the limitations of the mathematical modeling techniques of earthmoving operations as well as other shortages of the current simulation models. The main objective of the developed DES model is broken down into the following sub-objective:

- Verify the developed MIP model in subsection 3.2.
- Overcome the limitation of MIP in capturing the uncertainties of earthmoving operations.
- Capture the interactions and properties of the elements involved in earthmoving operations.

Purpose Specification

At this stage, a precise definition of the objective highlighting the question to be answered should be developed. For instance, the aim of using the simulation is to create a decision-making tool or optimize the production rate, etc. Also, it is necessary to develop a plan for evaluating the effectiveness of the used method and other alternatives. In the problem formulation stage, the general objectives of the DES model have been identified. However, the precise goal of the DES model is obtaining the least cost of an earthmoving of a highway construction project by considering the dynamic change of the fleet as the project progress. Moreover, the model should capture the interaction and the uncertainties of all elements in the model, such as waiting time at loading queues and dumping queues, hauling, and returning time.

Data Collection

Having the problem clearly specified, it is time to collect the relevant data that will be used as an entry for the model. This step contributes to the large portion of the total time required to build and run the simulation. However, for the successful data collection that matches the simulated model to the reality is being investigated, a full understanding of the process is required. To further illustrate, assume the bank manager wants to investigate the relation between the length of waiting time and the number of tellers change. In this scenario, the required data would be a teller service time distribution, distribution of interval times, and historical data related to the length of waiting time at the varying conditions. The latter is used for the model validating purpose. An earthmoving project was investigated by (Alshibani and Moselhi 2012), used to develop and validate the DES model. The project involves moving an 80000 m3 of soil from four cut sections to five fill

sections. A detailed explanation of the project profile, including hauling roads and their grade and rolling resistance is portrayed in chapter four subsection section 4.4.

Model Conceptualization

This stage involves initiating the logic and relationship between the different activities. Morris 1967 states that "Although it is not possible to provide a set of instructions that will lead to building successful and appropriate models in every instance, there are some general guidelines that can be followed". It is advisable to start with a simple model, then enrich and elaborate until an approximation of the expected result is achieved. On the other hand, it is not recommended to extend the model complexity beyond the purpose intended, which will increase the expenses (e.g., it requires a higher computer capability). A comprehensive explanation of the developed DES model components is provided in subsection 3.3.2 below.

Model Simulation

Completing the first four steps, the modeler has the choice either to select a simulation language or a special-purpose software to implement the conceptual model. This step involved representing the flow chart of the model in suitable software. This study utilized Arena software for the model implementation.

Model Verification

It is necessary to make sure that the obtained data from the simulation is reliable and anticipated the outputs for given inputs. Furthermore, check if the entities are following the same proposed logic. In other words, this step is used to answer the following question

('Is the software performed properly?'). Model verification can be achieved by using real data from previously existing systems. In this case, the exact data distribution is used, and the output is compared to historical results. For non-exist systems, a group of expertise subjectively verify the outputs baes on their experience. However, as demonstrated earlier, the verification process of the developed model will be performed utilizing the earthmoving project published by Alshibani and Moselhi 2012.

Model Validation

Validation means that the simulation outputs have been agreed upon, and the model is representing the real-world problem, so it can be used for solving the problem at hand. This is typically accomplished through model calibration, which involves model improvement through an iteration process of comparing the model against the behavior of the actual subsystem. The iteration should perform until the model accuracy is recognized as acceptable. In this study, the developed model is based on an optimization model. Hence, the output of the DES model will be compared against the result obtained from the MIP model.

Documentation

Documentation is a crucial step after model validation, as it enhances user confidence in using the model for solving real-world problems. The modeler is required to develop a user manual containing the necessary steps for developing the model, setting up input data values as well as how to run the model. This contributes to modifying the model for further future improvement.

Following the previously domesticated steps of developing a DES model for construction operation, detailed components of the DES model are explained below.

3.3.2 DES Model for Earthmoving Operations

In this research, the developed DES model is of an earthmoving operation of a highway construction project that includes pushers and scrapers. Accordingly, the process would be as follows: 1) pushers at each cut section push the scraper for a particular time to be loaded; 2) scrapers transport the loaded earth to a different fill location; 3) scrapers dump their loads in the fill sections; 4) scrapers travel back to the cut locations to carry more excess until the required road profile is achieved. A comprehensive explanation of the DES model component will be defined as follows:

Input Data

The developed model integrates the output of the MIP model, namely the final fleet configuration of each working day to be used as the starting point of the simulation. In addition, the user-defined data are as follows: 1) Soil quantities available at each cut area; 2) Soil quantities needed at each fill area; 3) Scraper loading, hauling, dumping, returning time; 4) trip cost between multi-cut-fill area; 5) setup cost of each cut and fill site; 6) Pusher cycle time; 7) the number cut and fill sections.

Entities (attribute and variables)

Entities represent an object that flows in the system, size resources, get processed Then exist the system. In this model, the scraper is an entity. The two properties of the scraper are 1) variables related to the properties that change due to the interaction with

other elements of the model, 2) attributes, which are fixed properties that are unaffected by other elements of the system. The scraper properties are portrayed in Table 3.2 below.

Table 3. 1: Scraper Properties

Entity	Attributes	Variables
Scraper	Capacity	• Number of trips (NTR) • Quantity Transported (QT) • Loading Time (LT) • Hauling Time (HT) • Dumping Time (DT) • Returning Time (RT)
Truck/s	Capacity	• Number of trips (NTR) • Quantity Transported (QT) • Loading Time (LT) • Hauling Time (HT) • Dumping Time (DT) • Returning Time (RT)

It is important to stress the available soil quantities at cut areas, and the needed soil amounts at each fill area are represented in terms of the scraper capacity, as elaborated earlier. Hence, there is no need to consider the scraper capacity as an attribute. However, the **Number of Trips** refers to the number of times the scraper traveled between different cut-fill sections per day. **Quantity Transported** refers to the soil quantities carried by the scraper each trip. The previous variables are updating variables. Moreover, **Loading Time** represents the time it takes for the scraper to leave the loading queue, get in the loading position, and leave the loading area. **Hauling Time** refers to the time takes the scraper to travel from the loading area to the dumping area. Similarly, **Returning Time** refers to the period it takes the scraper to travel back from the dumping area to the loading area. **Dumping Time** refers to the time it takes the scraper to leave the dumping queue, get in

the dumping area and dump the carried soil at the fill section (dumping area). It should be noted that the scraper cycle time (loading, hauling, dumping, return) depends on the properties of the hauling roads and the loading and dumping areas, such as the grade and rolling resistance and the available space for maneuvering.

Resources

The developed DES model accommodates two types of resources, namely static resources and moving resources. Static resources are fixed in place, such as equipment. However, in this model soil at each cut area is considered a static resource. Contrarily, the pushers in this model represent the moving resource. Pusher's properties are shown in Table 3.3

Table 3. 2: Pusher Properties

Resources	Attributes	Variables
Pusher	Maximum scraper can load per day	• Loading Time (PLT) • Time to begin next Loading (ADT)
Loader/s	Maximum trucks can load per day	• Loading Time (PLT) • Time to begin next Loading (ADT)

Loading Time

represents the time it takes the pusher to load the scraper.

Time to begin next Loading

refers to the time it takes the pusher to adjust its position and start loading the next scraper.

Queues

Two queues are considered in developing this model. The first queue is at the loading area (cut sections). The second queue is at the dumping area (Fill sections).

Event

Events update the state of the system at each time the scraper completes the trip between the loading and dumping area, including loading, hauling, dumping, and returning time.

Simulation Clock

It is an important concept in the simulation model. It is mainly used for recording the time. However, the simulation clock unit is the same as the input parameters units. As an illustration, if the input parameters are in minutes, the simulation clock must be in minutes. This clock is initialized at zero at the start of the model and then advanced at the occurrence of the next event.

3.3.3 DES Model Resolution Steps

A detailed elaboration of the resolution steps of the developed DES model is shown in Figure 3.15.

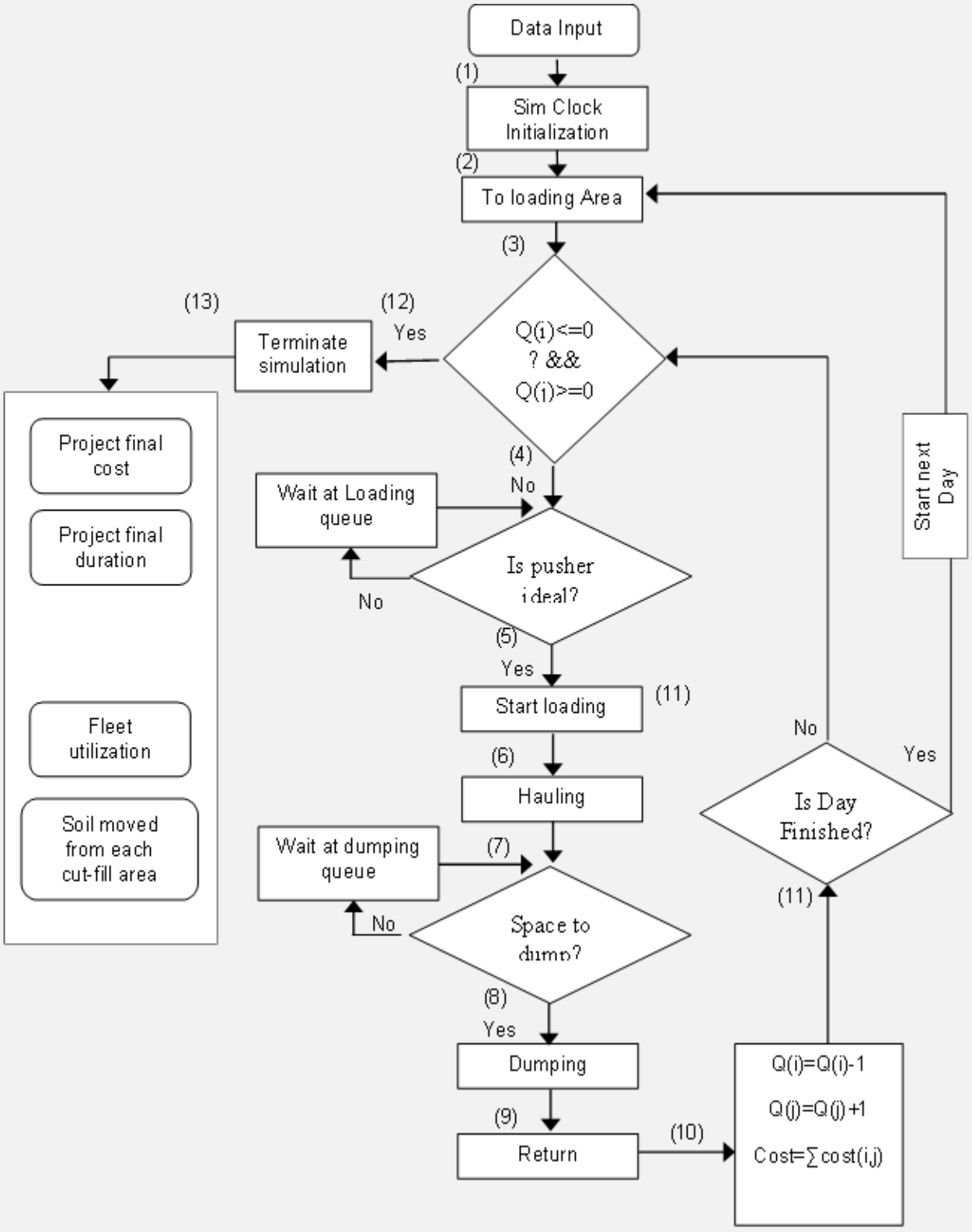


Figure 3. 15: Resolution Steps of the Developed DES Model

As depicted in the above Figure 3.15, the resolution steps of the developed DES model will be divided into three main classes as follows:

- User-defined Input

This class involves the input data inserted by the user. As elaborated earlier, these data include the available earth quantities at each cut area, earth amounts needed at each fill area, number of cuts and fill sections, the cycle time of the scraper between different cut-fill areas, daily fleet configuration obtained by the MIP model. However, there is no need to define the hauling roads between each cut-fill area as it is already defined in the excel sheet. The input data interact with the developed model, get processed to generate output.

- Process

  As soon as the user runs the model, the process will start. However, the process will continue until the termination condition is satisfied. Overall, the process can be explained as follow:

1) Simulation clock assigned value zero at the begging of the process
2) At the loading area, the pushers are ready to load the scrapers
3) It is necessary that one of the cut sections has soil available and one of the fill sections is not fully satisfied
4) The scrapers leave the loading queues to the loading areas seizing pushers if the pushers are ideal
5) The pushers start loading the scrapers
6) The scarpers leave the loading area to the dumping area (hauling process starts).

7) The scrapers will wait at the dumping queues if there are other scrapers in the dumping area.
8) If the dumping area is clear of other scrapers, the scrapers dump the load (dumping process starts),
9) As son the scrapers empty the load, they travel back to the loading area (returning process starts).
10) After completing each cycle time between each cut-fill section, 1) the cost of each trip will be recorded, 2) the soil quantities at the dumping area will increase by one trip (soil amount equal to the scraper capacity), 3) the soil quantities will decrease by one trip (soil amount equal to the scraper capacity).
11) This process continues until the working day is completed
12) As soon the first working day is completed, the next working day start after 14 hours
    - Output
13) The simulation will continue until the termination condition is met
14) As the termination condition is met, the simulation process is finished. In this model, the termination condition is achieved when there are no remaining soil amounts at the cut section, and all fill sections are satisfied
15) The output screen shows the following output, 1) project final cost, 2) project duration, 3) final fleet configuration, 4) Soil amounts moved from each cut-fill section, 5) fleet utilization.

CHAPTER 4: IMPLEMENTATION

4.1 Chapter Overview

This chapter is dedicated to presenting and describing the implemented model and its component. Accordingly, it depicts the use of programming language and the utilization of the DES simulation to create a model for an earthmoving process that can be used in 1) obtaining the least possible project total cost, 2) planning of earthmoving operations, 3) biding submission process, 4) providing day by day fleet configuration for multiple sources and destinations based on the contractor available resources.

