Temporary Haul Road Design and Earthmoving Operation Planning on Rough Grading Projects: Integrated Optimization Approach

by

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

Doctor of Philosophy

in

Construction Engineering and Management

Department of Civil and Environmental Engineering

University of Alberta

ABSTRACT

Site rough-grading operations entail massive earthworks and are critical to plan and control large-scale land development projects and industrial construction projects. The material haulage cost typically accounts for around 30% of the total cost of the entire rough grading project. To improve hauling efficiency and save earthmoving operation cost, the common practice is to empirically construct limited lengths of temporary haul road (i.e. gravel surfaced high grade haul road, rough-ground low grade haul road) to handle the bulk of earthmoving jobs. In current practice, earthmoving jobs are generally planned based on cut and fill requirements prior to haul road layout design. However, the earthmoving operations and temporary haul road layout should be planned as a holistic system, because the two planning tasks are highly intertwined with each other (i.e. high grade haul roads are more expensive to build, but less expensive to operate while low grade haul roads are less expensive to build, but more expensive to operate). This separation introduces research opportunity as well as proposes challenges in planning earthmoving operations and temporary haul road layout design in an integrative fashion. This thesis applied existing scientific knowledge in both mathematical programming and computer science to address a practical problem in civil engineering by providing an integrated optimization framework that is capable to provide field planners with cost-effective solutions, verified in simulated realistic environment and ready for immediate implementation to guide earthworks planning practice. In particular, this thesis develops a complete package of applied science in construction engineering and management (i.e. apply existing scientific knowledge to develop practical applications in construction, and verify the solution generated by the science being applied in practical settings), including three parts:

Part I applied latest advances in mathematical programming and computer science to develop an integrated optimization approach to simultaneously generate earthmoving operation planning and temporary haul road layout design resulting in the minimum cost. This includes mathematical modelling of the construction site, problem formulation, and algorithms devising. In particular, this thesis proposes a Cutting Plane Method based Mixed-integer Linear Programming (C-MILP) approach to optimize the temporary haul road layout design and generate earthmoving operation plans analytically by considering field constraints. The proposed method is capable to automatically produce the optimum solution in terms of minimizing the total earthmoving cost of a site grading project (i.e. a combined cost consisting of earthmoving crew cost, haul road construction and removal cost, and road maintenance cost).

Part II devises an MILP based post-optimization sensitivity analysis approach to identify optimization model input parameter stability regions with the intention to provide the decision makers with enhanced confidence of the proposed mathematical model and insight in the optimum solution for possible practical application. This includes formalizing sensitivity analysis model, proposing a one-at-a-time (OAT) method, and designing algorithms. To be specific, this thesis firstly proposes a generic MILP sensitivity analysis model. Next, a one-dimensional line search approach is devised to find the boundaries of a stability region on each input parameter of the MILP optimization model, within which the optimum solution can be retained irrespective of the change to the input value.

Part III develops an earthmoving operation analysis tool to facilitate validating the optimum solution resulting from applying science in math and computer science. Since abstraction and implicitness of analytical methods present the common hurdles to effective solution communication and interpretation, computer simulation is adopted to bridge the gap between analytical methods and implementation in reality. In this thesis, an Earthmoving Operation Analysis Platform (EOAP) tool has been prototyped to identify crew configuration and to evaluate earthmoving crew operation cost by computer simulation, automating the evaluation of simulation scenarios and facilitating the comparison of different solutions.

The proposed approach was applied in a case study based on a real-world site grading project in Northern Alberta, Canada. The effectiveness of the proposed methodology was demonstrated in terms of generating optimum layout design and operation plan. Sensitivity analysis were conducted and the resulting parameter stability regions were validated and deemed conducive to determining a valuable “buffer” on each input parameter so to assist decision makers in assessing risks in planning and coping with changes in reality. Compared to the solutions to the same case problem which were collected from site managers, field engineers, and graduate students specializing in construction engineering, the optimum solution saved up to 18% of the total earthmoving cost and the time-consuming, complicated decision processes were substantially streamlined via computer automation and integration. Hence, the research deliverables have catered to the needs of earthworks contractors for enhancing current practices of planning site grading projects. The decision-makers are capable of taking advantage of the research for field productivity improvement and budget control purposes.

PREFACE

This thesis is an original work by Chaojue Yi.

Chapter 4 of the thesis has been in publication as a journal paper. Chaojue Yi and Ming Lu (2016). “A mixed-integer linear programming approach for temporary haul road design in rough-grading projects”. *Automation in Construction*, 71, pp.314-324. Dr. Ming Lu was the supervisor and co-author of the research and was involved with concept formation and manuscript composition.

Chapter 5 of the thesis has been submitted for publication as a journal paper: Chaojue Yi and Ming Lu. “Mixed-integer Linear Programming (MILP)-based Sensitivity Analysis in Optimization of Temporary Haul Road Layout Design for Earthmoving Operations” *Journal of Computing in Civil Engineering*, on July 6th, 2018. Dr. Ming Lu was the supervisor and co-author of the research and was involved the composition of the manuscript.

Chapter 6 of the thesis has been in publication as a conference paper. Chaojue Yi and Ming Lu (2018). “A Simulation-based Earthmoving Fleet Optimization Platform (SEFOP) for Truck/Excavator Selection in Rough Grading Project.”. *35th International Symposium on Automation and Robotics in Construction* (ISARC 2018), Berlin, German. Dr. Ming Lu was the supervisor and co-author of the research and was involved the composition of the manuscript. Chaojue Yi attended the conference from July 22 to July 25, 2018, to present the academic work in front of researchers and industry fellows.

ACKNOWLEDGEMENTS

I would like to thank Professor Ming Lu, my research supervisor, for his patient and professional support during my doctorial study at University of Alberta. I am grateful for his unreserved guidance to my Ph.D study.

I would also like to thank my committee members, Dr. Shizhong (Jesse) Kang, Dr. Simaan M. AbouRizk, Dr. Yasser Mohamed, Dr. Hooman Askari-Nasab, Dr. Mingjian Zuo, and Dr. Hubo Cai for their insightful comments and support for this research.

I wish to also express my special thanks to my parents who supported and encouraged me during my Ph.D study, without whom I could hardly survive my Ph.D.

I thank my love Mrs. Zheng for accompanying me and giving me courage and strength to get through my Ph.D study.

Finally, I would thank Sam Johnson, Project Manager, Graham Management Services for sharing his vision and insight and providing case study support in the present research.

God bless you all.

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NOMENCLATURE

$\mathrm{x}_{(\mathrm{i,j})}$	=	Boolean variable which is determined by whether to build higher-grade temporary haul road on edge $(\mathrm{i,j})$;
G	=	undirected graph;
V	=	node set;
E	=	edge set;
v	=	node;
$(\mathrm{i,j})$	=	directed edge;
$t_{(i,j)}$	=	truck haul time per truck load on edge $(\mathrm{i,j})$;
$s_{(i,j)}$	=	distance of edge $(\mathrm{i,j})$;
$v_{(i,j)}$	=	haul speed of a truck on edge $(\mathrm{i,j})$;
$f_{(i,j)}$	=	allocated earthwork quantity on an edge $(\mathrm{i,j})$
t_{avg}	=	averaged round-trip haul time per truck load
$\Delta t_{(i,j)}$	=	difference in haul time per truck load on edge $(\mathrm{i,j})$ if a truck travels on “gravel-surfaced” road, instead of “rough-ground” road;
$f^{+}(v)$	=	earth volume flowing into node v;
$f^{-}(v)$	=	earth volume flowing out of node v;
D_v	=	earth demand (cut or fill) as per cut and fill design of node v;
C_{total}	=	total earthmoving costs;
$C_{duration}$	=	project duration related costs;
C_{road}	=	haul road construction and removal costs;
$C_{construction}$	=	construction and removal costs of the gravel-surfaced road;
$C_{maintenance}$	=	haul road maintenance costs;
p	=	a number series from 1 to r for denoting all the relevant duration-dependent rates;
α	=	the sum of hourly rates of the hauling crew;
T	=	total haul duration;
n	=	truck number (optimization);
c	=	volume capacity of one truck in cubic meters;

f = operations efficiency factor;

φ = combined duration-dependent cost parameter;

β = unit construction and removal cost of the gravel-surfaced road;

σ_1 = unit maintenance cost if trucks haul on rough ground;

σ_2 = unit maintenance cost if trucks haul on gravel-surfaced haul road;

TH_1 = the threshold earthwork quantity for maintenance on rough ground haul road given typical haulers;

TH_2 = the threshold earthwork quantity for maintenance on gravel-surfaced haul road given typical haulers;

$f_{(i,j)}^{(1)}$ = allocated earthwork quantity on rough ground haul road;

$f_{(i,j)}^{(2)}$ = allocated earthwork quantity on gravel-surfaced haul road;

m = label set number;

L = label set;

$x(E)$ = edge set of higher-grade (gravel-surfaced) road;

$x(V)$ = node set of higher-grade (gravel-surfaced) road links;

S = set(s) of connected component(s) with the largest number of same label (i.e. longest connected component(s));

$\delta(S)$ = edge cut set of S;

SF = shrinkage factor;

BF = swelling factor;

V_E = volume of excavated material;

V_C = volume of compacted material;

V_L = volume of loose material;

H_{ij} = haul job from cut grid i to fill grid j;

P_{ij} = haul path from cut grid i to fill grid j;

Res_{ij} = integer number starting from 1 to indicate truck numbers allocate to H_{ij} ;

C_{ij} = total cost of haul job H_{ij} ;

T_{ij} = total duration of haul job H_{ij} ;

Q_{ij} = earth volume of haul job H_{ij} ;

$t_{ij}^{(k)}$ = the shortest excavator travel time from cut cell i to cut cell j such that all intermediate nodes on the path (if any) are in set {1, 2..., k};

$p_{ij}^{(k)}$ = the shortest excavator-travel-time path from cut cell i to cut cell j;

$u_{ij}^{(k)}$ = zero-one variable indicating whether $p_{ij}^{(k)}$ is one optimal path;

$\mathrm{P_{ex}}$ = production rate of the excavator in bank cubic meters per hour;

$\mathrm{P_t}$ = production rate of the truck in bank cubic meters per hour;

$\mathrm{N_t}$ = the number of trucks;

$\mathrm{t_{h(i,j)}}$ = truck haul cycle time for haul job H_{ij} ;

$\mathrm{v_1}$ = speed of a specific truck hauling on rough ground haul road (loaded);

$\mathrm{v_1'}$ = speed of a specific truck hauling on rough ground haul road (empty);

$\mathrm{v_2}$ = speed of a specific truck hauling on gravel-surfaced haul road (loaded);

$\mathrm{v_2'}$ = speed of a specific truck hauling on gravel-surfaced haul road (empty);

$\mathrm{d_{g(i,j)}}$ = hauling distance on gravel-surfaced haul road for haul job H_{ij} ;

$\mathrm{d_{r(i,j)}}$ = hauling distance on rough ground haul road for haul job H_{ij} ;

$N_{c(i,j)}$ = the number of truck hauling cycles for haul job H_{ij} ;

N_b = the number of bucket loads to fully load a truck;

b = bucket capacity in m^3;

T_{avg} = average haul job duration;

U_t = unit cost of truck in \$/hour;

U_{ex} = unit cost of excavator in \$/hour;

U_{oh} = unit cost of field overhead in \$/hour;

Δl = step length for parametric analysis;

t = tolerance value to secure sufficient accuracy for sensitivity analysis

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Chapter 1. INTRODUCTION

Heavy construction includes the construction of highways, roads, dams, airports, commercial buildings and industrial plants (Fu 2013). Generally, these heavy civil or industrial projects entail massive site grading endeavors – mass earthworks to be executed prior to building structures. Earthworks are a fundamental part of construction engineering and involve moving and processing of soil materials in accordance with grading design. Due to involvements of large amounts of expensive heavy equipment, including excavators, trucks and other auxiliary machines, earthworks account for about 25% of the total construction cost (Hare et al. 2011). Among the total earthmoving operation, truck haulage costs can account for up to 50% (Thompson and Visser 2003). According to Peurifoy and Oberlender (2002), the total operating cost of truck haulage comprises driver costs, fuel costs, maintenance costs and other indirect costs. Driver costs and fuel costs are identified as the dominant costs which occupy 60% and 20% of the total operation cost respectively (Hare et al. 2011). Therefore, it is indisputable that improving the earthmoving efficiency will reduce the total operation cost by a large margin.

For improving hauling efficiency in large site grading projects, the common practice is to build a limited length of temporary haul road (e.g. gravel surfaced road) along hauling paths on site frequently traveled by trucks. Due to its “temporary” nature, temporary haul road is typically built with pit run, limestone or gravel with minimum thickness or even directly laid on rough ground. The temporary haul road can be simply classified as high grade vs. low grade. High grade haul road can have stiffer pavement design with the use of gravel whereas low grade haul road remains rough ground requiring frequent maintenance (by grader). Generally, high grade temporary haul road is worthy of the investment only if savings on earthmoving operations exceed the investment on haul road construction. More elaborately, a trade-off lies between (1) building higher grade of haul road (e.g. gravel-surfaced) that needs less frequent repair or routine maintenance during operation, and provide more efficient and safer haulage conditions – more expensive to build, but less expensive to operate; and (2) building rough ground haul road that needs more repair, higher maintenance over its life - less expensive to build, but more expensive to operate. This justifies that earthmoving operation planning (i.e. earthworks assignment) and temporary haul road layout design should be conducted simultaneously.

However, in current industry practice, earthworks assignment and haul road layout design are two separate tasks. In particular, field managers or superintendents firstly assign the earthmoving tasks based on cut and fill requirements, and then design the high grade haul roads to account for the bulk of traffic based on experience instead of science. This separation exists in related academic research as well. In order to analyze hauling operations and improve earthmoving efficiency, Peurifoy and Schexnayder (2002) summarized three major factors that warrant analysis in construction planning and estimating, namely: (1) the quantity of earth to be moved, (2) the haul routes to move the materials, and (3) the grade and layout of haul road. The first two factors have attracted a considerable amount of research endeavors over the past two decades by applying latest advances in mathematical programming and computer science in civil and industrial construction projects (related literatures are carefully reviewed in section 3.1). Despite significant contributions made in earthworks planning through Construction Engineering and Management (CEM) research, there still lacks a formalized methodology to integrate temporary haul road layout design with earthmoving operation planning (i.e. identify the quantity of soil to be moved and plan the haul routes to move the soil in order to define each haul job).

The separation between earthworks assignment and haul road layout design, however, not only leads to insufficient construction planning and missed opportunities for productivity improvement and cost savings but also increases the likelihood of field workers encountering unknown safety hazards (e.g. striking on obstacles due to long stop distance on poor road surface).

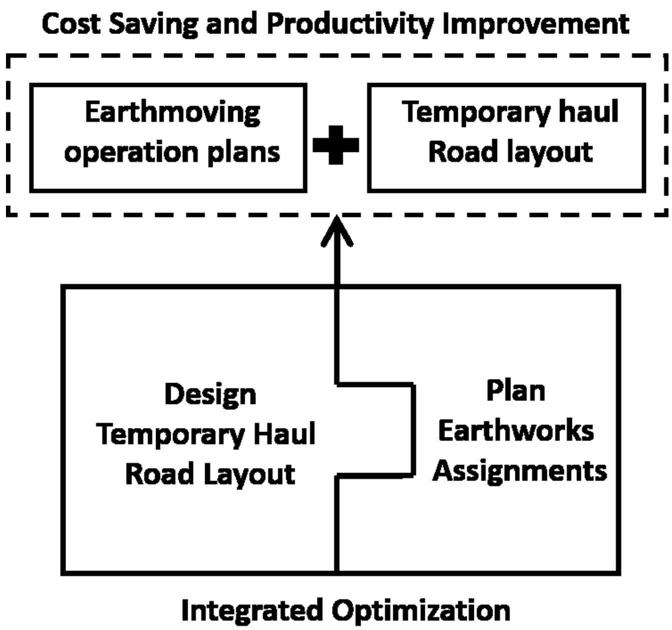


Figure 1-1: The gap between designing temporary haul road layout and planning earthworks assignments in current management practice.

This introduces the research opportunity on modelling and optimizing the earthmoving operations and temporary haul road layout design in a seamlessly integrative fashion. To simultaneously generate optimized earthmoving operation plan and temporary haul road layout design, the following challenges must be addressed:

- **Reconciling the conflict between haul road design and earthworks operation planning.** Complex interplay exists between the earthworks assignment and haul road layout design. The analytical model should be able to find an equilibrium between haul road design and earthworks operation planning in terms of minimizing earthmoving cost.

- **Ensuring haul road continuity and accessibility.** Generally, temporary haul road layout should be designed to be inter-connected rather than sporadically scattered within the earthmoving site, in addition to ensuring a single or multiple site entrance(s) connect temporary haul road to offsite road (Liu and Lu 2015). This constraint increases the complexity and difficulty in mathematical optimization.
- **Generating optimized earthmoving operation plan and temporary haul road layout design solution.** The analytical model should be able to model the construction site quantitatively. In the end, it should produce an optimized solution resulting in a minimal cost.

1.1 Research Objectives

Having identified research problems and challenges, the overall objective of the thesis is to develop an integrated optimization framework that is capable to provide field planners with executable cost-effective earthmoving operation plans and temporary haul road layout design. This research intends to pursue the ultimate goal by realizing the following sub-objectives:

Objective 1. Developing novel integrated optimization approaches, based on flow network model and mathematical programming methods, to generate earthmoving operation planning and temporary haul road layout design with minimum cost. This includes:

- Creating a flow network model that can capture sufficient characteristics of a typical earthmoving site for optimization.
- Devising mathematical model and algorithms that generate executable earthmoving operation plans as well as accessible and continuous temporary haul road layout design at the minimum cost.

Objective 2. Devising post-optimization sensitivity analysis approach to identify the stability region on each input parameter of the optimization model, over which the optimum solution remains unchanged. This includes:

- Producing a generic sensitivity analysis model and applicable rules as basis for parameter stability region identification.
- Designing mathematical algorithms that determine values for both the upper bound and lower bound so as to identify stability region one parameter at a time.

Objective 3. Devising earthmoving operation analysis methods and computer tools to evaluate and validate the optimum solution resulting from optimization in simulated realistic settings.

1.2 Research Methodology

The research develops a systematic framework composed of three components: (1) Integrated earthworks optimization system; (2) Post-optimization sensitivity analysis system and (3) Earthmoving operation analysis system. The first component focuses on Objective 1 which proposes an integrated optimization system based on the flow network model by network optimization and mathematical programming theory. The second component focuses on Objective 2, which helps the decision makers to identify optimization model input parameter stability regions, and gain confidence and insight in the optimal solution in decision making. The third component focuses on Objective 3, proposing an earthmoving operation analysis tool to assist in evaluating and validating derived optimum solutions.

Integrated earthworks optimization system. The system is the core of this thesis, proposing an automated approach for optimized earthmoving operation plan and temporary haul road layout design generation that considers practical site constraints and engineering design constraints. For this problem, two primary considerations are how to model the earthmoving site capable of capturing sufficient site characteristics and constraints; what mathematical method to be used to automatically generate the earthmoving operation plans and temporary haul road layout designs while ensuring practical concerns are addressed. Hence, I divide the optimization system into **two sub-problems**: (1) the mathematical modelling problem that models the earthmoving site using carefully designed flow network model; and (2) the optimization problem that optimizes earthmoving operation plans and temporary haul road layout designs with practical constraints using carefully designed mathematical programming algorithms.