GAMS (General Algebraic Modeling System) is dedicated to solving the developed MILP model. In light of that, GAMS consists of several models concerning the optimization of engineering and science problems ranging from agriculture, production and shipment, macroeconomic stabilization, and many more. These models are included in several libraries. In general, GAMS is a programming language in which the user defines his model using one or more sentences (statements), then identifies the symbolic relationships between the data using equations. Finally, the user runs the model to process the data and inspects the generated result in an output file. In this study, the generated GAMS output presents an input for the simulation model.

On the other hand, Arena software is utilized to solve the DES model. In view of that, Arena is a DES and automation software that uses the simulation language and SIMAN process. In general, the user represents the experiment or the problem by a group of modules (blocks of different shapes) joined together using lines (connectors) to reflect a specific process or logic. Lines specify the flow of entities where blocks perform an action

related to the entities defined by the user. During the process, the modules record data and produce output as reports. Figure 4.1

portrays the breakdown of the implemented process.

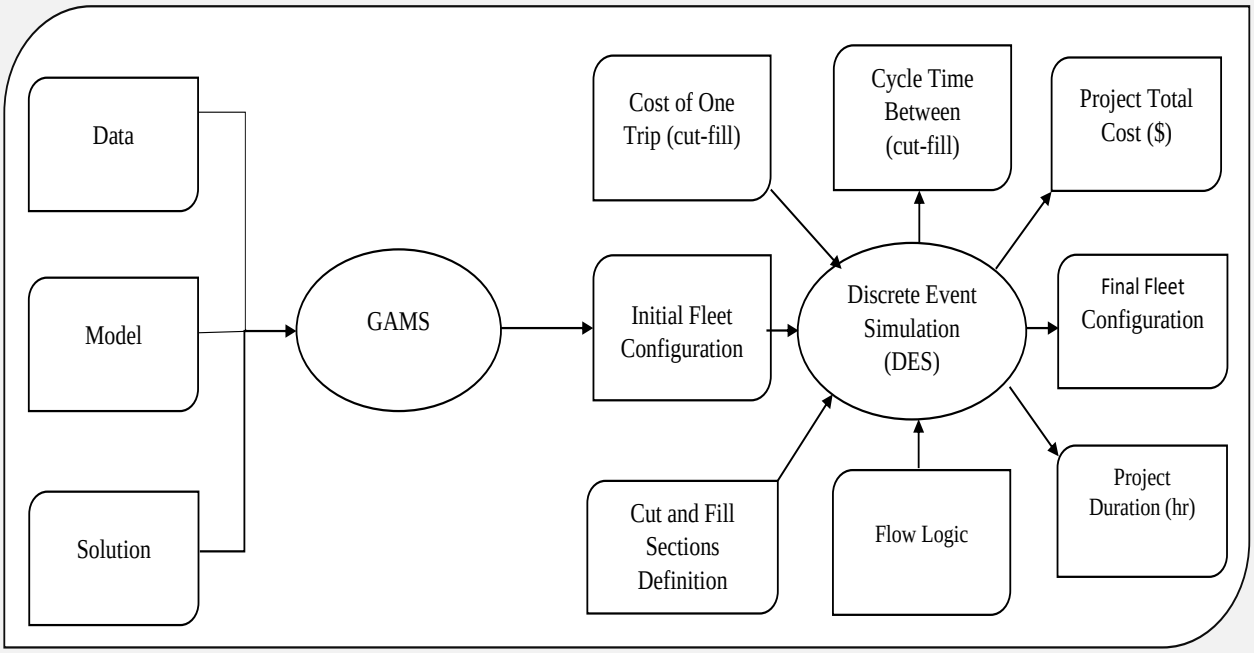


Figure 4. 1: Breakdown of the Implemented Process

4.2 MILP Model Components

There are two styles of organizing the GAMS statements 1) placing the data, followed by the model and the solution statements (Figure 4.2), 2) placing the model before the data (Figure 4.3). The latter is considered a useful order when there is a need to solve the model repeatedly for various data set. A detailed explanation of the first style is provided in the following subsections.

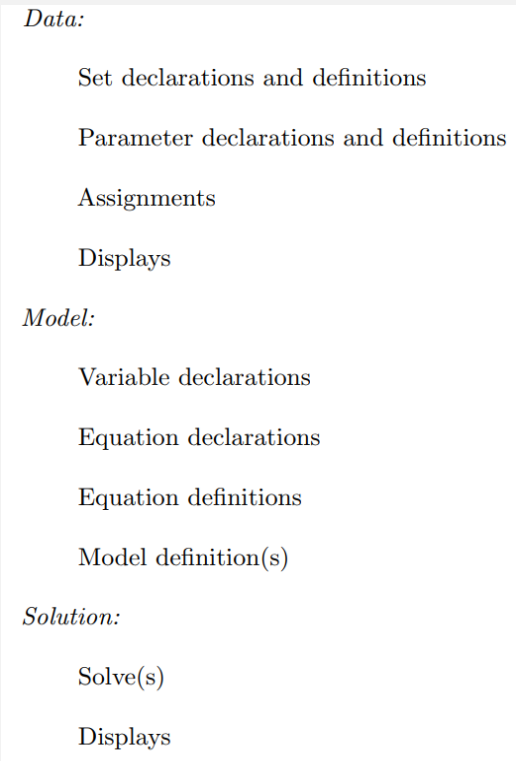


Figure 4. 2: GAMS Organizing Style 1

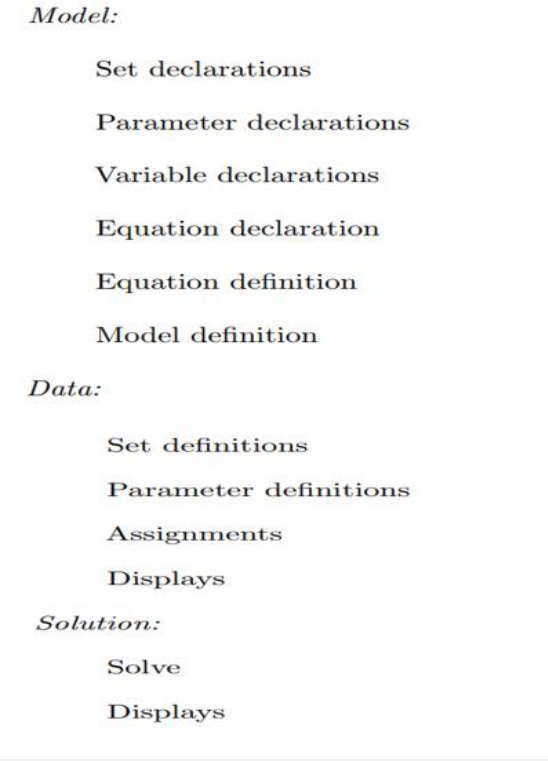


Figure 4. 3: GAMS Organizing Style 2

4.2.1 Data

- **Set declarations and definitions**

Sets are the basic building blocks of any model implemented in GAMS. They ease the readability and succinct state of the model. The sources, destinations, and duration are

the sets of the implemented model. Table 4.1 portrays the GAMS Set declarations and definitions of the model. Sometimes it is necessary to have the two names of the same set to avoid ambiguity while specifying the problem. In this model, when the equipment is shifted from source i to a new source i' or from the destination j to destination j', the sets (i, i') and (j, j') have the same elements. Hence defining multiple sets that have the same elements with different names creates ambiguity in the model. Therefore, the statement "Alias" is used to indicate that these two sets are one set. In GAMS the symbol (′) has a meaning that is number (1) is used. Lastly, the $\boldsymbol{t}$ simple indicates the maximum possible duration to complete the project (the user can choose any positive integer value, where the model finds the minimum completion duration. Also, it is used for what-if analysis scenarios).

Table 4. 1: Model Set Declarations and Definitions

Set	Definition
i	sources (cut sections, borrow pits)
j	destinations (Fill sections, landfills)
t	Max project duration

- **Parameter declarations and definitions**

The parameters are mainly used for entering the data into the model. According to the GAMS manual, there are various ways to represent the parameters based on the data type. For instance, scaler type is used when a single entry, a parameter for list-oriented data, or table-oriented data for data of multiple dimensions. There is a special case where the data is entered by the assignment expression. An explanation of the model parameters of scenario A is provided below (Table 4.2).

Table 4. 2: Model Parameter Declarations and Definitions

Parameter	Definition
Qi(i)	Available soil in source i
Qj(j)	Demand of destination j
Table CT(i,j)	Scraper cycle time between each source and destination (Minute)
Sc(i,j)	Scraper one trip(cycle) cost between each source and destination
Pc	Pusher cost for each time load a scraper
NT(i,j)	Number of trips that can be done by one scraper each day
oh	Overhead Cost per day
NPL	Number of scrapers that one pusher can load per day
ENVCP	Environmental Cost of Pusher per trip
ENVCS	Environmental Cost of Scraper per trip
Scalar Parameter	
C	Scraper hourly operating cost
Phc	Pusher hourly operating cost
Ohh	Overhead cost $/hour
ENVP	Hourly environmental Cost of Pusher
ENVS	Hourly environmental Cost of Scraper
WH	Working hours per day
Pcy	Pusher cycle time (Minute)
npa	Contractor available pushers
nsa	Contractor available Scarpers
Ics	Initial setup cost of each cut section
Icd	Initial setup cost of each fill section
M	Very big Number
e	Very small Number

4.2.2 **Model**

- **Variable declarations**

In general, variables are entities whose values are unknown until the model run is completed. As for other identifiers, variables are declared before any reference is made. Another point is variables can be of several types, namely, free (not bounded, from -∞ to ∞), Positive (from 0 to ∞), negative (from -∞ to 0), integer (0 to +∞), and binary (0 or 1). The declared variables and their type are explained below (Table 4.3).

Table 4. 3: Model Variable Declarations

Variable	Definition
Qit(i,t)	The quantity (m3) of earth available at source i-day t
Qjt(j,t)	The quantity (m3) of earth available at landfill j day t
Tcost	Total transportation costs in dollars
Ns(i,j,t)	Number of scrapers transported from source i to destination j at day t, integer variable
Np(i,t)	Number of Pusher assigned to source i at day t, integer variable
Free variable	TCost
Positive variable	Ns, Qit, Qjt, Duration
Integer variable	Np, N1s
Binary variable	BD(t) (Duration)

- **Equitation declarations and definitions**

In the GAMS environment, the term equation indicates that a group of constraints are about to be defined. Hence, the equation is used to establish the algebraic relation between the variables. Equation's definitions and their block of constraints for the implemented model are shown in Table 4.4.

Table 4. 4: Model Equitation's Declarations and Constraints

Equation	Definition
cost	Define objective function
supply(i)	The remaining quantity (m3) of the earth at borrow pit (i)at day t
demand(j)	The new quantity (m3) of the earth at fill site (j)at day t

dailyscrapertripsday1(i,j)	Number of trips that scrapers can perform from source i to destinations j at day 1
ScraperAssigneddday1(i,j)	Number of scrapers Assigned to source i to serve destinations j at day 1
PusherAssignedsday1(i)	Number of pushers Assigned to source i at day 1
dailyscrapertrips(i,j,t)	Number of daily trips that scrapers can perform from source i to destinations j at day t
Optscrapernumber(i,j,t)	The optimum scraper number to finish the work at least possible cost
Optpushernumber(i,t)	The optimum pusher number to serve the selected scraper to finish the work at the least possible cost
dailypusherloading(i,t)	Number of scrapers loaded by pusher per day from source i to destination j
dailysupplyday1(i)	Amount of soil remaining at each source after the amount transported at day 1
dailysupply(i,t)	Amount of soil remaining at each source after the amount transported at day t excluding day 1
dailydemandday1(j)	Amount of soil cumulated at each landfill after the amount received at day 1'
dailydemand(j,t)	Amount of soil cumulated at each landfill after the amount received at day t excluding day 1
avpusher(t)	Total number of pushers available to the contractor
avscraper(t)	Total number of scrapers available to the contractor
ISWorkingday(t)	Check if there is fleet working at day t
IsN1s(i,j,t)	Check if there are fleet assigned at day t
NOworkingday(t)	No working ad day 1
ContWorking(t)	Continuous working day
DUR	Duration

4.2.3 Model definitions

The final stage in the model implementation is to collect all equations into groups to solve them. This can be done by using the model statements combined with the term all including the model type.

- **Solve**

Once the model statement is defined, the model is solved by calling one of the solvers intergraded with the GAMS system. The solve statement is used to solve the model.

- **Display**

The statement display is used at the end of the model to write the data in an output file. Table4.5 below shows the model, solve, and display statements of the implemented model.

Table 4. 5: Model definitions, Solve, and Display

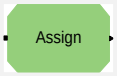
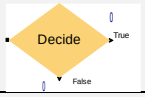
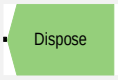
Model	transport
Solve	Transport using MIP minimizing TCost
Display	Pc,Sc , TCost.l, Duration.l, Qit.l, Qjt.l, Np.l, N1s.l, Ns.l, BD.l, NT, NPL

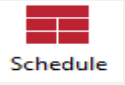
4.3 DES Model Components

In Arena software, the model window consists of two types of basic blocks called modules. The first module called the flowchart that describes the model dynamic processes. In particular, it represents a place where the entities flow, get processed, and leave the system. Second, a module called data defines the characteristics of various elements, such

as resources, queues, entities. Also, it is used to set up the expressions, variables, and other numerical values that pertain to the model as a whole. The blocks of the developed models are presented in Table 4.6 below.

Table 4. 6: DES Model Blocks

Block	Symbol
Create	
Assign	
Separate	
Decide	
Delay	
Route	
Process	
Station	
Dispose	
Queue	
Variable	
Attribute	

Block	Symbol
Entity	
Queue	
Recourse	
Schedule	
Set	

4.3.1 Cut-fill sections and Entities

In this model, the cut and fill sections are represented as one group for control purposes. This creative way of representation enables the model to accommodate projects with a large number of cut-fill sections. Moreover, (create block) is used to generate both cut-fill sections (treated as entities in this model) and the scrapers (Entity). Figure 4.4 portrays the cut-fill section and entities representation.