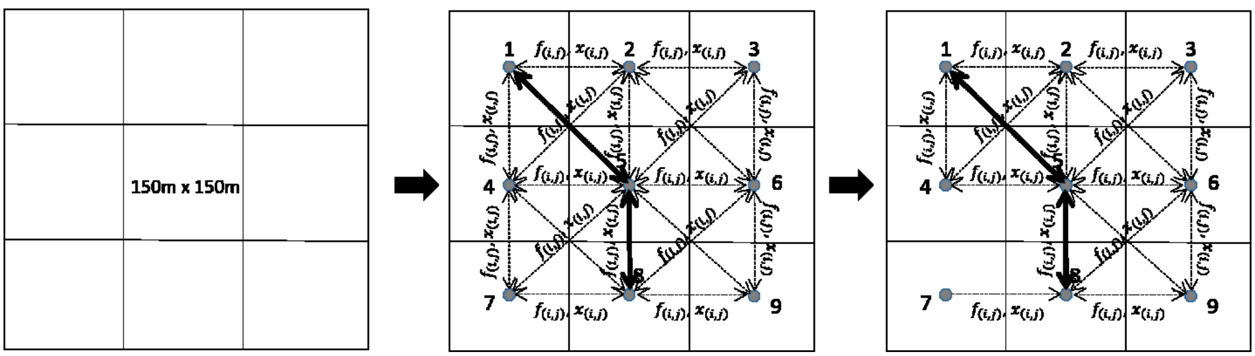


Figure 1-2: Earthmoving site modelling using flow network model. (a) Construction site being delineated by grids (b) Base flow network model to represent material flows and temporary haul road layout design (c) flow network model with practical site constraints being modelled (edge 4-7, edge 4-8, edge 5-7 removed; edge 7-8 changed to single direction)

To address the **first sub-problem**, a flow network model is proposed as shown in Figure 1-2. Firstly, a construction site is demarcated into square grids sized to facilitate modelling earthmoving operations and temporary haul road layout in a practical fashion. For each grid, the centroid is simplified to be the grid's geometric center and is denoted by a node. After that, the potential temporary haul road is denoted by undirected edges, each connecting the adjacent nodes with straight-line sections vertically, horizontally, and diagonally. The road type of each edge can be distinguished by a dot line for low grade haul road by default and by a solid line for high grade haul road, as shown in Figure 1-2. These nodes and edges constitute the base of a flow network model. In addition, by adjusting the structure of the flow network, it allows to embed the practical site constraints intuitively and to validate the formulation of the problem visually.

To address the **second sub-problem**, firstly the cost function including crew haulage cost, road construction and removal cost, and road maintenance cost is carefully formulated. Then, a Mixed-Integer Linear Programming (MILP) model integrated with a cutting plane method, is established to simultaneously generate (1) the quantity of earth to be moved, (2) the haul route to move the earth, and (3) the layout plan of high-grade haul road on a rough grading site. In particular, the cutting plane method is introduced to refine the optimization formulation by maintaining field accessibility and haul road continuity, thus ensuring practical feasibility of the analytical solution. The earthmoving operation plans are presented in haul job format consisting of source, destination, volume of earth to be excavated, and haul route for truck to follow. An overview of the methodology is given in Figure 1-3.

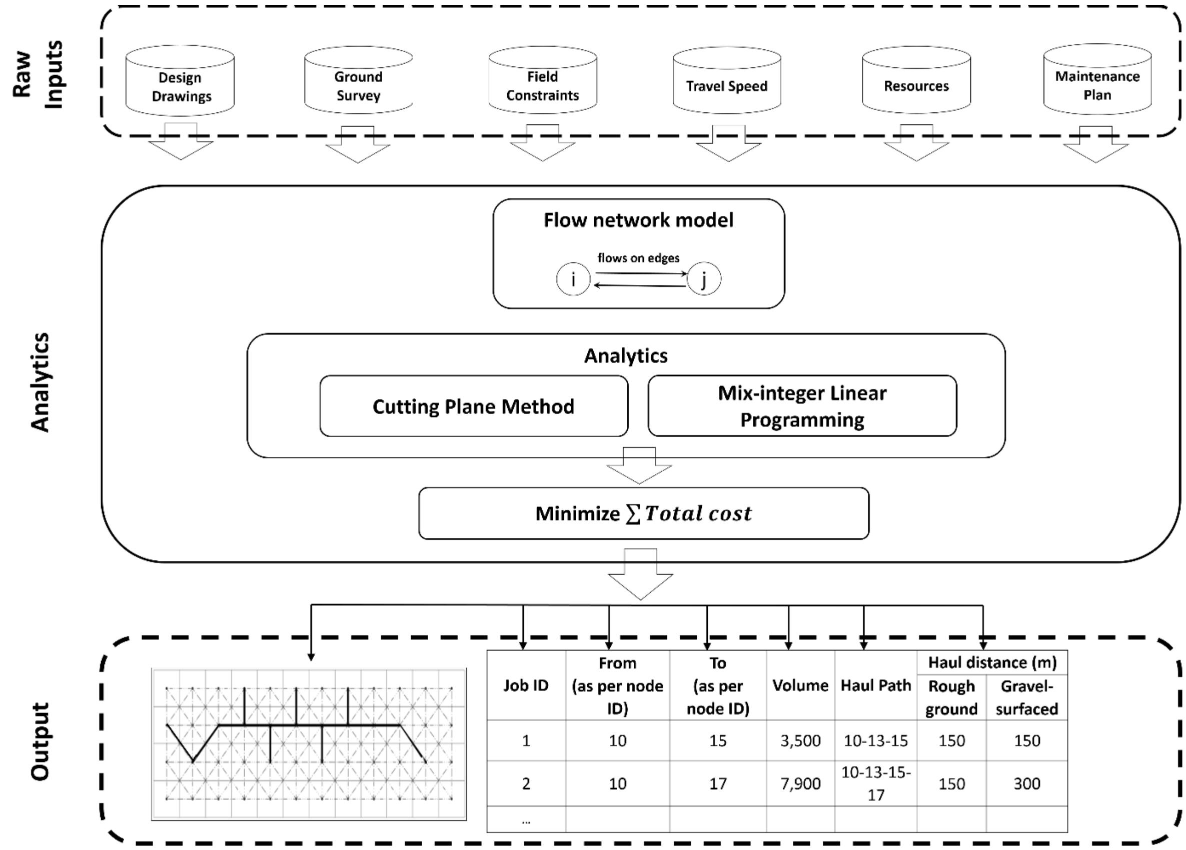


Figure 1-3: Earthmoving operation plan and temporary haul road layout optimization based on flow network model, mixed-integer linear programming and cutting plane method.

Post-optimization sensitivity analysis system. To provide confidence for earthmoving professionals and gain insight in the applicability of the optimum solution from MILP, I have developed generalized techniques for MILP post-optimization sensitivity analysis over the optimum solution by accounting for uncertainties inherent in model input data in the real world. First, a generic MILP sensitivity analysis model is proposed. Then, a one-at-a-time (OAT) parameter sensitivity measure is defined to analyze one parameter at a time while holding all other parameters at their nominal values (i.e. the most likely values of input parameters with which the optimum solution to the MILP model is realized). Next, a one-dimensional line search approach based on the constrained optimization theory is carefully developed to find the boundaries of a stability region around the parameter nominal value for each input parameter of the optimization model; as such, any fluctuation of the parameter value away from its nominal value within the region would not lead to any change in the optimum temporary haul road layout design. The proposed MILP sensitivity analysis methodology was applied on a “site grading haul road layout design and earthmoving operation planning” problem based on a real-world site grading project. The resulting MILP sensitivity information is conducive to determining a “buffer” on each input parameter so to assist decision makers in assessing risks and coping with changes in reality with reference to the optimum solution.

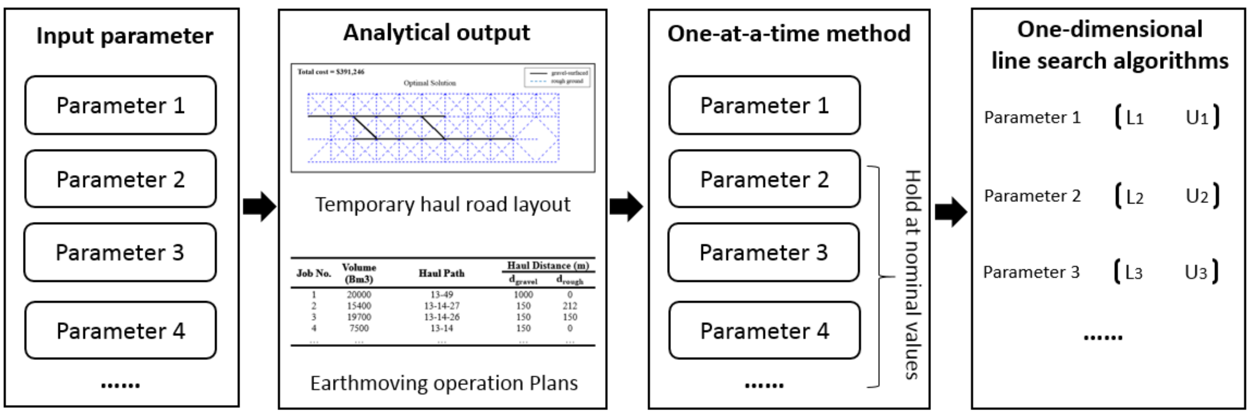


Figure 1-4: Optimization model input parameter stability region identification using one dimensional line search method.

Earthmoving operation analysis system. To evaluate and validate the optimum solution, I have designed an earthmoving operation analysis platform (EOAP) tool specifically tailored to current problem to output crew operation cost based on discrete event simulation (DES) in an automated manner. To validate that the proposed integrated optimization system can produce cost-effective yet practically executable temporary haul road layout design and earthmoving operation plan, two controlled experiments are designed: (1) respondents are given the project settings and required to design the temporary haul road layout; the collected layout alternatives are compared to the optimized layout based on an identical earthmoving operation plan; and (2) respondents are given the project settings and the haul road layout that is optimized by this research and required to produce earthmoving operation plans; the collected plans are compared to the optimized plan based on identical haul road layout.