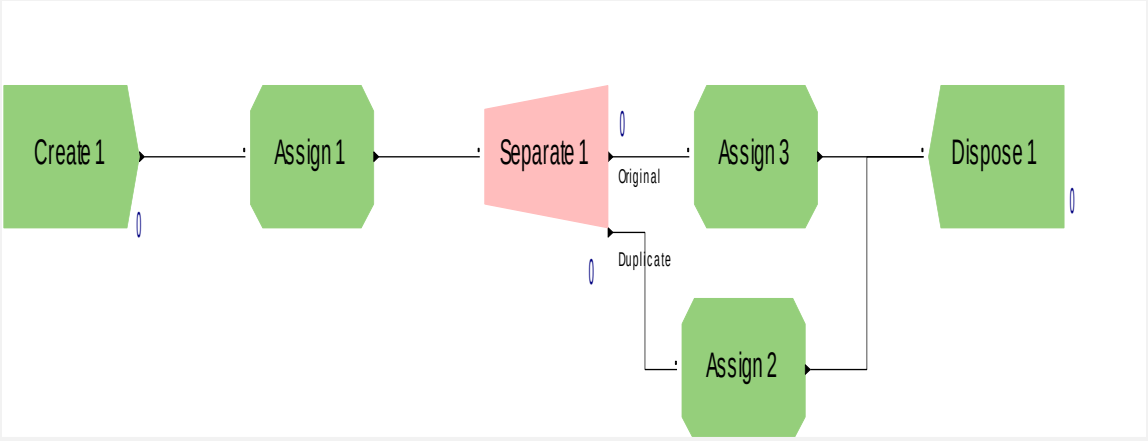


Figure 4. 4: Cut-Fill Section and Entities

The interoperation of the Figure is as follows: create1 block generates four entities, which represent the four cut sections. Assign1 assigns an attribute value of each cut section (so = 0 to 4). Separate1 duplicates each cut section into five fill sections. In other words, each cut section can provide soil to the five fill sections. Assign2 assign attribute for each fill sections (de = 0 to 5). Assign3 initializes the attribute (de) after each section (so) passes through separate1 and is duplicated five times. As the cut and fill section is completed, the entities will be disposed of by dispose1.

4.3.2 **Working Days**

As depicted in Figure 4.5, separate blocks (DAY1 to DAY5) read the fleet for each working day from a 2D variable containing the number of scrapers operating between different cut-fill sections. Decide1 represents the starting of each day. Create2, Assign4, and dispose2 generate entities for each working day. Route block directs the fleet to its assigned cut-fill areas.

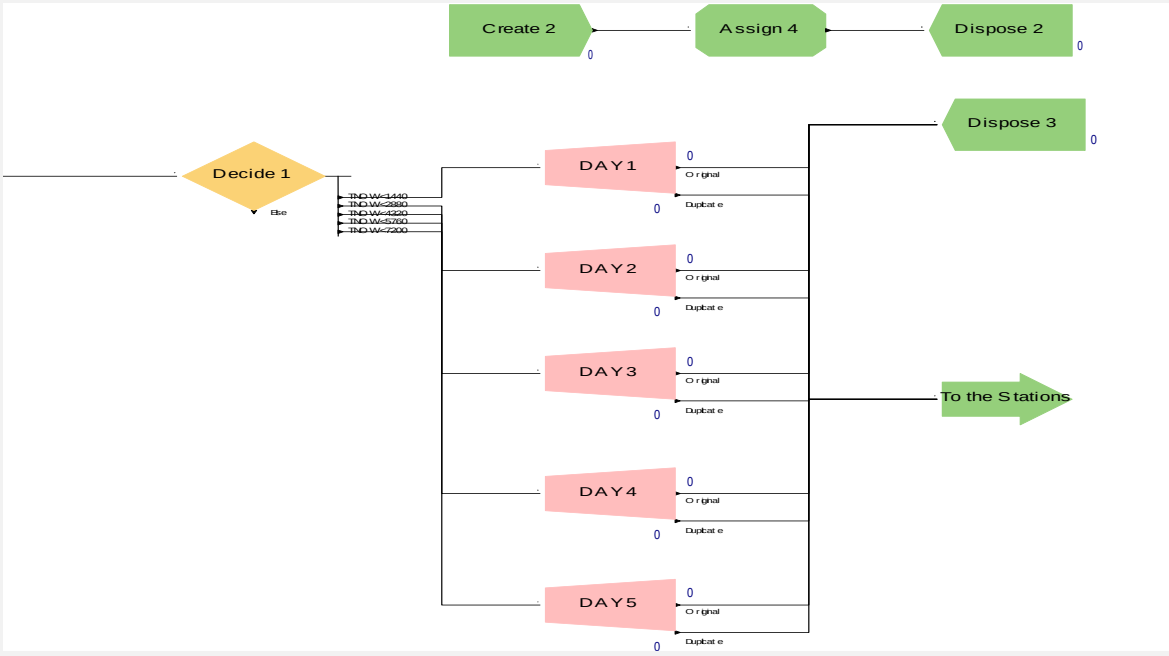


Figure 4. 5: Working Days Representation

4.3.3 **Earthmoving Operations Process**

Figure 4.6 shows the earthmoving process where decide2 checks the availability of the soil available at the cut sections and soil needed at the fill sections. Assign5 updates the cut section after each trip loaded by subtracting one trip from the cut area. Assign6 is used to calculate the project cost and the number of trips performed between cut-fill sections. Decide3 check if the working day is finished. Decide4 is used to check if the remaining time at the end of the day is enough for the scraper to perform the complete cycle time between cut-fill sections. The loading process is used for loading the scrapers by pushers. Hauling route is used to route the scraper to the fill areas (destination block). Delay represents the dumping of the load in the fill section. Assign7 updates the fill section each time trips arrive. Returning route is used to route the scrapers to loading sections.

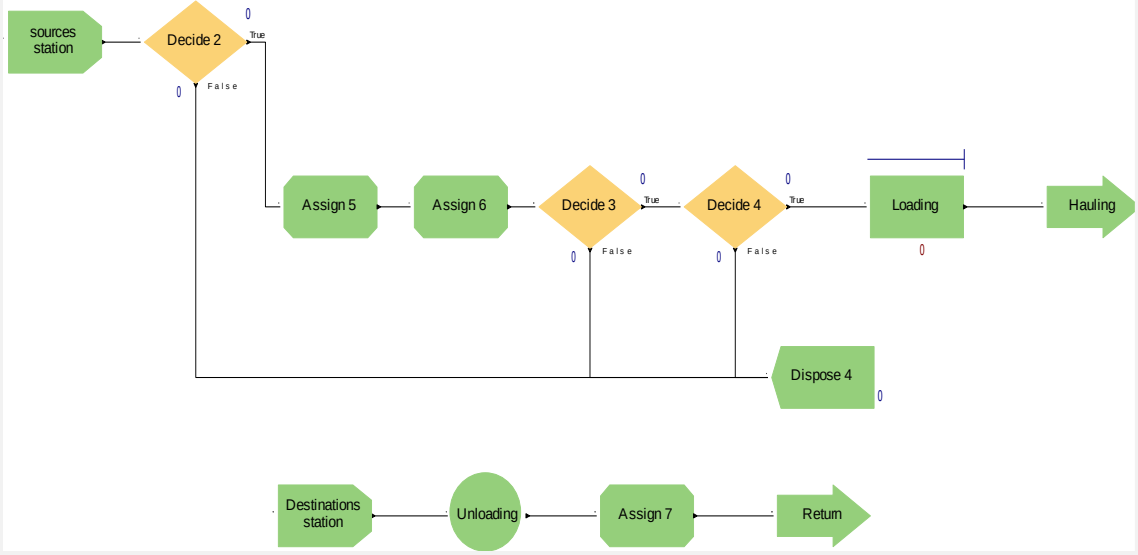


Figure 4. 6: Earthmoving Process

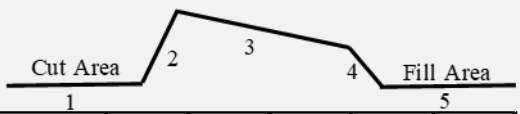
4.4 Model Verification

This section is reserved to test and validate the developed MIP and DES simulation model. The validation is done in two steps. First considering one borrow pit and landfill.

Second, Multi borrow pits and landfill sites. Both examples are extracted from the lectures. A detailed explanation of the validation process is provided below.

4.4.1 Case Study One Scope Description

This example is employed to test the developed model in planning and optimizing the earthmoving operations. It was initially analyzed using (PSFLEET Model); a probabilistic technique that was developed by Farid and Husaini (1990). The model aimed to select a fleet configuration of scraper–pusher equipment to carry out an earthmoving project at least total cost based on the contractor's available resources. The PSFLLET suggested an optimum of three D10N pushers and nineteen 631E scrapers out of ten different combinations of pushers and scrapers. However, the most cost-effective production rate of 2195 Bcy/hour was achieved at 0.7 minutes optimal loading time. Moreover, the overall cost of the project was found to be 224 031$. On the other hand, Alshibani and Moselhi (2012) re-analyzed the same example to validate their model (It will be referred to later as A & M). This time the A & M model selected an optimum of three D11 pushers and fourteen 657E scrapers. Compared to PSFLEET, A & M model found that the selected fleet could complete the project at least a total cost of 206 735.674 at a fleet production rate of 2049.23 m3(7.72% reduction in the total cost of the PSFLEET). Project input data and the haul-road summary are portrayed in Table 4.7 and Figure 4.7.



Segment	1	2	3	4	5
Length (m)	91.44	152.4	1371.6	365.76	91.44
Rolling %	7.5	2.5	2.5	2.5	2.5
Grade %	0	10	-2.5	-4	0

Figure 4. 7: Example one profile view

Table 4. 7: Example 1 Data

Earth-moving volume (m3)	198 784.3
Max project duration (days)	50
Bank density (kg/m3)	2037.62
Available number of pushers for each type	3
Available number of scrapers for each type	20
Length of haul-road (m)	2072.74
Daily working hours	8 h
Daily indirect cost $	3000
Job conditions	Favorable
Scraper load time (min)	0.80 to 1.20
Push-loading method	back-tracking
Maximum allowed speed (km/h)	40

4.4.2 Case Study Two Scope Description

This example is utilized to demonstrate the full features of the developed model in optimizing earthmoving operations, taking into account multi-cut and fill sites, it will be referred to later as the A&M2 model, (Alshibani and Moselhi 2012). As depicted in the plan and profile view of the project (Figure 4.8), A total of 80,000 m3 bank volume of density 1323.059 kg/ m3 were required to be moved to five different fill sites. Regarding the available equipment and their characteristics (Table 4.8), three D9 pushers and twenty 631E (capacity of 23.7 m3) scrapers were available to perform the task. The chain push-loading method is chosen to load the scrapers. Furthermore, the rolling resistance has a varying value of the haul-road between 2% to 5%. Also, the authors assumed that all haul-roads (Table 4.9) are flat except the sections S1-S8 and S7-S9 (Figure 4.9). Moreover, they restricted the scraper's maximum speed to 30 km/hr. Finally, the authors identified a setup

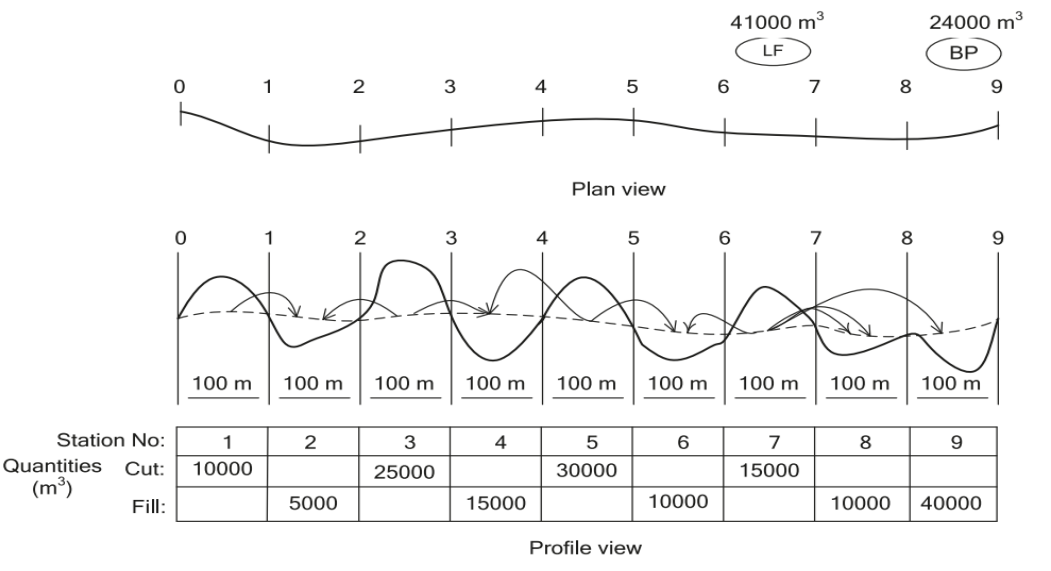
cost of 2000$ for each cut and fill section. Additional detail about the example can be found in the cited paper. The model suggested that the project be completed within 50 h at a total cost of 138 140 $. On top of that, the model selected a fleet configuration of 14 out of 20 scrapers and 3 out of 3 pushers. The quantities transferred from each cut section to fill location are presented in Table 4.10. It should be noted that the MILP model considered the average hauling distance between different cut-fill sections rather than the A&M2 model where the GIS technique is utilized to measure the real-time hauling duration.

Table 4. 8: Equipment Characteristics

Equipment Characteristics	Scraper	Pusher
Capacity m3	23.7	**
Hourly cost ($)	150	90
Loading Time (min)	0.9	0.9
Dumping Time (min)	0.55	**

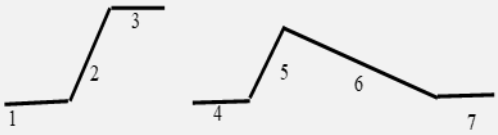
Table 4. 9: Lengths of the Haul-Road

Section	1	2	3	4	5
A	100	300	400	700	800
B	100	200	100	200	300
C	400	200	100	200	300
D	500	500	200	100	800



Station No:	1	2	3	4	5	6	7	8	9
Quantities (m^3) Cut:	10000		25000		30000		15000		
Fill:		5000		15000		10000		10000	40000

Figure 4. 8: Proposed Road Plan and Profile view



	S1-S8			S7-S9			
Segment	1	2	3	4	5	6	7
Length	35	630	35	35	365	365	35
Rolling	3	4	3	0	4	4	0
Grade %	0	2	0	0	2	-2	0

Figure 4. 9: S1-S8 & S7-S9 haul-road layout

Table 4. 10: A&M Model Output (Alshibani and Moselhi 2012)

From cut	To fill	Q (m3)	From cut	To fill	Q (m3)
A	2	1793.47	B	9	10000
A	6	4126.98	C	9	30000
A	8	4079.55	C	4	7611.49
B	2	1621.83	D	2	1584.7
B	4	7388.51	D	6	2890.93
B	6	2982.09	D	8	2912.88
B	8	3007.57			

4.5 Developed Model Results and Discussion

4.5.1 **MILP Results and Discussion**

Case Study one Results

As indicated in Table 4.11, a comparison between the results of the selected models (PSFLEET and A&M models) and the developed model (MILP) was conducted to test the MILP acquired results. Comparing the same resources of the PSFLEET, the results indicated that the developed model selected two optimum crews to complete the project as follows, 1) three D10 pushers and twenty 631E scrapers for the first seven days, 2) one D10 pusher and four 631E scrapers for the last day. Based on the latter fleet configuration, the developed model was able to complete the project within cost and time limit of 208 284.36$ and 64 hours, respectively. As regard fleet-maximum utilization, the developed model suggested an hourly fleet production rate of 3466.125m3/hr. That is 7.029% overall cost and 45.763% project duration reduction compared to the PSFLEET model. Most significantly, it can be noted that the developed model found the remaining soil quantities require no more than four scrapers and one pusher on the last working day. Hence, eliminating the extra equipment can significantly reduce operational costs.

On the other hand, utilizing the same resources of the A&M model, the developed model selected two crews as follows 1) three D11 pushers and fifteen 657E scrapers for the first six days, 2) three D11pushers and twelve 631E scrapers for the last day. The latter fleet configuration of the developed model indicated that the project total cost 154 132.5% and 56 hours, which are 25.44% and 42.27% less than the cost and duration of the A&M

model. To strict the fact that the developed model reduces the operational cost by getting rid of unnecessary equipment, it eliminated the fleet by three scrapes on the last day.

Table 4. 11: MILP Output Data VS Other Models

Model	Pushers	Scrapers	Near Optimum Loading Time	Least Total Cost	Duration (h)	Production (m^3/hr)
PSFLEET	3-D10	19-631E	0.7	224 031	118	1678.29
A&M	3-D11	14-657E	1	206 735.67	97	2049.32
MILP vs PSFLEET	3-D10 1- D10*	20-631E 4-631E*	0.7	208 284.36	64	3466.125
MILP vs A&M	3-D11	15-657E 12-631E*	1	154 132.5	56	3666.6

* Crew configuration for the last day

Emission Amount and Cost Comparison

According to the data found in the environmental defense fund (EDF) website and the congressional research service (CRS, 2019), the current estimate of the environmental cost of carbon dioxide is around $50 per metric ton in today's dollars. Hence, this value is used for calculating the CO2 cost.

Based on the fleet selected by each model, the emissions amount and cost for each are the following (Figure 4.10):

- PSFLEET emission amount is 384 tons at the cost of 20414$
- A & M emission mount is 500 tons at the cost of 24444$
- MILP model vs. PSFLEET emission amount is 196 tons at the cost of 10424$

- MILP model vs. A & M emission amount is 296 tons at the cost of 14472$

The above results showed the superiority of MIP in terms of emissions compared to other models.

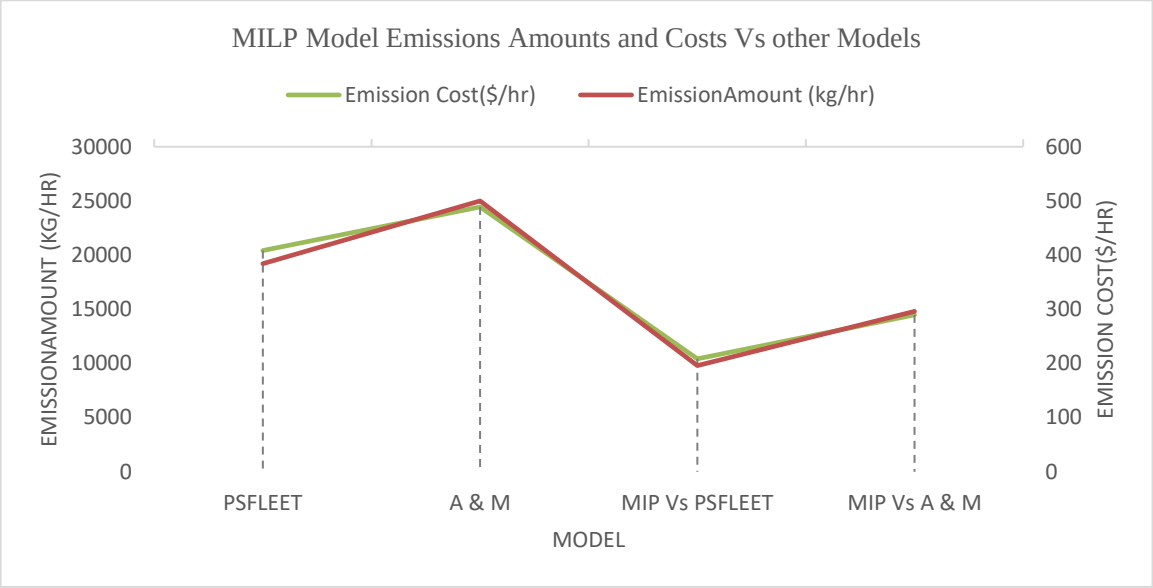


Figure 4. 10: Emissions Amount and Cost of MILP Model VS the Selected Models

Case Study Two Results

According to the A&M2 model, the selected fleet was utilized to move the soil from one cut to multiple fill areas until the cut section was consumed. Then the same fleet was moved to the next cut section. The process continued until all cut sections were consumed. On The Contrary, the developed model selected multiple daily crews for different cut-fill sites. In addition, it identified the optimum soil quantities to be moved each day between different cut-fill sections. However, the output of the developed model considering eight working hours per day was found as follows 1) a total of eleven crews selected for five consecutive days, 2) an overall project cost was 45 691$ (33.07 cost reduction compared to A&M2 model), 3) the project duration was 40 hours A detailed explanation of output results is summarized as follows, 1) daily crew configuration (Table 4.12), 2) daily moved

soil quantities, scrapers trips between cut-fill sites, cost, and duration (Table 4.13), 3) total soil quantities moved from each cut to fill sites (Table 4.14), 4) soil amount remaining in the borrow pits each day, new soil amount increased each day at each landfill site (Figure 4.11).

As indicated by Table 4.12, 1) on the first day, three crews were selected between cut-fill sections (C5, D3, D4), 2) at day two, two crews operated between cut-fill sections (B5, C3), 3) at day three, two crews utilized between cut-fill sections (C5, B2), 4) at day four, three crews moved soil between cut-fill sections (B2, A2, A1), 5) at day five, one crew committed to servin cut-fill section (C5). It should be noted that the pushers at the same cut area can serve more than one fill section at the same time (e.g., crews 5 and 7 are served by the same two pushers).

Table 4. 12: Daily fleet configuration

Day	Crew ID	Total N of Equipment		From Cut	To Fill
		Pushers	Scrapers		
1	1	1	2	C	5
	5	2	1	D	3
	7	2	2	D	4
2	2	2	4	B	5
	6	1	1	C	3
3	3	2	4	C	5
	9	2	1	B	2
4	8	1	2	B	2
	10	1	2	A	2
	11	1	1	A	1
5	4	1	1	C	5

As depicted by Table 4.13, a detailed representation of soil quantities, total trips, duration, and the operational cost of each crew is provided as follows 1) crew ID1 (7536.6 m3, 318 N, 7 hr, 2107$), 2) crew ID2 (15002.1 m3, 633 N, 7 hr, 4214$), 3) crew ID3

(15073.2 m3, 636 N, 7 hr, 4214$), 4) crew ID4(2393.7 m3, 101 N, 4 hr, 669$), 5) crew ID5 (7536.6 m3, 318 N, 7 hr, 2107$), 6) crew ID6 (5000.7 m3, 211 N, 7 hr, 976$), 7) crew ID7 (10001.4 m3, 422 N, 7 hr, 1952$), 8) crew ID8 (7536.6 m3, 318 N, 6 hr, 1789$), 9) crew ID9 (2464.8 m3, 104 N, 5 hr, 585$), 10) crew ID10 (5000.7 m3, 211 N, 7 hr, 976$), 11) crew ID11 (5000.7 m3, 211 N, 7 hr, 976$),

Table 4. 13: Daily Moved Soil Quantities, Scrapers Trips, Cost, And Duration Between Cut-Fill Sites

Day	Crew ID	Quantity m^3	N Trips	Time (hr)	Cost ($)
1	1	7536.6	318	7	2107
	5	5000.7	211	8	1187
	7	10001.4	422	7	1952
2	2	15002.1	633	7	4194
	6	5000.7	211	7	976
3	3	15073.2	636	7	4214
	9	2464.8	104	5	585
4	8	7536.6	318	6	1789
	10	5000.7	211	5	1398
	11	5000.7	211	7	976
5	4	2393.7	101	4	669
	∑	**80011.2**	**3376**		**20047**

As portrayed by Table 4.14, for each cut-fill section, the overall trips, soil quantities, duration, operational cost are as follow, 1) A1 (211 N, 5001.7 m3, 7 hr, 976$), 2) A2 (211 N, 5001.7 m3, 5 hr, 1398$), 3) B2 (422 N, 10001.4 m3, 7 hr, 976$), 4) B5 (633 N, 15002.1 m3, 7 hr, 4194$), 5) C3 (211 N, 5001.7 m3, 7 hr, 976$), 6) C5 (1055 N, 25003.5 m3, 18 hr, 6990$), 7) D3 (211 N, 5001 m3, 8 hr, 1187$), 8) D4 (422 N, 10001.4 m3, 7 hr, 1952$).

Table 4. 14: Total Soil Quantities Moved from Each Cut to Fill Sites

Cut	Fill	N Trips	Quantity (m^3)	Time (hr)	Cost ($)
A	**1**	211	5001.7	7	976
	2	211	5001.7	5	1398
B	**2**	422	10001.4	11	2374
	5	633	15002.1	7	4194
C	**3**	211	5001.7	7	976
	5	1055	25004.5	18	6990
D	**3**	211	5001.7	8	1187
	4	422	10001.4	7	1952
∑		**3376**	**80012.2**		**20047**

Figure 4.11 reflects the amount of soil (trips) remaining at each cut section, and the new soil amount (trips) increased at each fill section. This figure can be used for monitoring and controlling purpose of the project However, it is worth mentioning that the computational model time is part of the second (0.16 sec).

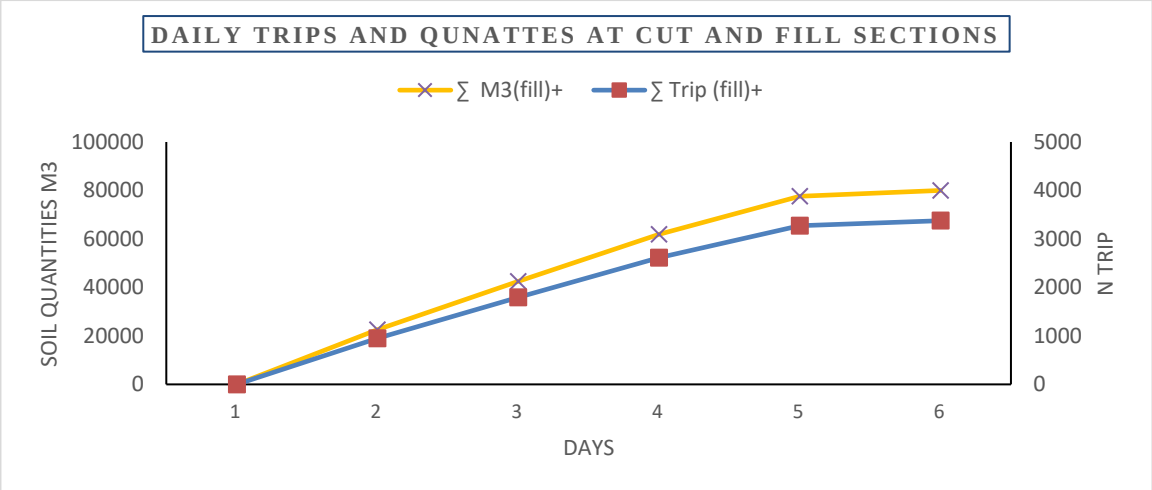


Figure 4. 11: MILP Model Emissions Amounts and Costs Vs A&M2

Emission Amount and Cost Comparison

The MILP model found that the total emission amount is 41.583 tons compared to the A & M2 (125.211 tons) whereas the cost of emissions is 2200$ compared to 6650 $ of the A & M2 model (Figure 4.12).