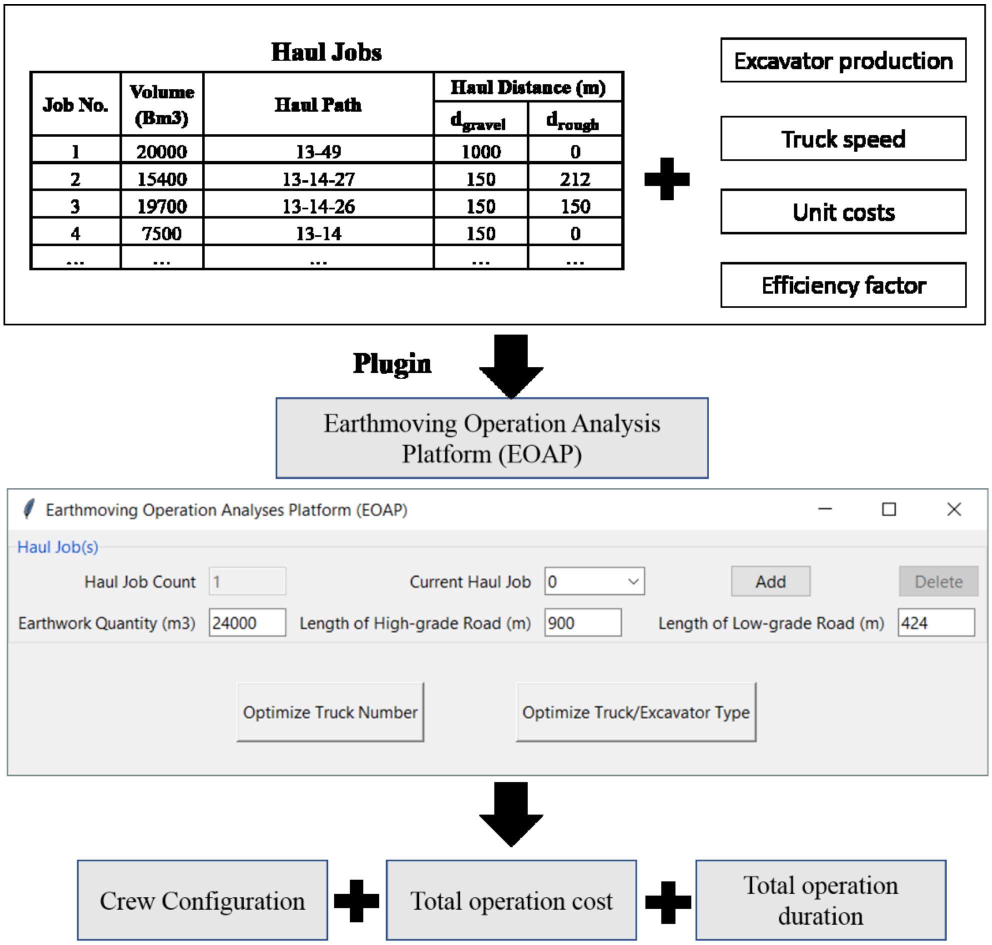


Figure 1-5: Earthmoving operation analysis for solution evaluation and validation. The developed Earthmoving Operation Analysis Platform (EOAP) tool enable automated cost estimation, fleet selection, and simulation.

Validation methodologies for each component are briefly summarized in Table 1-1 to present an overview of how the author applied established approaches in verifying and validating the science being applied in current thesis.

Table 1-1: Validation methodologies

Components		Methodology	Description
Integrated earthworks optimization system	Flow network model to represent construction site	Face validation	Industry practitioners served in heavy earthworks were asked whether or not the physical model can reasonably represent the earthmoving site and crew operations.
	C-MILP model to optimize temporary haul road layout and earthmoving operation plan	Condition tests; controlled experiment	Condition tests is to test whether the change of parameter value of C-MILP model would lead to the change of optimum solution by following a certain logic pattern that is compatible with the common wisdom in the problem domain. Controlled experiments are designed to validate the optimized solution is better than the solutions that practitioners can produce by benchmarking with layout design alternatives and earthmoving plan alternatives collected from site manager, field engineers, and graduate students majored in civil engineering
Post-optimization sensitivity analysis system		Numerical analysis	A numerical experiment is performed to test (1) whether the change of parameter value within its stability region would result in the optimum solution remains unchanged; (2) whether parameter values outside of the stability region would result in the change of optimum solution.
Earthmoving operation analysis system		Cross-verification	The earthmoving operation analysis tool is contrasted with two other simulation platforms, *SDESA* and *Symphony*, based on different earthmoving cases in terms of the average total durations outputted from simulation software.

1.3 Hypothesis

In brief, I intend to devise a system to optimize temporary haul road layout design and earthmoving operation plan in a seamlessly integrative fashion, as well as to provide the practitioners with confidence in applying the optimum solution in practice. So, the **main hypothesis** for this research is: the gap between designing temporary haul road layout and planning earthworks assignments can be bridged and the art of earthworks planning can be turned into science by taking advantage of latest advances in optimization and automation, ready for immediate implementation to guide earthworks planning practice. Corresponding with each objective, the main hypothesis is further decomposed to three sub-hypotheses including:

Hypothesis 1. An optimization framework can be developed to simultaneously generate temporary haul road layout and operation job plan resulting in a minimum cost.

Hypothesis 2. A post-optimization sensitivity analysis system can be designed to provide the optimization model users with the confidence by answering the question: to what extent the optimum solution still holds valid subject to the variations in optimization model input parameters.

Hypothesis 3. An earthmoving operation analysis tool can be created to facilitate the evaluation and validation of the optimum solutions in simulated realistic settings in order to attract real world applications.

1.4 Thesis Organization

The present thesis consists of eight chapters.

Chapter 1 introduces the research motivation, identifies research objectives and scope, and summarizes the methodology of the research.

Chapter 2 presents background information of site grading project in terms of project features and site context.

Chapter 3 contains a brief overview of the literatures and previous studies in the fields of earthworks planning and optimization, and mathematical model sensitivity analysis.

Chapter 4 describes the mathematical approaches to model the construction site, and the optimization framework to automatically produce cost-effective earthmoving operation plans and temporary haul road layout design.

Chapter 5 describes the mathematical approaches to identify optimization model input parameter stability region and to answer the question: will the derived optimality be upheld when input data values are changed?

Chapter 6 introduces earthmoving operation analysis approach to evaluate crew operation cost in a simulated realistic environment, facilitating validation of the performances of optimization results through quantitative comparison.

Chapter 7 focuses on the computer implementation and validation of the developed model in a real-world rough grading construction project. Optimized temporary haul road layout design and earthmoving operation plans are presented. Stability regions of input parameters are described with numerical experiments to demonstrate the effectiveness of the approaches. The controlled experiments are described and results are analyzed to demonstrate the advantage of the proposed optimization system.

Chapter 8 summarizes the conclusions, the contributions, the limitations of the research and recommendations for future development.

Chapter 2. BACKGROUND

This chapter mainly introduces the basic features of a typical site grading project, aiming to lay practical background for current research problem. Firstly, basic information of a site grading project and earthworks with respect to site grading design plus cut and fill volumes are introduced. Then, heavy equipment for site grading operations are introduced. The equipment selection criteria in regards to different soil conditions, haul distance and etc. is also presented. Next, earthmoving operation process is illustrated. Finally, temporary haul road fundamentals are presented in the perspective of construction engineering and management.

2.1 Site Grading Fundamentals

2.1.1 Site Grading Design

Site grading design is the engineering work of designing a level base, or a specified slope for construction works. It shows contours and grade elevations for existing and proposed ground surface at a given site for the site grading contractors to plan earthmoving operations and execute the grading jobs. The preparation of a site grading design generally occurs at some point after a preliminary site plan is prepared, requiring professional knowledge on site grading engineering designs, such as drainage design, access drive, parking lot, stabilized landscaped areas, retaining walls, berms and etc.

A good design integrates the natural landforms of the site with the proposed ground elevations to create a functional yet cost-effective site plan. Generally, the grading of a site serves two basic purposes: (1) grading reforms the ground surface to make it compatible with the intended land use; and (2) grading helps define the characters of the site. Firstly, the relative elevations and gradients of finished ground surface, existing surrounding terrain, and planned superstructures such as roads, buildings, parking areas and vehicle accesses must be mutually compatible. Any incompatibility will lead to excessive earthworks, the use of retaining walls, and drainage problems, which inevitably increases construction costs. Secondly, site grading design is the foundation upon which many other elements of development depend. Proper grading should be cost-effective to the developer. In this way, it enhances property values and contributes to the success of a site grading project.

The site grading design establishes the finished ground elevations of buildings, grades and slopes of non-building elements. Typically, the grading designer will prepare a contour study model to help visualize and evaluate grading design, as shown in Figure 2-1. Generally, a site grading design is determined after one or more exploratory grading designs are developed, as the designer works through the process of determining a grading solution. The contour model may be used as part of a presentation of the site grading design to the client. More importantly, the contour model could assist the designer in assessing the grading solution. Once site grading design is done, earthworks volumes can be calculated, which will be explained in next session.

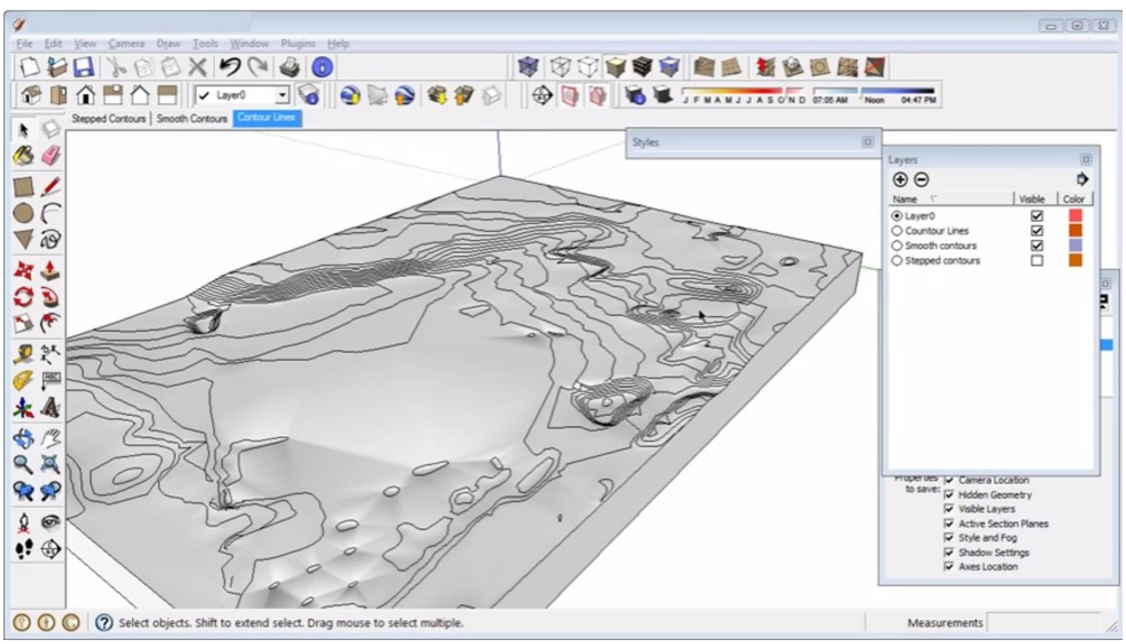


Figure 2-1: Contour model for grading design (SketchUp 2017)

2.1.2 Site Grading and Earthworks

The topography of a site is not always ideal for the construction of civil and industrial project. In most cases, portions of a site's topography will need to be modified so as to accommodate the uses and activities envisioned in the site grading design. Generally, site grading jobs consist of excavation, loading, haulage, unloading, grading, and compaction of materials, aiming to adequately shape the natural field to a specified design (Prata 2008). Due to involvements of large amounts of expensive heavy equipment, including excavators, trucks and other auxiliary machines, earthworks generally account for about 25% of the total construction cost (Hare et al. 2011). The proportion would be even higher where earthwork would represent the major expense of a construction budget for constructing some sport facilities, such as soccer field and golf course.