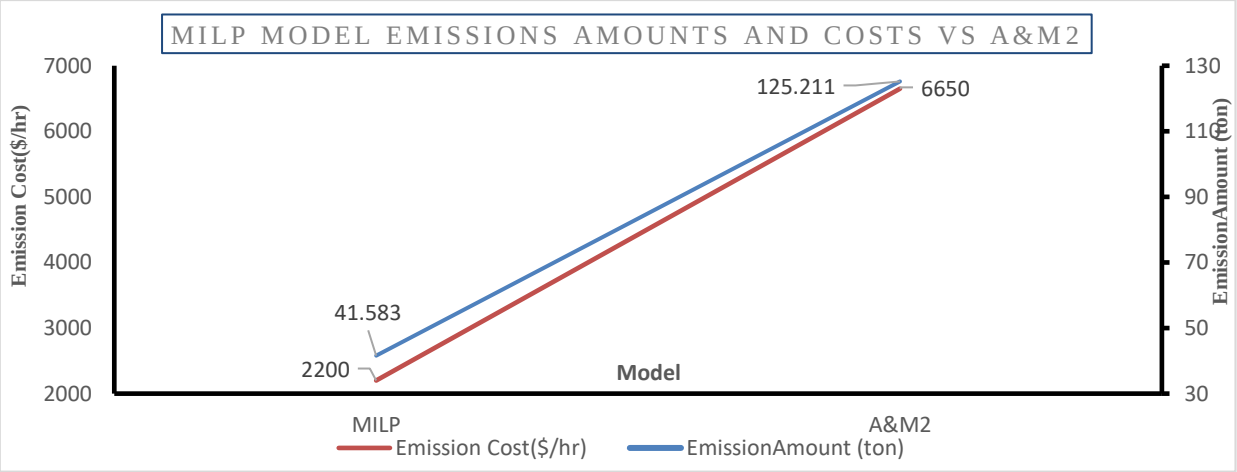


Figure 4. 12: Daily Update of Trips and Quantities at Different Cut-Fill Sections

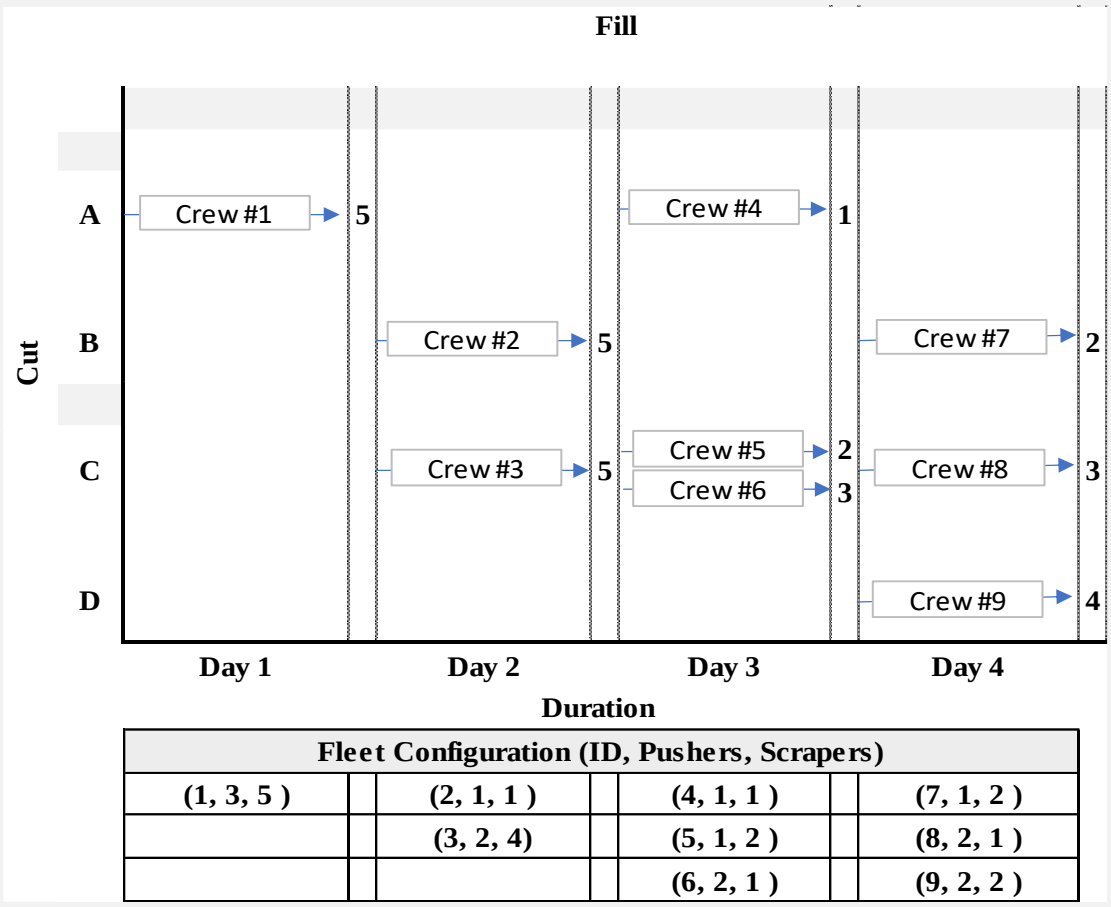
MILP Results Discussion

The acquired results from the developed model indicated that the developed model has superiority over the discussed model. For instance, 7.029%, 25.44%, 33.07% cost reductions are achieved by the developed over the PSFLEET, A&M, A&M2 models, respectively. Similarly, 45.763%, 42.27%, 20% duration reduction are obtained, respectively.

However, it is important to stress the fact that all previous calculations did not consider the overhead costs. Therefore, there was an interruption in the crews working between some cut-fill sections. To illustrate, taking fill section number 5 as an example, three crews served to fill section 5 at the first three working days. However, on day four,

an interruption occurred in the crews that serve landfill 5. On day five, one crew-served to fill 5. In contrast, in real-life projects, as soon as the crews start operating between different cut sections to specific fill sections, the work continued until the fill section is completed. Hence, the developed model is enhanced to overcome the latter issues. To illustrate the full feature of the developed model, a daily 3000$ overhead cost is added to model A&M2.

Adding the overhead costs, the project was completed at 57691.64$ and a duration of 32 h. It can be seen that the model reduced the overall cost of the project by adding more crews to finish the project earlier to get rid of the extra overhead cost. However, the new fleet configuration for each day (crew ID, N pushers, N scrapers, cut-fill section) is as follows 1) day one (1, 3, 5, B5), 2) day two ((2, 1, 1, B5), (3, 2, 4, C5)), 3) day three ((4, 1, 1, A1), (5, 1, 2, C2), (6, 2, 1, C3)), 4) day four ((7, 1, 2, B2), (8, 2, 1, D3), (9, 2, 2, D4)). The representation of the daily planned operations is provided in Figure 4.13. Another significant feature of the developed model is the ability to investigate several scenarios that eff the project construction process (What If-analysis) such as adding more resources, decreasing the project duration, etc.



Fleet Configuration (ID, Pushers, Scrapers)							
(1, 3, 5)		(2, 1, 1)		(4, 1, 1)		(7, 1, 2)
		(3, 2, 4)		(5, 1, 2)		(8, 2, 1)
				(6, 2, 1)		(9, 2, 2)

Figure 4. 13: Daily Planned Operations for Non-Interruption Crews

4.5.2 DES Model Results and Discussion

As demonstrated in section 3.2.3, the MILP model assumed optimal operational conditions, which is not the case in real-world projects. Therefore, the DES model is used to validate the MILP model and consider other aspects (e.g., queues at the loading area, uncertainty in hauling and returning time, etc). The validation process is performed in two steps. The first step represents inputting the output of the MILP model in the DES model and comparing the results where the loading, hauling, dumping, and returning time is treated as a constant value to imitating the MILP model. The second step is used to check if there are other optimal fleet configurations. Applying the MILP results into the DES model as the first step suggested, the DES model results are portrayed in Table 4.15.

Table 4. 15: Soil Amounts transfer Utilizing MILP Fleet Configuration

Cut	Fill	N Trips	Quantity (m^3)	Operational Cost ($)
A	**1**	197	4669	1447
	2	223	5285	1867
B	**2**	410	9717	3298
	5	594	14078	5521
C	**3**	167	4669	1433
	5	1040	24678	9308
D	**3**	167	3958	1657
	4	380	9006	2880
∑		3208	76029.5	*45411

As indicated in Table 4.15 above, borrow pit A supplied two fill sections (LF1and LF2) with a soil quantity equal to 4669 $m^3$and 5285 m^3. However, it took 197 and 223 trips to move the soil amount to two landfills at a cost 1447$ and 1867$ consequently. That is 6.635% less than the result obtained from the MILP model for the LF1 and 5.687% more than the MILP model results for the LF2. Regarding borrow pit B, it served landfills (LF2 and LF5) with soil amounts equal to 9717 m3 and 14078 m3. A total of 410 and 594 trips were performed to transfer the soil quantities at costs of 3298$ and 5521$. The results indicate that 2.84% less than the amount achieved by the MILP model for LF2 and 6.16% less than the MILP model results for LF5. As for the borrow pit C, it provided soil to landfills (LF3 and LF5) with a quantity equal to 4669m3 and 24678m3. It required 167 and 1040 trips to deliver the whole quantities at 1433$ and 9308$. The results showed that is 6.63% less than the value acquired by the MILP model for LF3 and 1.42% less than the value attained by the MILP for LF5. Concerning borrow pit D, it charged landfills (LF3 and LF4) with an excess amount of 3958m3 and 9006m3. It required 167 and 380 trips for the soil quantities to be moved at 1657$ and 2880$. This reflected that is 20.85% less than what was acquired by the MILP model for LF3 and 9.95% of the results of the MILP model

for LF4. Moreover, the total quantities transferred by the DES model are 7030 m3 which is equal to 3208 trips at 45411$. That is 4.97% lower compared to the MILP model.

It can be noted that the results acquired from utilizing the same fleet configuration obtained from the MILP model (Table 4.15), the fleet is not capable of finishing the project within the time and cost limit. Hence, several scenarios have been implemented using the DES model to find the optimum fleet configuration that reflects the MILP results. The summary of the implemented scenarios is portrayed in Figure 4.14

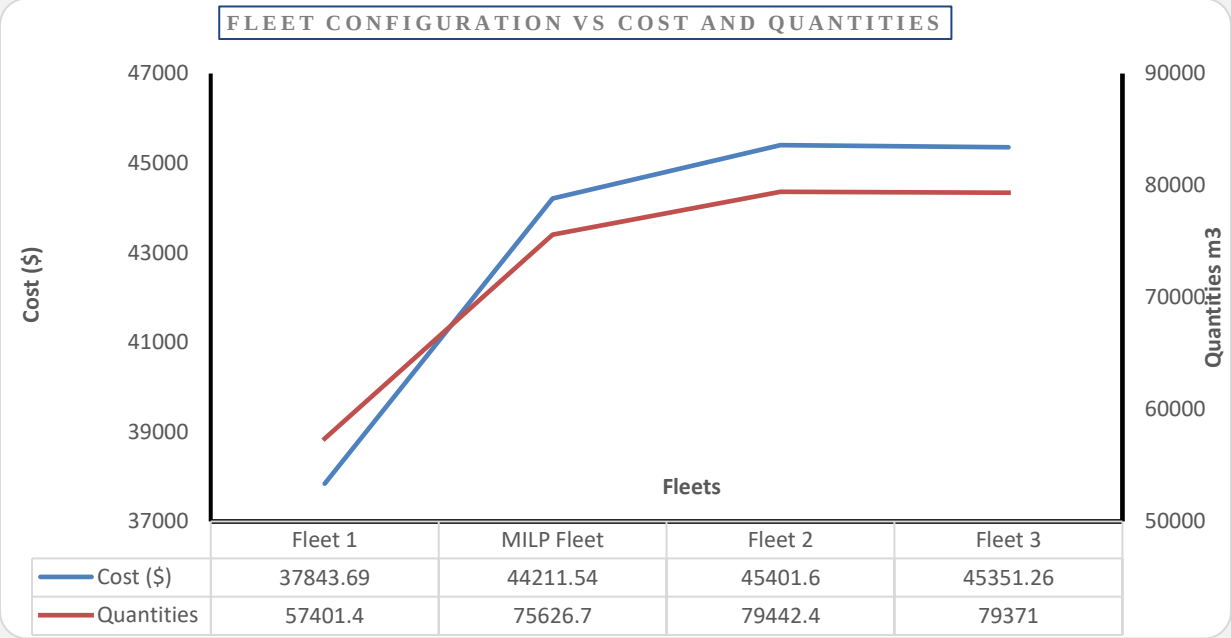


Figure 4. 14: Fleet Configuration VS Cost and Quantities

As depicted by Figure 4.14, fleet 2 reflects the near-o results compared to the MILP model. The detailed representation of Fleet 2 and the quantities moved between different borrow pit and landfill sites are shown in Table 4.16 and Table 4.17.

Table 4. 16: Daily Fleet2 Configuration

Day	Crew ID	Total N of Equipment		From Borrow Pit	To Landfill
		Pushers	Scrapers		
1	1	1	2	C	5
	5	2	2	D	3
	7	2	3	D	4
2	2	2	5	B	5
	6	1	2	C	3
3	3	2	4	C	5
	9	2	1	B	2
4	8	1	2	A	2
	10	1	2	A	2
	11	1	2	A	1
5	4	1	1	C	5

As explained by Table 4.16, the following crew IDs 5, 2, 6, 8, 11 increased by one additional scraper. Hence, utilizing the new fleet configuration as an input for the DES model, the project was completed with time and cost near to the time and cost acquired by the developed MILP model. The new quantities transferred by fleet2 are provided in Table 4.17.

Table 4. 17: Soil Amounts Transfer Utilizing MILP Fleet Configuration

Cut	Fill	N Trips	Quantity (m^3)	Operational Cost ($)
A	**1**	211	5001	1447
	2	211	5001	1867
B	**2**	413	9788	3251
	5	642	15215	5698
C	**3**	210	4977	1440
	5	1046	24790	9290
D	**3**	212	5024	1665
	4	421	9978	2894
∑		3366	79774	*45552

It can be noted that fleet2 provided results close to the results obtained by the developed model. For instance, borrow pit A supplied landfills (LF1 and LF2) with exact soil achieved by the developed model, whereas borrow pit B served landfills (LF2 and LF5) with quantities representing 2.13% less than the developed model for LF2 and 1.42% more than the developed model for LF5. On the other hand, borrow pit C supplied landfills (LF3 and LF5) with soil quantities representing 0.047% and 0.853% less than the developed model. Finally, borrow pit D charged landfills (LF3 and LF4) with excess amounts of 0.474% more than and 0.237% less than the developed model.

4.5.3 **Sniping from the DES model**

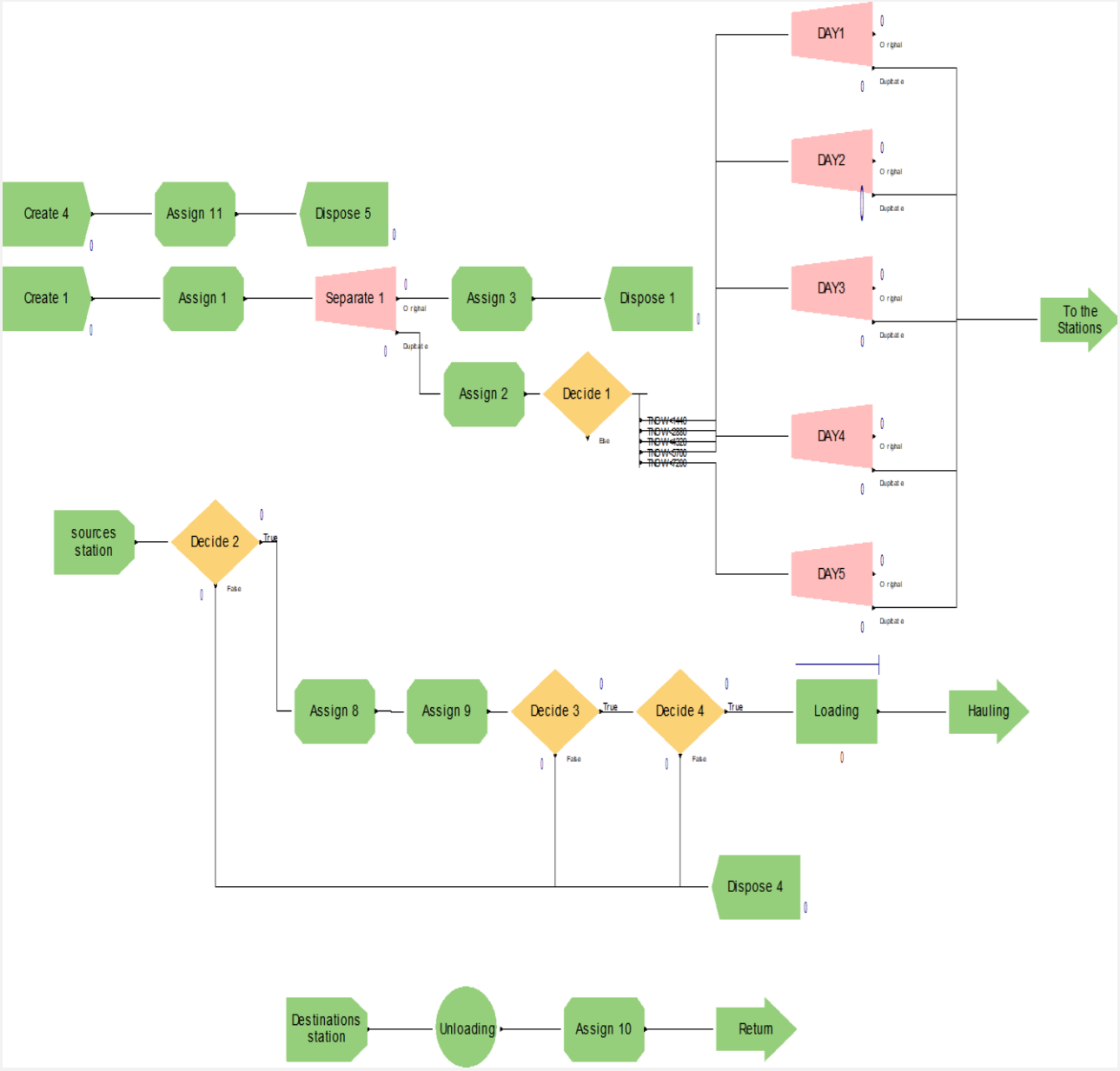


Figure 4. 15: DES Model Flow Logic

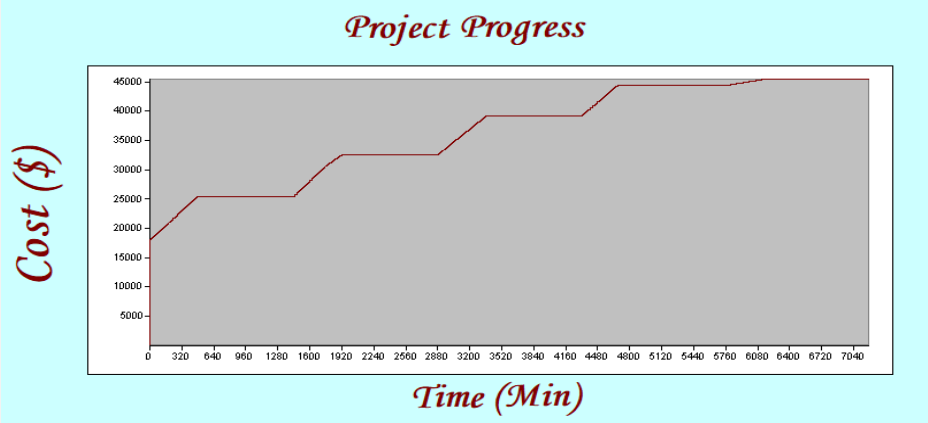


Figure 4. 16: Project Progress Chart

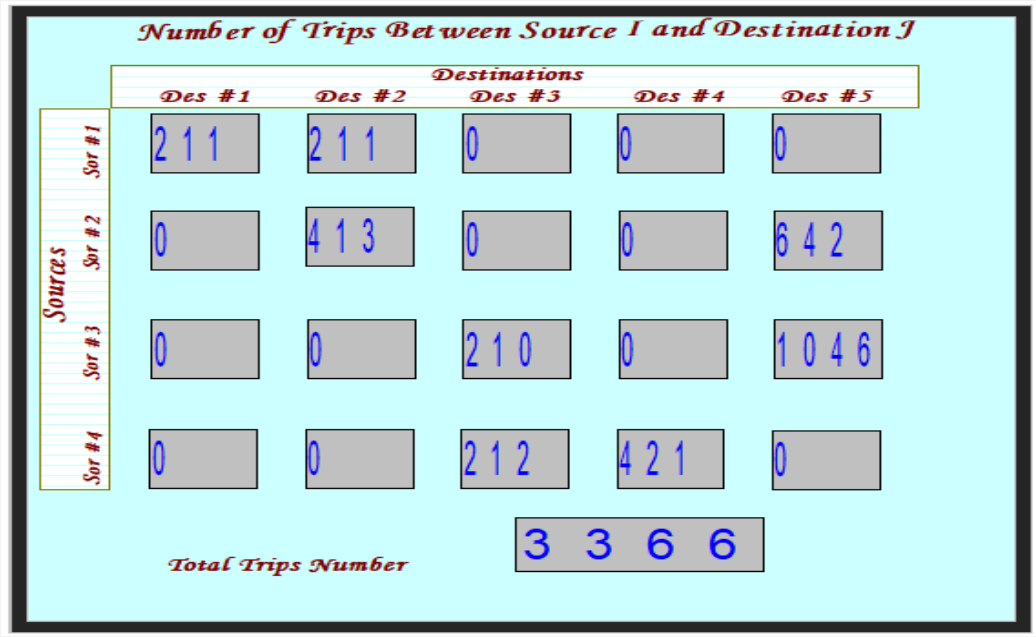


Figure 4. 17: Trips Number Between Different Cut-Fill Areas

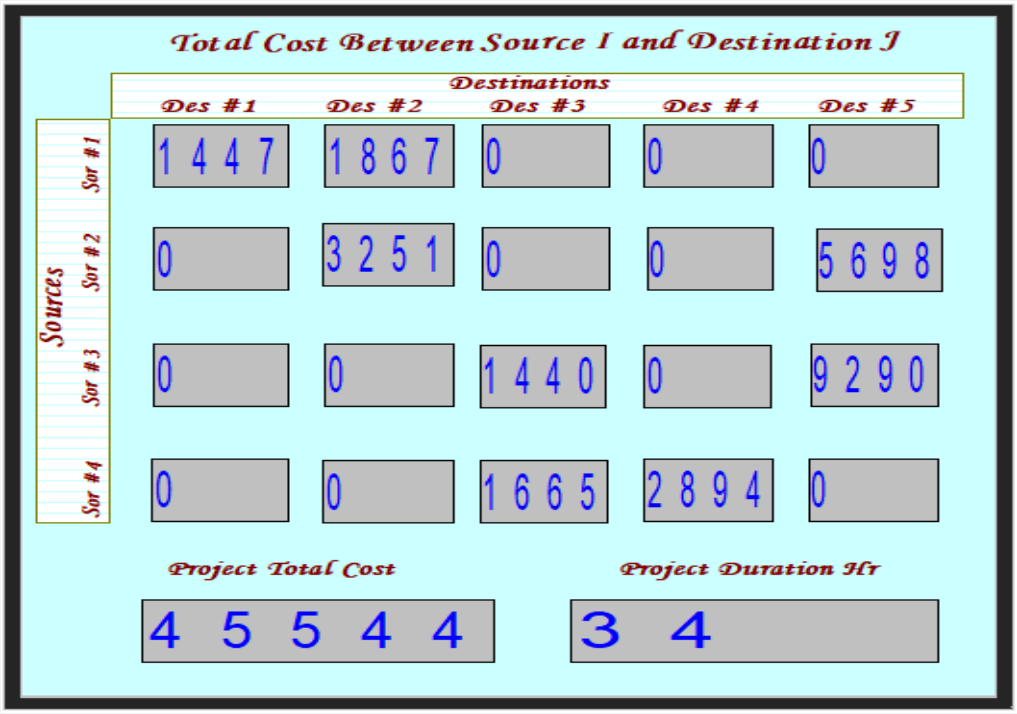


Figure 4. 18: Total Cost Between Different Cut-Fill Areas

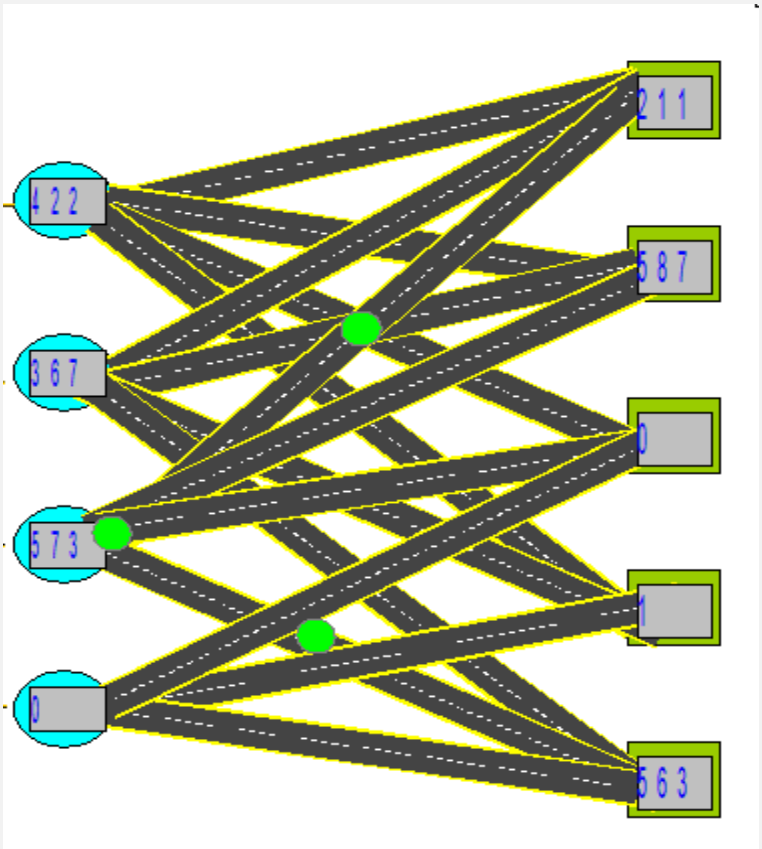


Figure 4. 19: Cut-Fill Section Representation

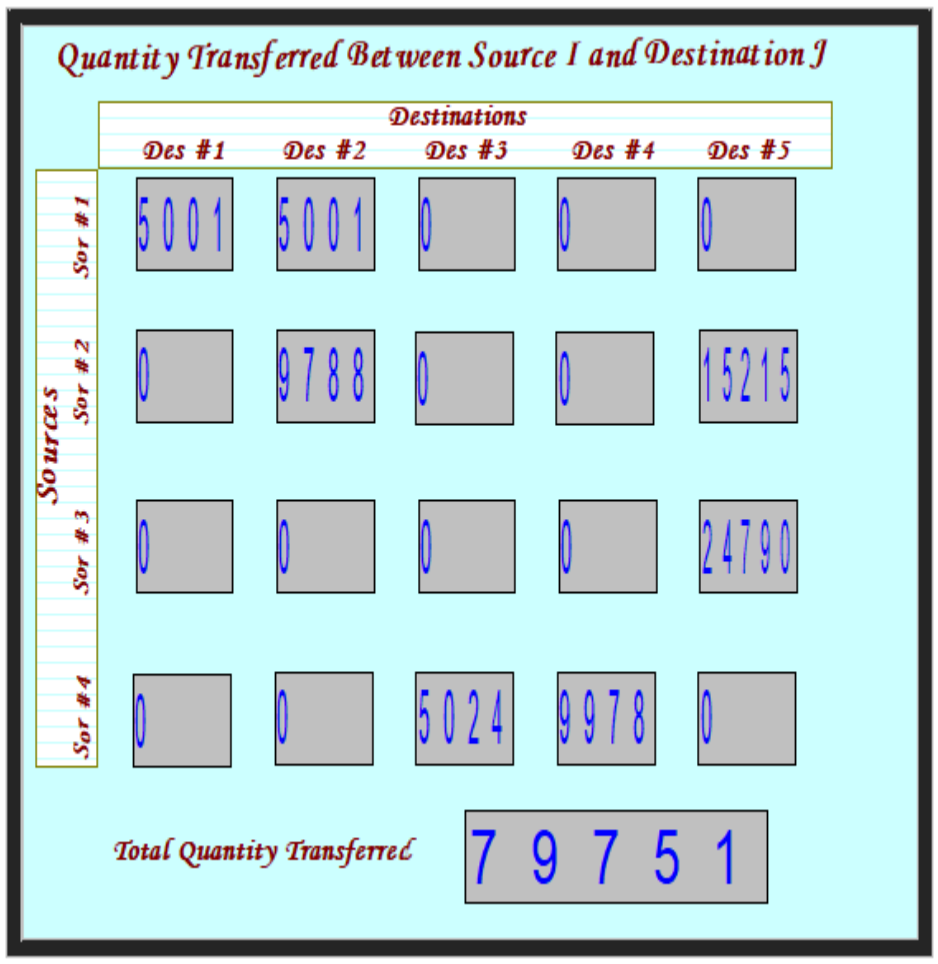


Figure 4. 20: Total Soil Quantity Moved Between Different Cut-Fill Areas

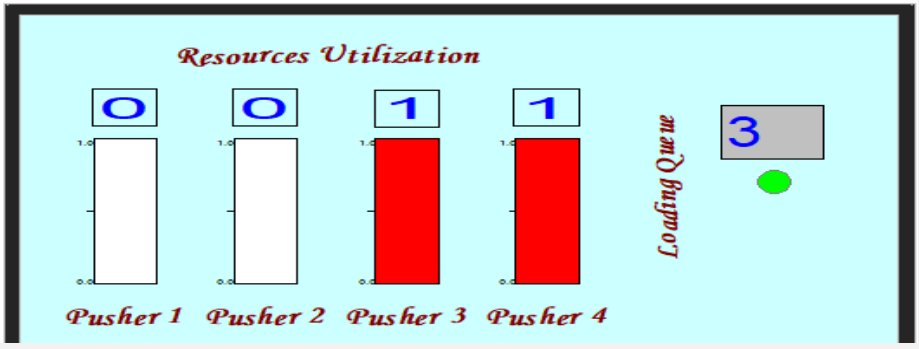


Figure 4. 21: Fleet Utilization

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Research Summary and Conclusions

This research proposed a DES-based MILP model for earthmoving operations. In particular, it presented an effective tool for planning earthmoving operations of highway construction projects. Moreover, the model integrated the mathematical optimization techniques that provide an optimal solution with the simulation techniques that account for the uncertainties associated with earthmoving operations. This integration allowed the model to overcome the limitations of the current earthmoving modeling practice.

In light of that, a comprehensive literature review concerning the current mathematical and simulation techniques of earthmoving operations in general and highway construction, in particular, was conducted. As regards, mathematical optimization techniques (i.e., heuristic, and deterministic) and computer simulation techniques (e.g., DES, ABMS, and SD) were investigated in depth. Furthermore, the limitations of the aforementioned methods were identified. However, an in-depth study of the DES technique in construction management and highway construction projects was carried out to identify the gaps and limitations of the existing models.

Fundamentally, the strength of the developed model is that it provides the optimum fleet configuration with regard to optimum its dynamic changes as the project progresses. This feature resulted in a significant reduction in the overall cost and duration. In addition to providing the optimum crew arrangement, the model also determined the optimum earthmoving quantity hauled between each cut and fill within the project. Knowing such

things will not only help with the operation's planning however also with the monitoring and control process during implementation.

The developed model was verified using three projects that were acquired from the literature. The presented model indicated a significant improvement in project cost by 7.029% for the first case project, 25.44% for the second, and 33.07% for the third. As for the project's overall duration, the improvement percentage was 45.763% for the first case, 42.27% for the second case, and 20% for the third. The enhancement in the results obtained by the proposed model over the selected ones is that our model accounts for the dynamic change of the fleet configuration as the project progresses. In addition, the results revealed that the fleet configurations generated by the DES model are in agreement with those selected by the MILP model by 95.023%.

5.2 Research Limitations

The following points ssummarize the limitations of the proposed research.

- Even though the model considered the uncertainties related to cycle time, there are other issues in real-life projects that need to be taken into consideration such as weather conditions, equipment failure, the obstacle in the hauling roads.
- The model considered a limited number of resources (e.g., scrapers, pushers). However, other equipment is required for earthmoving operations (e.g., loader, truck, grader).

5.3 Recommendations and Future Work

Based on the abovementioned limitations, recommendations and future work are as follows:

- Enhance the model to accommodate other uncertainties, namely obstacles in hauling roads, equipment failure, and work interruptions due to weather conditions.
- Upgrade the model to include other elements such as spotters, graders, loaders, and trucks.
- Link the model with a GIS map to provide real-time monitoring of the process and more accurate cycle time.
- Develop a stand-alone software of the developed model.

References

Abduh, M. (2007). “The Development of Simulation Technology for Construction Operations”. (in Indonesian). Proc. of Seminar Nasional Teknik Sipil 2007. Univ. Maranatha. Bandung, Indonesia.

AbouRizk, S. (2010). Role of Simulation in Construction Engineering and Management. J. Constr. Eng. Manag. 136, 1140–1153.

Ahn, C., Pan, W., Lee, S., & Peña-Mora, F. (2010, June). Enhanced estimation of air emissions from construction operations based on discrete-event simulation. In Proceedings of the International Conference on Computing in Civil and Building Engineering, Nottingham, UK (Vol. 30).

Alkass, S., Aronian, A., Moselhi, O., 1993. Computer-aided equipment selection for transportation and placing concrete. J. Constr. Eng. Manage. 119 (3), 445–465.

Alshibani Adel and Moselhi Osama (2012). "Fleet selection for earthmoving projects using optimization-based simulation." Canadian Journal of Civil Engineering 39(6): 619-630.

Alzraiee, H. S. (2013). Hybrid Simulation for Construction Operations. Ph.D. Dissertation, Building, Civil and Environmental Engineering Department, Concordia University, Montreal, QC, Canada

Alzraiee, H., Zayed, T., & Moselhi, O. (2015). Dynamic planning of construction activities using hybrid simulation. Automation in Construction, 49, pp. 176-192.

Alvanchi, A., et al. (2012). "Off-Site Construction Planning Using Discrete Event Simulation." Journal of Architectural Engineering 18(2): 114-122.

Alvanchi, A., Lee, S. H., & AbouRizk, S. (2011). Modeling framework and architecture of hybrid system dynamics and discrete event simulation for construction. Computer-Aided Civil and Infrastructure Engineering, 26(2), pp. 77-91.

Arslan, M.C., Catay, B., Budak, E., 2004. A decision support system for machine tool selection. J. Manuf. Technol. Manage. 15 (1), 101–109.

Aziz, Z., Qasim, R.M. and Wajdi, S. (2017), "Improving productivity of road surfacing operations using value stream mapping and discrete event simulation", Construction Innovation, Vol. 17 No. 3, pp. 294-323. https://doi.org/10.1108/CI-11-2016-0058

Babulak, E. and M. Wang (2008). "Discrete Event Simulation: State of the Art." International Journal of Online Engineering (iJOE) 4: 60-63.

Banks, J. and J. S. Carson (1984). Discrete-event system simulation, Englewood Cliffs.