Site grading inevitably entails large amounts of earthworks. More specifically, the designer will need to shift soil from some parts of the site to others in order to create topography suitable for superstructures. To achieve the topographic modifications detailed in the site grading plan, earth may need to be removed from "cut areas" to "fill areas" requiring additional material to reach the designed elevation. The process of moving and shifting earth around a site involves cutting and filling. Cutting away a portion of a hill slope to create an as-designed area and placing the cut material (or borrowed material) at another area on the site is common. However, the goal is to balance cut and fill whenever feasible to minimize earthmoving costs.

Figure 2-2 helps visualize the concept of cutting the existing ground in one area and placing the cut material at another area.

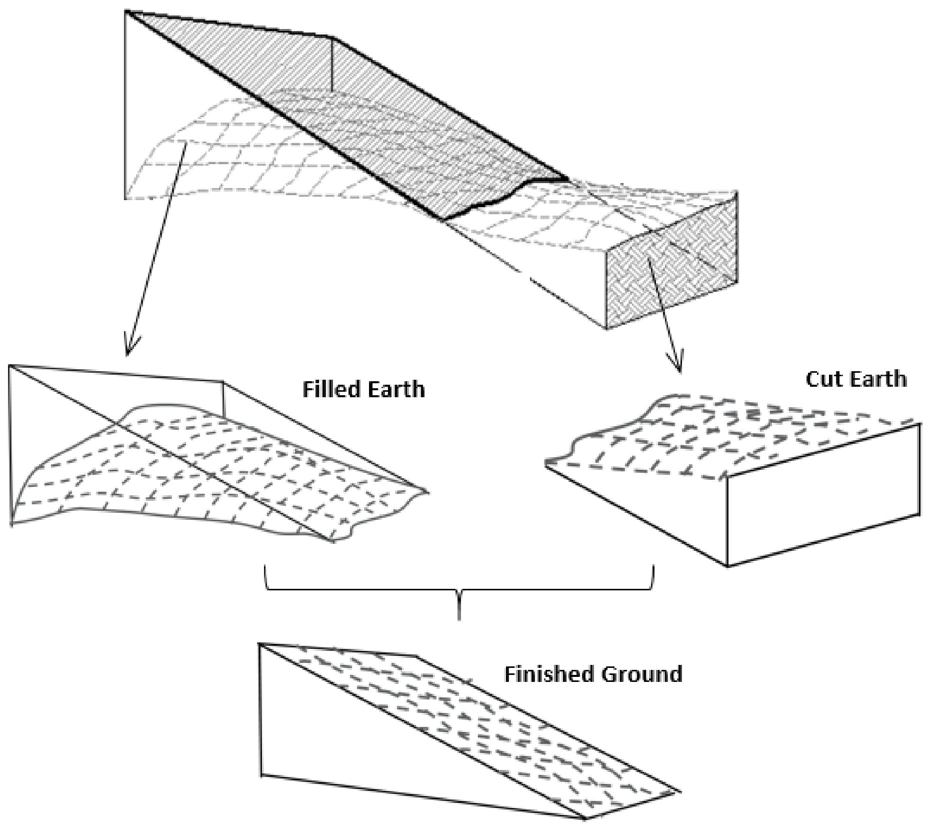


Figure 2-2: Cut condition and fill condition illustrations

2.1.3 Cut vs. Fill

The term ‘‘cut’’ refers to an area where soil is removed, while the term ‘‘fill’’ refers to the area where soil is added. Cut and fill areas are indicated on the grading design drawings by comparing the existing contour lines to the proposed contour lines at a specific location. Where the designed contour line elevation is higher than the existing contour line elevation, the area is a fill. Conversely, a cut area is one in which the designed elevation is lower than the existing elevation.

Cut Features. Excavation is the process by which soil or rock is removed in order to reach the required elevation. If the overall quantities of earthworks material for the scheme are in balance, the material resulting from such excavation will be employed as engineering fill for embankment construction. When the material is unacceptable, or the overall earthworks quantities are in deficit, acceptable fill material may be excavated from specially designated areas outside of construction site, often termed ‘borrow pits’. Even when the earthworks are in balance and the material is acceptable, on some earthworks contracts it may be more cost effective to excavate borrow pits locally in order to meet the overall construction progress, as haul distances are prohibitive or parts of the site are inaccessible. The latter is usually the case where the haul route is traversed by major rivers, roads or railways, where additional local excavation is more cost effective when compared to the cost and time required to construct a temporary crossing.

Fill Features. Backfill should follow the principles that (1) the fill must have sufficient strength and stability; and (2) the amount of settlement is minimized. Therefore, apart from carefully choosing the fill materials, a scientific fill guidance is needed. All fill should be stratified, and the thickness of each layer should be based on soil type and compaction mechanical properties. The compaction is generally conducted through means such as rolling, vibration and other methods. For large industrial and civil site grading projects, backfill compaction generally adopts the combination of rolling from rollers and passing haulers.

2.1.4 Haul Job

In site grading project, haul job is the fundamental unit for earthmoving planning. In this thesis, a haul job is defined by four attributes: **source, destination, earth volume, and haul path**. Generally, a source is defined by a cut area where a destination is defined by a fill area. A haul route corresponds to a pair of source and destination with a re-planned haul path, through which the trucks pass to haul the material from cut to fill. Mathematically, a haul job is defined as $H_{ij} = \{v_{\mathrm{ij}}, P_{ij}\}$. v_{ij} is the soil volume to be hauled from cut area i to fill area j. P_{ij} is the haul path between cut area i and fill area j.

2.2 Earthmoving Equipment

Earthmoving operations are equipment-intense processes and the equipment costs constitute a major part of the operating cost. In general, the most frequently used equipment for earthworks are excavators, loaders, haul trucks, scrapers, bulldozers, and compactors.

Excavator. Excavators are construction machines designed and manufactured for excavating earth and loading it on haul trucks. The bucket is connected to the vehicle's cabin by an articulated arm. The cabin is sitting on a rotating platform with a tracked undercarriage. The track offers the vehicle a better mobility over rough terrains and the rotating platform gives a broad working angle for the arm. Additionally, the articulated arm allows the bucket to move in different directions. Excavators are flexible not only for earthworks, but also various tasks in construction operations (e.g. pile installation). With different attachments like breaker and auger, an excavator can be used for many other purposes in earthworks such as breaking material into smaller pieces, lifting or dragging, and drilling.

Loader. Loader is a kind of earthwork construction machinery which is widely employed in the construction of highway, railway, building, hydropower, port, and mining projects. It is mainly used for shoveling soil, gravel, coal and other bulk materials. Loader can also be used for light excavating tasks of hard soil and ores. In the construction of roads, especially in highways construction, the loaders are usually used for excavating and filling roadbed, and loading and unloading asphalt mix and cement concrete operations. Because the loader has the advantages of fast operation, high working efficiency, good maneuverability and flexibility, it is one of the main equipment employed in earthworks construction.

Truck. Articulated trucks are the most common haul trucks for transport earth from cut areas to fill areas. The haul truck is composed of two basic units. The front unit is the tractor section and the back unit is called the hauler or trailer section. The articulated haulers could operate smoothly and safely, taking the shortest route between cut and fill areas. Due to the maneuverability and accessibility in severe road environments, articulated haulers are usually employed in off-road operations, such as earthmoving site.

Bulldozer. Bulldozers are equipment with a metal blade installed at the front end of the vehicle, and are aimed for pushing excavated earth or other materials in earthworks. The position and angle of the metal blade can be adjusted to complete multiple earthmoving tasks including excavating, transporting and dumping the earth within an earthmoving site. Bulldozers have the advantages such as flexible operation, easy rotation, fast moving and so on.

Scraper. Scraper is a kind of "all-in-one" machinery that uses the bucket to shovel and load the earth. It is applicable to construction of railway, roads, water conservancy, and other site grading projects. Scraper has the advantages of simple operation, fast transportation and high production rate. However, it is not economic to employ scrapers performing earthmoving with long hauling distance and large quantities of soil.

Compactor. Compactor is a construction machinery used to reduce the volume of soil by adding pressure through a heavy metal roller. By driving back and forth on the newly filled area, the crushing effect by the use of roller increase the density of the fill material to meet the engineering requirement. Once the site is compacted, testing for the engineering properties of the compacted soil will be conducted by QA/QC to ensure the ground is feasible for the construction of superstructure. Compactors are widely used in road construction, embankment and dam construction and other works need of compaction.

General Equipment Selection Criteria. No one earthmoving system is optimal for every earthmoving site. Consider the dilemma of choosing between an articulated truck paired with an excavator or a wheel tractor scraper. The unique cut and fill conditions of the earthmoving site determine which system could provide a better solution. Conventional wisdom suggests that the haul distance is the principal criteria for the right choice of equipment on a given project (Equipment Today Staff 2005). In addition to the haul distance, there are several application-related and economic-related factors which influence the decision on equipment selection. These include the material, space constraints, weather, operator skill and owning and operating costs. As a typical example, under the right conditions (e.g. sandy soil), wheel tractor scraper will dominate the production. However, scrapers are not suitable for wet, sticky clay that is more difficult to load, and rocky soils which don't allow the scrapers to pull through smoothly. Weather changes can be an influential factor as well. Articulated trucks can work in all year round, where scrapers are usually limited by weather conditions (e.g. wet and sloppy ground). In general, the industry rule of thumb in selecting earthmoving equipment in regards to site condition, haul distance and soil type are (Equipment Today Staff 2005):

1. Bulldozers are preferred for site grading project with average haul distance within 150 meters;

2. Scrapers are preferred for large site grading project with slope within 20º, soil moisture content less than 27%, average haul distances within 500 m;

3. Excavator and haul truck combination is preferred for soil materials of earth, clay, cobble, or gravel, the soil to be excavated is 3 meters thick or more, and haul distance is more than 500 m;

4. When the soil to be removed is shallow, and there is bulldozer to help pile up the soil, loader and truck combination is preferred.