Binder, T., Vox, A., Belyazid, S., Haraldsson, H., & Svensson, M. (2004). Developing system dynamics models from causal loop diagrams. Proceedings of the 22nd International Conference of the System Dynamics Society, July 25-29, Oxford

Bokor, O., Florez, L., Osborne, A., & Gledson, B. J. (2019). Overview of construction simulation approaches to model construction processes. Organization, Technology and Management in Construction: an International Journal, 11(1), 1853-1861.

Borshchev, A., and Filippov, A. (2004). "From system dynamics and discrete event to practical agent-based modeling: reasons, techniques, tools." Proceedings of the 22ndinternational conference of the system dynamics society, Oxford, England, No. 22.

Borshchev, A. (2013). Multi-method modeling. In: Pasupathy, R., Kim, S. -H., Tolk, A., Hill, R., & Kuhl, M. E. (eds.) Proceedings of the 2013 Winter Simulation Conference. IEEE, Washington DC, USA, pp. 4089-4100. Available at https://informs-sim.org/ wsc13papers/includes/files/410.pdf.

Boyde, S., 2002. Green lubricants, Environmental benefits and impacts of lubrication. R. Soc. Chem. 2002 (4), 293–307.

Brailsford, S., and Hilton, N. (2001). "A comparison of discrete event simulation and system dynamics for modelling health care systems." School of Management, University of Southampton, UK.

Carmichael, D. (1987). “Optimal pusher–scraper loading policies.” Eng. Optim., (Bellingham, WA, U.S.) 12(4), 255–267.

Caterpillar, 2011. Caterpillar Performance Handbook. Peoria, USA

Caterpillar Inc. Caterpillar Performance Handbook, 50th ed. Peoria, IL: Caterpillar Inc.,

2018.

Chen, L., & Fong, P. S. (2013). Visualizing evolution of knowledge management capability in construction firms. Journal of Construction Engineering and Management, 139(7), 839-851. https://doi.org/10.1061/(asce)co.1943-7862.0000649

Dangerfield, B. (2014). Systems Thinking and System Dynamics: a primer: 29-51.

Dantzig, G.B., Ramser, J.H. 1959. The truck dispatching problem, Management Science, 6 1, pp. 80-91

De Lima, R. X., et al. (2021). "Optimization of Earthmoving Operations Planning: A Novel Approach Considering Interferences." Journal of Engineering, Project, and Production Management **11**(2): 158-168 . https://doi.org/10.2478/jeppm-2021-0016

Douglas D, Jorge A, (2020). Construction Equipment Management for Engineers Estimators and Owners.

El-Adaway, I. H., and Kandil, A. A. (2009). "Multiagent system for construction dispute resolution (MAS-COR)." Journal of Construction Engineering and Management, 136(3), 303-315.

Eldabi, T., Brailsford, S., Djanatliev, A., Kunc, M., Mustafee, N., & Osorio, A. F. (2018, December). Hybrid simulation challenges and opportunities: a life-cycle approach. In 2018 Winter, Simulation Conference (WSC) (pp. 1500-1514). IEEE.

Eldin, N.N., Mayfield, J., 2005. Determination of most economical scrapers fleet. Journal of Construction Engineering and Management 131 (10), 1109–1114.

Elwakil, E. (2011). Knowledge discovery-based simulation system in construction. Ph.D. Dissertation, Building, Civil and Environmental Dept., Concordia University, Montreal, QC, Canada).

Falcão, V., et al. (2020). "Truck routing cut and fill problem in roadworks using integer programming." TRANSPORTES 28.

Forrester, J. (1961). Industrial dynamics. Cambridge, MA: Productivity Press.

Gates, M., Scarpa, A., 1980. Criteria for the selection of construction equipment. J. Constr. Div. 106 (2), 207–219.

Goh, Y. M. and M. J. Askar Ali (2016). "A hybrid simulation approach for integrating safety behavior into construction planning: An earthmoving case study." Accident Analysis & Prevention 93: 310-318.

Goldenberg, M., Shapira, A., 2007. Systematic evaluation of construction equipment alternatives: Case study. J. Constr. Eng. Manage. 133 (1), 72–85.

Gransberg, D.D., Popescu, C.M., Ryan, R.C., 2006. Construction Equipment Management for Engineers, Estimators and Owners. Taylor & Francis, London.

Grimm, V., and Railsback, S. F. (2013). Individual-based modeling and ecology. University Press, Princeton, NJ.

Guggemos, A.A., Horvath, A., 2006. Decision-support tool for assessing the environmental effects of constructing commercial buildings. Archit. Eng. 12 (2), 87–195.

Hajjar, D., & AbouRizk, S. (1997). AP2-earth: A simulation-based system for the estimating and planning of earth moving operations. Proceedings of the 29th Conference on Winter Simulation, Dec 7-10, Washington, DC, USA. 1103-1110.

Hajjar, D. and M. AbouRizk Simaan (1998). "Modeling and Analysis of Aggregate Production Operations." Journal of Construction Engineering and Management 124(5): 390-401.

Hajjar, D., and AbouRizk, S. (1999). "Simphony: an environment for building special purpose construction simulation tools." Proceedings of the 31st Conference on WinterSimulation: Simulation---a Bridge to the Future-Volume 2, ACM, Phoenix, AZ, USA, 998-1006.

Hajji, A.M., 2013. Estimating the emissions of nitrogen oxides (NOX) and particulate matter (PM) from diesel construction equipment by using the productivity model. World J. Sci. Technol. Sustainable Dev. 10 (3), 212–228.

Halpin, D. W. and Riggs, L. S. 1992. Planning and Analysis of Construction Operations. John Wiley and Sons, Inc., New York, NY, USA.

Halpin, D., & Woodhead, R. (1997). Construction management (2nd ed.). New York, USA: Wiley

Hare, W., et al. (2011). "Models and algorithms to improve earthwork operations in road design using mixed integer linear programming." European Journal of Operational Research 215: 470-480.

Helal, M. (2008). A hybrid system dynamics-discrete event simulation approach to simulating the manufacturing enterprise. Ph.D.Thesis, University of Central Florida,Orlando, FL, USA.

Huang, R., & Halpin, D. (1994). Visual construction operation simulation: The DISCO approach. Computerö Aided Civil and Infrastructure Engineering, 9(3), 175-184.

Icmeli, O., Selcuk Erenguc, S., Zappe, C. J. 1993. Project scheduling problems: a survey, International Journal of Operations & Production Management, 13 11, pp. 80-91

Idoro, G.I., 2011. Effect of mechanization on occupational health and safety performance in the Nigerian construction industry. J. Constr. Dev. Countries 16 (2), 27–45.

Ingalls, R. (2002). Introduction to simulation: introduction to simulation. Proceedings of the 2008 Winter Simulation Conference, June 2008.

Jabri, A., (2014). Agent-Based Modeling and Simulation of Earthmoving Operations. Master's thesis, Building, Civil and Environmental Engineering Department, Concordia University, Montreal, QC, Canada.