In this thesis, only the classic excavator and truck system is applied in the earthmoving operation analysis in subsequent sessions and chapters. The application of other equipment systems is stated as one of the limitations of current research in conclusion and is worthwhile pursuit in the future work.

2.3 Earthmoving Operations

Earthmoving operation is a relatively straightforward process consisting of loading, hauling, dumping, returning, and waiting (not necessary), aiming to move the soil from cut area to fill area along onsite temporary haul roads. Generally, the entire site grading project is completed by executing hundreds of thousands such earthmoving cycles following a well-planned schedule. In the earthmoving process, truck drivers will follow the pre-planned haul route to haul the soil from cut area to fill area (or off-site dump pit) once the soil is loaded up. After dumping the soil with the help of a flagman, truck will return back to the cut area following the same the route. The summation of all the executed earthmoving operations within a pair of cut and fill location, defines the workload of a haul job. The activities in the earthmoving process are further discusses below.

Loading. Loading is the process of transporting earth from the ground or prepared pile into trucks through excavating. Excavators are used for loading the soil to the trucks. Typically, excavators have relatively small bucket volume (compared to loader) but can load while remaining in the same position. Excavators can dig material from the untouched natural state, and can also separate large pieces of earth into smaller sizes. Excavators are generally placed on higher ground relative to the haul trucks for easy loading purpose.

Hauling. Hauling involves haul trucks traveling through roads with varying slopes and ground conditions as well as traffic intersections in order to transport earth to fill areas or off-site deposit location. Trucks are full loaded with earth in the hauling process where the gross vehicle weight (GVW) reaches maximum. Truck drivers are often mandatorily required to reduce speed to guarantee safety hauling work when the truck is fully loaded. Various truck driving safety awareness programs are available to increase driver safety awareness and force them to pay more attention to hazardous zones, poor haul roads, or high hills where line of sight is blocked. A driver needs to be able to perceive a road hazard or obstacle and decide on a course of action.

Dumping. Depending on the final purpose of the operation, the earth is transferred from the trucks onto spreading piles or into crushers at the fill area. If crushers are needed, the earth is dumped into the hopper which is connected at the top of the crusher, to transform the transported earth into smaller pieces. The crushed earth is essential material in civil engineering for construction projects such as houses, roads and bridges.

Returning. After depositing its load, the haul truck returns to the loading area to start another earthmoving cycle. Without special designation, truck follows the same route back to loading area at higher speed compared to that in the hauling process. Despite running empty, truck drivers should still drive carefully because of possible surface hazards such as potholes, rutting, settlement, wash-boarding, and heaving caused by heavy traffic volume and not-in-time maintenance.

Queuing. Sometimes, the returning truck needs to wait until it can be loaded up for the reasons that there might be other trucks loading ahead of the waiting truck, or the excavator need some preparation work before it can start loading the truck. For the former situation, excavator will be the dominant resource (i.e. excavator governs the earthmoving duration and production). However, it may not be the most economic scenario to let truck wait. Therefore, resource balancing is needed to be done mathematically, aiming to result in economic resource allocation plan, which will be elaborately discussed in subsequent chapter.

The earthmoving process is intuitively depicted in following Figure 2-3.

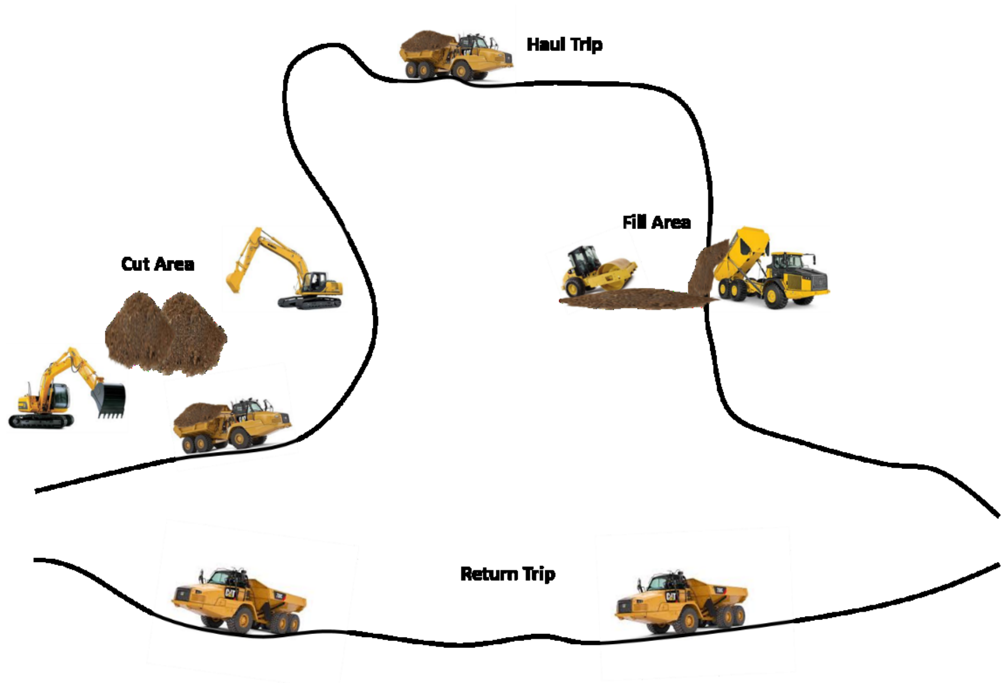


Figure 2-3: Earthmoving operational process

2.4 Temporary Haul Road

2.4.1 General Introduction

Haul roads are most commonly built in mining projects to improve hauling efficiency and ensure hauling safety on haul jobs. According to (1) traffic volume anticipated over road life; (2) vehicle type (largest anticipated truck fully loaded on the road); (3) permanence (service life of road); and (4) performance (or service) level required, the haul roads are generally classified into permanent, semi-permanent and temporary haul road (Holman 2006). As stated in Guidelines for Mine Haul Road Design (Dwayne and Regensburg 2001), grade selection in the haul road construction is much more complicated than just calculating the road construction cost. Rather, for a true understanding of haul road economics, full life-cycle costs must be considered, including construction costs, road removal costs, impact on productivity of the fleet, different road maintenance costs, extra indirect costs, and time value of money. Thompson and Visser (2003) further indicated that when considering the quality of the road construction, the most important items are: (1) life of road; (2) use of road, and (3) location of road. Unfortunately, in most projects, road construction is more focused on previous practices than economic perspective (Dwayne and Regensburg 2001). In many cases, previous practices have produced cost-effective roads since they are based on experience and judgmental background. For instance, in a mining site, it tends to place temporary roads to shovel faces, semi-permanent roads (main in-pit haul roads) and permanent roads (out-of-pit haul roads) (Tompson and Mieaust 2015).

In current practice of mining and transportation engineering, different aspects of haul road design, including its layout and alignment, pavement structure, maintenance and repair, and environmental issues have been critically investigated and studied by many researches. (Thompson and Mieaust, 2015; Kaufman and Ault, 2001; Tannant and Regensburg, 2001; Holman, 2006). As stated in Caterpillar Haul Road Design and Management (Holman 2006), the expected service time for permanent haul roads, semi-permanent haul roads and temporary haul roads are 5-10 years, 1-5 years, and weeks or months, respectively. Unlike the mining project, for site grading and earthmoving operations in a large area, it is uncommon to link a loading area (cut) and a dumpsite area (fill) by permanent or semi-permanent haul roads since the project only lasts several months (a relatively short period of time). Therefore, temporary haul roads are constructed to improve the truck hauling efficiency and safety along the on-site arteries with frequent truck passes. As a critical component of planning mass earthworks projects, the temporary haul road should be well designed by considering (1) the amount of production over the temporary haul roads; (2) the cost-effectiveness of the entire material handling system; and (3) the expected total service time before being removed.

2.4.2 Temporary Haul Road Classification: High Grade vs. Low Grade

In this thesis, the current temporary haul road layout design problem is placed in a perspective of construction engineering and management and hence temporary haul road classification is effectively made with regards to hauling efficiency and field productivity. Detailed road engineering design, such as geometric design and structural design is not focus of current research. Generally, due to different functional design standard, the temporary haul road is classified as high grade vs. low grade. High grade haul road can be gravel surfaced whereas low grade haul road remains rough ground, or "goat trails" in jargon by the field engineers. The different haul road pavement designs (high grade vs. low grade) lead to different rolling resistance to trucks (Douglas and Lawrence 2014). Due to its rough nature, the rolling resistance (i.e. physical resistance impeding the free rolling of the vehicle) of rough ground haul road is much higher compared to gravel-surface haul road at 10% vs. 5% (MSHA 2016), resulting in reduced truck hauling productivity. Moreover, the poor "dusting" properties of rough ground haul road (i.e. the material is easily broken down by traffic or naturally to generate an abundance of loose fines to form dust) plus the vulnerable surface conditions (e.g. potholes, rutting, settlement) lead to more frequent maintenance by grader (Tannant and Regensburg 2001; Thompson and Visser 2003; Thompson and Visser 2006).

2.4.3 Rolling Resistance and Grade Resistance

Rolling resistance is defined as the combination of forces a vehicle must overcome to move on a specified surface, posing direct effect on vehicular performance. This factor is usually expressed in pounds of resistance per ton of gross vehicle weight caused by the bearing friction losses resulting from tires sinking in poor road surface material. At many rough grading sites, especially small earthmoving operations, little consideration appeared to be given to the construction of high-grade temporary haul road surface. In fact, development of the haulage way is typically accomplished by simply clearing a path over existing terrain. While this practice is undoubtedly the most economical means of road construction in terms of initial cost, the benefit is seldom long lived. Failure to establish a good haulage road surface will add extra rolling resistance to truck hauling, resulting in increased vehicle and road maintenance costs and will severely retard the ability of a vehicle to safely negotiate the route.

Rolling resistance varies considerably with the type and condition of the surface over which a machine moves. Generally, soft earth offers a higher resistance than hard-surfaced roads as concrete pavement. For the majority of road surface materials, an increase in coefficient of road adhesion can be directly related to a reduction in rolling resistance. Table 2-1 illustrates this point by presenting the rolling resistance values associated with several road surface materials and their road adhesion characteristics. The data in table indicate that a good road surface will, in many cases, decrease operational costs by reducing resistance to haul on the road, providing reduced cost on operations and increased truck hauling safety.

Table 2-1: Rolling resistance for various surface types (Kaufman et al. 2001)

Surface type	**Road adhesion coefficient (approx.)**	**Rolling resistance pounds per ton gross vehicle weight (approx.)**
Cement, asphalt, soil cement	0.8	40
Hard-pack gravel, cinders or crushes rock	0.7	60
Moderately packed gravel, cinders, or crushed rock	0.6	100
Unmaintained loose earth	0.5	150
Loose gravel	0.4	200 - 400

Rolling resistance is expressed as kg of resistance per ton of vehicle weight or as an equivalent grade resistance. For example, if a loaded truck that has a gross weight equal to 20 tons is moving over a level road whose rolling resistance is 100 kg/ton, the tractive effort required to keep the truck moving at a uniform speed will be 2000 kg.

Grade resistance is easy to perceive as it simply represents the component of vehicle weight which acts parallel to an inclined surface. Straightforwardly, when a vehicle is traveling on a graded haul road, the upgrade resistance provides positive force while downgrade resistance is negative.

The total resistance comes up from summing up grade resistance and rolling resistance, which have a combined effect on the speed of a vehicle in a specific situation. This combined effect is termed "effective grade" in transportation and mining engineering, and can be easily calculated by use of Eq. (2-1) (Caterpillar Handbook 2017).

$$\text{Effective Grade (\%)} = \text{Grade (\%)} + Rolling\ resistance\ factor\ (Lb/t)/20 \qquad (2\text{-}1)$$

The relationship between effective grade and truck haul speed is elaborated in Appendix A.

2.4.4 Haul Road Accessibility and Connectivity

On the earthmoving site, the current best practice suggests several connected "main roads" to be designed and constructed with higher grade of wearing course (surface) to account for the bulk of the traffic. The main roads generally connect major cut areas and fill areas, will have a higher traffic volume than on the "branch roads" branching off the main road and getting the trucks to smaller cut or fill areas. In this thesis, the "main road" corresponds with "high grade haul road" where "branch road" corresponds with "low-grade haul road", which are defined in the thesis in previous session. Generally, high grade temporary haul roads are worthy of the investment only if savings on operations exceed the investment on haul road construction. Thus, an optimization problem lies in balancing between the earthmoving operation cost and the haul road construction cost. More elaborately, a trade-off lies between (1) building higher grade of haul road (e.g. gravel-surfaced) that needs less frequent repair or routine maintenance during its life-cycle, and provide more efficient and safer haulage conditions - expensive to build, but cheaper to operate; and (2) building rough ground haul road that needs more repair, a high-intensity of maintenance and rehabilitation over its life - cheap to build, but expensive to operate. The high grade haul roads and low grade haul roads will be connected as a temporary haul road network on the earthmoving site as the foundation for earthmoving system, as shown in Figure 2-4.

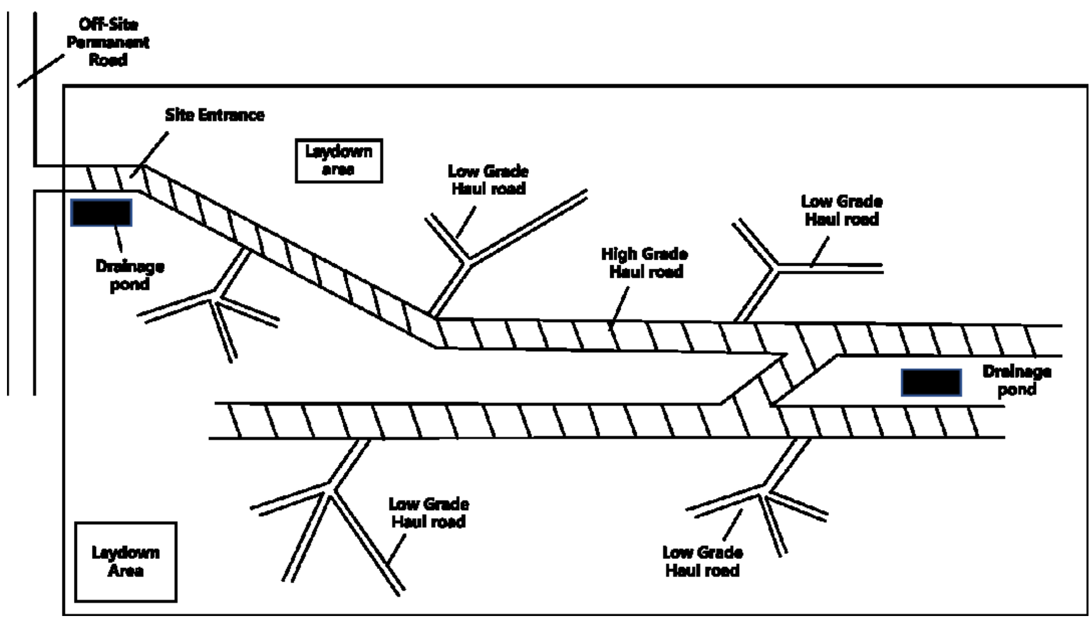


Figure 2-4: Haul road network of site grading site

Chapter 3. RELATED WORK

The work described in this thesis has three interrelated objectives: (1) to develop integrated optimization approaches to generate earthmoving operation planning and temporary haul road layout design with minimum cost; (2) to devise post-optimization sensitivity analysis approach to identify optimization model input parameter stability regions, over which the optimum solution remains unchanged, and (3) design earthmoving operation analysis tool to evaluate and validate the optimum solution by optimization in simulated realistic settings. In this chapter, I review related work on each of the objective: earthworks planning and optimization (Section 3.1), post-optimization sensitivity analysis (Section 3.2), and earthmoving operation analysis (Section 3.3).

3.1 Earthworks Planning and Optimization

Earthworks planning are defined as a cut-fill pairing which signifies a volume of material that must be excavated from a specified location and hauled to another. The optimization of earthworks planning is well-established upon previous researches and evolves with the development of computational power in past decades. In general, optimization techniques have been exquisitely devised in (1) determining earthmoving volumes from cut areas to fill areas on site (i.e. earthworks assignment problems) (Moselhi and Alshibani 2009; de Lima et al. 2012; Liu and Lu 2015; Ji et al. 2010), and (2) identifying hauling routes (paths) (Gwak et al. 2015; Kang and Seo 2013; L'Heureux et al. 2013; Son et al. 2005). However, the two critical tasks in earthmoving planning have yet to be tackled in one package in academic endeavors, let alone integrating the optimization of temporary haul road layout planning and earthwork assignment planning. Instead, existing literature tends to set focus on a single task in earthworks planning while considering various practical factors by applying the latest advances in quantitative techniques.

3.1.1 Earthworks Assignment

For earthworks assignments, it has been observed that the majority of existing related methods (Mayer and Stark 1981, Hare et al. 2011; Ji et al. 2010; Liu and Lu 2014) either modeled the whole earthmoving operations as a linear process or simply applied linear programming techniques to perform earthworks planning and optimization. However, the applications of linear programming techniques are often oversimplified without considering neither equipment haul routes or temporary haul road layout plan as variables (Kozan and Kenley 2015).

Other than linear programming methods, Mass Haul Diagram (MHD) method, is also one of the most widely applied methods in site grading projects for earthworks planning. This classic method was firstly proposed by Thomas Hickerson in 1967 (Hickerson 1967), and was continuously improved and optimized by following researchers (Mater and Stark 1981; Nassar et al. 2011). Mass Haul Diagram could straightforwardly represent the cumulative earthwork volumes among different areas, providing decision support for site managers to work out earthworks assignment plans. However, due to inherent limitations of being unable to provide clear earthworks assignment and haul routes between cut and fill locations, MHD method is hardly applied in planning earthworks assignment in large site grading projects.

Heuristic methods were designed for earthworks assignment with more complicated mathematical models. Genetic Algorithm (GA), as a classic evolutionary algorithm for optimization, was used in earthworks assignment (Tom and Mohan 2003). However, GA has its inherent limitation in that it potentially converges towards a local optimum instead of the global optimum, which undermines the quality of optimization outcome. Later, Ant Colony Algorithm and Particle Swarm Algorithm were adopted to optimize the earthworks allocations (Wang et al. 2006; Chen and Li 2010). Recently, Liu (2014) utilized an updated version of GA named Multi-Generation Compete Genetic Algorithm (MCGA) to optimize both earthworks assignment and temporary haul road layout design based on the grid system defined for site grading design. The applied algorithm allows earlier generations to participate in the current iteration of competition. Despite the capability of producing feasible solutions within a limited time period, the optimization process still has good chances of converging to local minima due to the fundamental shortfall of GA. In short, though the latest advances in mathematical programming and computer science have been applied for planning earthworks assignments, one common assumption has been made that the temporary haul road layout design has already been finished. The complex interplay between earthworks assignment and temporary haul road design is generally neglected, leading to missed opportunities for both productivity improvement and cost saving.

3.1.2 Haul Path Selection

The selection of haul path for earthmoving in civil infrastructure projects must be carefully determined for the reason that truck's travel time and the consequent earthmoving costs are profoundly dependent on the efficiency of the path. Specifically, the haul path indicates the distance between cut and fill areas, the surface conditions of the haul road, and grades of haul roads, all will significantly affect truck travel time. For haul routes selection, shortest-path search algorithms such as Dijkstra's algorithm or Floyd-Warshall algorithm were applied in haul path planning, considering the purpose and the operational characteristics of the path. However, in those earlier studies, the purpose of defining hauling paths was different from that of planning haul paths for temporary use during the construction stage; hauling paths identification was based on predefined haul road layout and earthworks assignments, which was not part of the optimization problem definition. Kang and Seo (2012) incorporated influential factors, such as haul road construction cost, operator safety, and complaint possibility into the least-cost path algorithm. Informatics such as geographic information system (GIS) or global positioning system (GPS) were also introduced in the optimization algorithms to jointly improve the selection of paths (Kang et al. 2013). Nevertheless, applications aforementioned in selection of haul paths were mostly related with planning long-haul problems by which a local site is commonly represented as one point connected to nearby highways via permanent haul road; while the site is associated with a particular quantity of earth to export or import (Liu and Lu 2015). Neither earthworks assignment nor temporary haul road layout plan are considered as variables in the optimization framework.