Jrade, A., Markiz, N., 2012. A decision-support model utilizing a linear cost optimization approach for heavy equipment selection. Constr. Res. Congr., 100–109.

Jassim, H. S. H., Lu, W., & Olofsson, T. (2016). A practical method for assessing the energy consumption and CO2 emissions of mass haulers. Energies, 9(10). https://doi.org/10.3390/en9100802 .

Ji, Y., Borrmann, A., Rank, E., Seipp, F., & Ruzika, S. (2010, June). Mathematical modeling of earthwork optimization problems. In Proc. of the International Conference on Computing in Civil and Building Engineering (ICCCBE), Nottingham, UK.

José Antonio Botín, Alexander Nicholas Campbell & Ronald Guzmán (2015) A discrete-event simulation tool for real-time management of pre-production development fleets in a block-caving project, International Journal of Mining, Reclamation and Environment, 29:5, 347-356

Karshenas, S., and Farid, F. (1988). "Multiloader-Truck Fleet Selection for Earthmoving." Transportation Research Record, NO. 1186, pp. 51-65.

Kim, B., Lee, H., Park, H., Kim, H., 2012. Greenhouse gas emissions from onsite equipment usage in road construction. Constr. Eng. Manage. 138 (8), 982–990.

Kittusamy, N.K., Buchholz, B., 2004. Whole-body vibration and postural stress among operators of construction equipment: a literature review. Natl. Inst. Occup. Saf. Health USA 35 (3), 255–261.

Klingstam, P.; Gullander, P. (1999). Overview of simulation tools for computer-aided production engineering. Comput. Ind. 38, 173–186.

Koo, D.H., Ariaratnam, S.T., 2008. Application of a sustainability model for assessing water main replacement options. J. Constr. Eng. Manage. 134 (8), 563–574.

Kuhn, H.W. (1955), The Hungarian method for the assignment problem. Naval Research Logistics quarterly, 2: pp.83-97. https://doi.org/10.1002/nav.3800020102

Lättilä, L., Hilletofth, P., & Lin, B. (2010). Hybrid simulation models - When, why, how? Expert Systems with Applications, 37(12), pp. 7969-7975.

Labban, R., et al. (2013). A discrete event simulation model of asphalt paving operations. 2013 Winter Simulations Conference (WSC).

Lewis, P., Rasdorf, W., Frey, H., Pang, S., Kim, K., 2009. Requirements and incentives for reducing construction vehicle emissions and comparison of nonroad diesel engine emissions data sources. Constr. Eng. Manage. 135 (5), 341–351

Li, H. and Z. Lei (2010). Implementation of Discrete-Event Simulation (DES) in estimating & analyzing CO2 emission during earthwork of building construction engineering. 2010 IEEE 17Th International Conference on Industrial Engineering and Engineering Management.

Lu, M. (2018). A Simulation-based Earthmoving Fleet Optimization Platform (SEFOP) for Truck/Excavator Selection in Rough Grading Project. Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC), International Association for Automation and Robotics in Construction (IAARC): 956-962.

Lu, M. (2003). "Simplified Discrete-Event Simulation Approach for Construction Simulation." Journal of Construction Engineering and Management 129(5): 537-546.

Lyneis, J. M., Cooper, K. G., and Els, S. A. (2001). "Strategic management of complex projects: a case study using system dynamics." System Dynamics Review, 17(3), 237-260.

Macal, C. M., and North, M. J. (2010). "Tutorial on agent-based modelling and simulation." Journal of Simulation, 4(3), 151-162.

Mackenzie, S., Kilpatrick, A.R., Akintoye, A., 2000. UK construction skills shortage response strategies and an analysis of industry perceptions. Constr. Manage. Econ. 18 (7), 854–862.

Martinez, J. C. (1998). EarthMover-simulation tool for earthwork planning. 1998 Winter Simulation Conference. Proceedings (Cat. No.98CH36274).

Martinez, J. (1996). Stroboscope: State and resource-based simulation of construction processes. Ph.D. Dissertation, University of Michigan, Michigan, MI, USA.

Martin, R., & Raffo, D. (2001). Application of a hybrid process simulation model to a software development project. Journal of Systems and Software, 59(3), 237-246.

Marzouk, M., and Moselhi, O. Object-orientedSimulation Model for Earthmoving Operations. Journal of Construction Engineering & Management, 129(2), 173.

Min, J. U., and Bjornsson, H. C. (2008). "Agent-Based Construction Supply Chain Simulator (CS 2) for Measuring the Value of Real-Time Information Sharing in Construction." Journal of Construction Engineering and Management, 24(4), 245-254.

Moradi, S., Nasirzadeh, F., & Golkhoo, F. (2015). A hybrid SD–DES simulation approach to model construction projects. Construction Innovation, 15(1), pp. 66-83.

Morris, W. T. (1967) "On the Art of Modeling," Management Science", vol. 13, No. 12.

Montaser, A., et al. (2012). "Estimating productivity of earthmoving operations using spatial technologiesThis paper is one of a selection of papers in this Special Issue on Construction Engineering and Management." Canadian Journal of Civil Engineering 39.

Moonseo, P., & Peña-Mora, F. (2003). Dynamic change management for construction: introducing the change cycle into model-based project management. System Dynamics Review, 19(3), 213-242. https://doi.org/10.1002/sdr.273

Moselhi, O., Alshibani, A. (2007). Crew optimization in planning and control of earthmoving operations using spatial technologies. Electronic Journal of Information Technology in Construction, 12(2), 121–137

Moselhi, O., Alshibani, A. (2009). Optimization of earthmoving operations in heavy civil engineering projects. Journal of Construction Engineering and Management, 135(10), 948–954.

Mustafee, N., Powell, J., Brailsford, S. C., Diallo, S., Padilla, J., & Tolk, A. (2015). Hybrid simulation studies and hybrid simulation systems: definitions, challenges, and benefits. In: Yilmaz, L., Chan, W. K. V., Moon, I., Roeder, T. M. K., Macal, C., & Rossetti, M. D. (eds.) Proceedings of the 2015 Winter Simulation

O'Brien, J.J., Zilly, R.G., 1971. Constructor's Management Handbook, 1st Ed. McGraw-Hill, New York.

Oloufa Amr, A. (1993). "Modeling Operational Activities in Object-Oriented Simulation." Journal of Computing in Civil Engineering 7(1): 94-106.

Park, M. (2005). Model based dynamic resource management for construction projects. Automation in Construction, 14 (5), 585-598. https://doi.org/10.1016/j.autcon.2004.11.001

Peña-Mora, F., Han, S., Lee, S. H., & Park, M. (2008). Strategic-operational construction management: Hybrid system dynamics and discrete event approach. Journal of Construction Engineering and Management, 134(9), 701-710.

Peurifoy, R.L., Schexnayder, C.J., Shapira, A., 2006. Construction Planning Equipment and Methods, 7th Ed. McGraw-Hill, New York.

Pinheiro Santos Fernandes, P., and A. Espindola (2019). Earthworks Planning Using Integer Linear Programming: Case Study in Brazilian Highway BR-316.

Prasertrungruang, T., Hadikusumo, B.H.W., 2009. Modeling the dynamics of heavy equipment management practices and downtime in large highway contractors. J. Constr. Eng. Manage. 135 (10), 939–947.

Richardson, G. (1986). Problems with causal-loop diagrams. System Dynamics Review, 2(2), 158-170.

Rodrigues, A., & Bowers, J. (1996). System dynamics in project management: A comparative analysis with traditional methods. System Dynamics Review, 12(2), 121- 139.

Rodrigues, A., & Bowers, J. (1996). The role of system dynamics in project management. International Journal of Project Management, 14(4), 213-220.

Rodrigues Mateus, O., et al. (2018). "Colored Petri Net Simulation Model to Allocate Motor Graders for Earthmoving Operations." Journal of Transportation Engineering, Part B: Pavements 144(4): 05018002.

Rohatgi, A. (2020). Webplotdigitizer: Version 4.5. https://automeris.io/WebPlotDigitizer

Sacks, R., et al. (2015). "Hybrid Discrete Event Simulation and Virtual Reality Experimental Setup for Construction Management Research." Journal of Computing in Civil Engineering 29(1): 04014029.

Sanford Bernhardt, K., and McNeil, S. (2008). "Agent-based modeling: approach for improving infrastructure management." Journal of Infrastructure Systems, 14(3), 253- 261.

Sawhney, A., & AbouRizk, S. (1995). HSM-Simulation–Based planning method for construction projects. Journal of Construction Engineering and Management, 121(3), 297-334.

Sharrard, A.L., Matthews, H.S., Roth, M., 2007. Environmental implications of construction site energy use and electricity generation. J. Constr. Eng. Manage. 133 (11), 846–854.

Shi, J. and S. Abourizk (2002). "An Automated Modeling System for Simulating Earthmoving Operations." Computer-Aided Civil and Infrastructure Engineering 13: 121-130.

Siebers, P. O., MacAl, C. M., Garnett, J., Buxton, D., & Pidd, M. (2010). Discrete-event simulation is dead, long live agent-based simulation! Journal of Simulation, 4(3), pp. 204-210.

Sing, M. C., Love, P., Edwards, D., & Liu, J. (2016). Dynamic modeling of workforce planning for infrastructure projects. Journal of Management in Engineering, 32(6), 04016019. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000463

Sterman, J. (2000). Business dynamics: Systems thinking and modeling for a complex world. New York, USA: McGraw-Hill.

Smith, S. D., et al. (1995). "Analysis of Earth-Moving Systems Using Discrete-Event Simulation." Journal of Construction Engineering and Management 121(4): 388-396.

Swinerd, C., & McNaught, K. R. (2012). Design classes for hybrid simulations involving agent-based and system dynamics models. Simulation Modelling Practice and Theory, 25, pp. 118-133.

S.W. Nunnally. Construction Methods and Management, 2nd ed. Englewood Cliffs, NJ:

PrenticeHall, 198

Tatum, C.B., Vorster, M., Klingler, M.G., Paulson, B.C., 2006. System analysis of technical advancement in earthmoving equipment. J. Constr. Eng. Manage. 132 (9), 976–986.

Tavakoli, A., Taye, E.D., Erktin, M., 1989. Equipment policy of top 400 contractors: A survey. J. Constr. Eng. Manage. 115 (2), 317–329.

Terouhid, S. A., & Ries, R. (2016). People capability: A strategic capability for enhancing organizational excellence of construction firms. Journal of Modelling in Management, 11(3), 811-841. https://doi.org/10.1108/JM2-04-2014-0028

Tommelein, I., Carr, R., & Odeh, A. (1994). Assembly of simulation networks using designs, plans, and methods. Journal of Construction Engineering and Management,120(4), 796-815.

United States Environmental Protection Agency (USEPA). 2007. Tier4 emission standards and certification requirements. Washington. DC

Valli, P., Jeyasehar, C.A., 2012. Genetic Algorithm based equipment selection method for construction project using MATHLAB tool. Intl. J. Optim. Civil Eng. 2 (2), 235–246

Waris, M., et al. (2014). "Criteria for the selection of sustainable onsite construction equipment." International Journal of Sustainable Built Environment 3(1): 96-110.

Wolstenholme, E. F. (1990). System enquiry: a system dynamics approach, John Wiley & Sons, New York, NY.

Wooldridge, M. & Jennings, N.R. (1995). Intelligent agents: Theory and practice. Knowledge Engineering Review, 10, 115–152.

Wu, G., Duan, K., Zuo, J., Yang, J., & Wen, S. (2016). System dynamics model and simulation of employee work-family conflict in the construction industry. International Journal of Environmental Research and Public Health, 13(11), 1059. https://doi.org/10.3390/ijerph13111059

Yeo, K.T., Ning, J.H., 2006. Managing uncertainty in major equipment procurement in engineering projects. Eur. J. Oper. Res. 17 (1), 123–134.

Yin, C. and A. McKay (2018). Introduction to Modeling and Simulation Techniques. The 12th China-Japan International Workshop on Information Technology and Control Applications (ITCA2018)

Yuan, H. P., Shen, L. Y., Hao, J. J., & Lu, W. S. (2011). A model for cost-benefit analysis of construction and demolition waste management throughout the waste chain. Resources, Conservation and Recycling, 55(6), 604-612.

Zaki, S.B.A., Mohamed, S.F., Yusof, Z.M., 1996. Construction skilled labour shortage – The challenges in Malaysian construction sector. Int. J. Sustain. Dev. 4 (5), 99–108.

Zhang, H. (2015). "Discrete-Event Simulation for Estimating Emissions from Construction Processes." Journal of Management in Engineering 31(2): 04014034.

Zhang, H., et al. (2005). "Activity Object-Oriented Simulation Strategy for Modeling Construction Operations." Journal of Computing in Civil Engineering - J COMPUT CIVIL ENG 19.

Zhou, F., et al. (2009). "Optimisation of construction site layout using a hybrid simulation-based system." Simulation Modelling Practice and Theory 17(2): 348-363.

Zulch, G., Jonsson, U., & Fischer, J. (2002). Hierarchical simulation of complex production systems by coupling of models. International Journal of Production Economics, 77(1), 39-51

Vitae

Name	Zaid Ahmad Khallaf
Nationality	Palestinian
Date of Birth	23-05-1995
Email	zaidkhallaf@gmail.com
Address	Academic Built-Dhahran-Saudi Arabia-31261
Academic Background	B.Sc. Civil and Environmental Engineering (KFUPM) M.Sc. Construction and Engineering Managements (KFUPM)

Publications

1. Dynamic Fleet Configuration Model for Optimizing Earthmoving Operations Using Mixed Integer Programing

   Zaid Khallaf[1,2], Adel Alshaibani[1,2*], Omar Alsawafy[3], Awsan Mohammed[1], and Abdulaziz Bubshait[1]

2. Simulation-Based Optimizing Model for Earthmoving Operations Considering the Dynamic Change in the Fleet Configuration

   Zaid Khallaf[1,2], Adel Alshaibani[1,2*], Omar Alsawafy[3], Awsan Mohammed[1], and Abdulaziz Bubshait[1]