3.2 Post-optimization Sensitivity Analysis

3.2.1 Local Sensitivity Analysis vs. Global Sensitivity Analysis

According to Hamby (1994), sensitivity analysis methods are classified into two categories: local parameter sensitivity analysis and global sensitivity analysis. In particular, local sensitivity analysis method is to repeatedly vary one parameter at a time while holding the others at their nominal values (Crick et al. 1987; Yu et al. 1991; Lu et al. 2001; Blacud et al. 2009; Borgonovo and Plischke 2016). Note, nominal values (or baseline values) represent the most likely values of input parameters, with which the optimum solution to the model is realized (Crick et al. 1987; Yu et al. 1991). This type of local analysis method has been referred to as one-at-a-time (OAT) sensitivity analysis method (Crick et al., 1987) since it defines model sensitivity relative to the chosen parameter rather than a set of parameters. In contrast, global sensitivity analysis is often implemented using probabilistic frameworks (e.g. Variance-based sensitivity analysis technique or Monte Carlo technique) to investigate a large array of randomly selected input parameter values and further characterize model output patterns. Specifically, the goal of global sensitivity analysis is to provide insight about how the interactions between parameters influence the objective value (Van et al. 2006). The general steps for global sensitivity analysis include (1) defining the model and its independent and dependent variables (2) assigning probability density functions to each input parameter, (3) generating an input matrix through an appropriate random sampling method for calculating an output vector, and (4) assessing the influences of input parameters and input-output relationships (Helton et al., 1986; Hamby 1994; Saltelli et al. 2000; Van et al. 2006; Iooss and Lemaître 2015; Pianosi et al. 2016). In a nutshell, global sensitivity is to evaluate interactions of all the input parameters and characterize their influences upon the overall model performance instead of an individual input parameter (Iooss and Lemaître 2015).

The use of probabilistic methods to tackle global sensitivity analysis entails executing the model for a large number of runs, which can be computationally intensive and prohibitively expensive when coping with MILP models of practical size. It can take high-performance computers days, weeks or even months to arrive at solutions, subject to size of the problem and the number of simulation runs (Arkadiusz 2010). In this research, sensitivity is defined and evaluated on the basis of individual parameters of MILP, leaving out analysing the combined variability due to all the input parameters for the future.

3.2.2 LP Sensitivity Analysis vs. MILP Sensitivity Analysis

Research for stability region identification as post-solution sensitivity analysis has been well established for LP problems, with a number of off-the-shelf software available at present (Jansen et al. 1997; Sherali and Driscoll 2000; Filippi 2005; Ebrahimnejad 2011).

In contrast, stability region identification on MILP is more challenging and continues to evolve in the domain of computing research. My investigation has uncovered that researchers seldom conduct post-optimization analysis to identify stability regions in MILP applications due mainly to the absence of effective methods in the literature. Specifically, the difficulty in stability region identification on MILP is attributable to the discontinuous solution domain along with the prohibitively expensive resources for associated computing (Greenberg 1998). Several researchers tried to find alternative solutions to identify the stability region of MILP. Schrage and Wolsey (1985) examined the type of information to be stored when implementing branch-and-bound procedures in order to address issues related to stability region such as the effect of right-hand side variations on the optimum solution, or the range of values of the cost coefficient. Later, Dawande and Hooker (2000) introduced inference duality by investigating the role that each constraint plays in deriving a bound on the optimum value, which was proved effective on several numerical cases. Hadzic and Hooker (2008) proposed a binary decision diagram method for stability region identification in MILP with binary or general integer variables. With growing size and complexity of the problem, the computational burden of the existing algorithms developed for MILP sensitivity analysis increases substantially. As such, searching for sensitivity solutions in MILP has been rarely applied and verified in practical applications.

The growth of computing power of commonly available PCs has significantly alleviated the computational burden, thereby providing the motivation for me to formalize a cost-effective technique for MILP sensitivity analysis, lending itself well to application problems in the real world of construction engineering.

3.3 Earthmoving Operation Analysis

Earthmoving operations are one of the most important construction operations needed to be analyzed for they are generally performed in a highly nonlinear environment. The truck queuing/waiting may exist in the earthmoving process and is much likely to be affected by the uncertain activity times. Thus, the earthmoving process is generally regarded as non-linear. The probable nature of earthmoving operations makes it difficult to plan.

Operation analysis method has been traditionally utilized as an efficient means to model and evaluate such non-linear process. Discrete Event Simulation (DES), as the most famous type of simulation, is a very powerful tool to analyze uncertainties and nonlinearities in earthmoving operations, allowing field planners and estimators to evaluate productivity, allocate equipment, and estimate time and cost before project execution. Resource-based earthmoving simulation shows its great value in practical applications (Oloufa 1993; Shi and AbouRizk 1994; Hajjar and AbouRizk 1997). A CAD-based integrated simulation environment that applied a product-oriented simulation methodology for simulating construction projects was proposed in Xu (2001). It enables a simple and straightforward way to build simulation models so as to evaluate haul job cost and duration; it is noteworthy truck hauling paths were predefined and earthworks assignments were directly derived from CAD software in generation of earthmoving simulation models. With the introduction of the optimization algorithms, the earthwork operation analysis tools are further enhanced. Marzouk and Moselhi (2003) successfully established an automated system named Earth Moving Simulation Program (EMSP). It will integrate heuristic algorithms into the simulation model to select a near-optimum fleet configuration. Cheng et al. (2005) proposed simulation optimization by combining GA with CYCLONE or other simulation techniques. Zhang et al. (2006) further proposed an integration of particle swarm optimization (PSO) and a construction operation analysis so as to identify the crew configuration and evaluate earthmoving cost for a heavy construction operation. Integrating pervious research, the model for large-scale earthmoving operations are developed and successfully applied to two numerical examples (Moselhi and Alshibani 2009). Morley et al (2013) applied simulation methods to assign trucks to earthmoving haul jobs and estimate earthmoving time and cost, with the considerations of varying haul distances. The method of using computer simulation based operation analysis for crew configuration identification and cost/duration evaluation in earthmoving project has been formalized as science widely taught in post-secondary institutions.

Computer-aided operation analysis can also be utilized as a mean to validate the solution from a given analytical model (Evans et al. 1977). The operation analysis in a simulated realistic environment allow researchers to accurately experiment with various approaches in a "virtual abstraction" with computer programs, thereby quantitatively or graphically helping with verify the analytical model (Sargent 2005). Carrying out such analysis generally yields better understanding of the process, lower project costs, shorter durations, improved quality, and increased certainty in project delivery (AbouRizk 2010). Liu et al. (2013) established earthmoving operation models and validated the optimized earthmoving plans created from optimization approaches by comparing the simulated results of three feasible earthmoving plans. Simulated animation fulfilled by Three Dimensional (3D) Modelling was produced to visualize the blocks adding and removing process in earthmoving operations for better communication and validation (Burdett and Kozan 2015). Furthermore, Li and Lu (2016), applied simulation-based method to validate that their proposed optimization algorithms performance could be 30% better than the previously established mathematical models in shortening the average haul distance and reducing the total haul effort in earthmoving operations.

Chapter 4. MATHEMATICAL MODELING AND OPTIMIZATION

The content in this chapter is the core of this thesis, describing the earthmoving site modelling methodology and analytics applied to derive optimum temporary haul road layout design and earthmoving operation plans. Detailed modelling and formulations are presented in this chapter. Algorithms are also presented in mathematical format with demonstrative cases. The proposed analytics is capable to simultaneously generate earthmoving plans and temporary haul road designs at minimum cost, providing new insight to site grading planning.

4.1 Earthmoving Site Modeling

The objective of modelling earthmoving site is to provide a simplified yet practical mathematical model, based on which analytics can be applied for planning earthworks assignments and designing onsite temporary haul road layout. Three modelling approaches that have been used in the literature to represent the earthmoving site are discussed in this section.

4.1.1 Earthmoving Site Modeling: a Review

Two-Dimensional (2D) Grid Model. The most commonly used earthmoving site modelling approach is to represent the earthmoving site with orthogonal grid. In this approach, the position of objects (i.e. cut and fill cells) is identified by a unique location reference that is assigned to grid cells. This approach facilitates the cut and fill assignments search process and the identification of conflicts between objects during the search. Unlike predetermined location based modeling approaches (Lima et al. 2013), the grid system enables the possibility of using the entire site space for modelling. In addition, the application of grid system could enable easy visualization, simplicity in modeling spatial constraints and providing full control over the flow of resources using predefined rules or algorithms (Liu and Lu 2014; Li and Lu 2016). In a simplistic use of the grid system, the net volume (cut or fill) of earth is assumed to be concentrated at the center of each cell for site grading operations (e.g. Son et al. 2005; Kang et al. 2013). Here, the size of the grid unit is selected considering the length of the truck and space between two trucks in a row, and the accuracy of site modelling. In a more advanced form of 2D grid representation, an object (i.e. area) can occupy multiple grid cells (Pradhananga and Teizer 2014; Nassar and Hosny 2012).

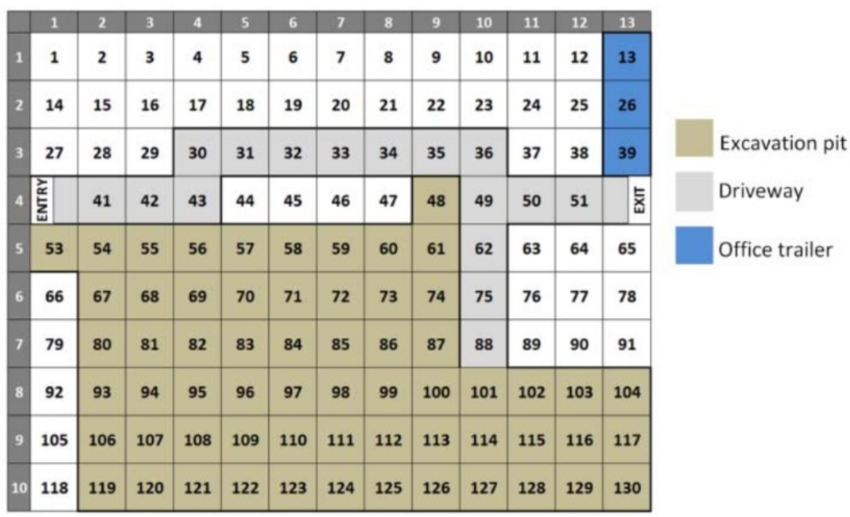


Figure 4-1: Grid system (Nipel and Jochen 2014)

Compared to the predetermined locations based modeling approach, dividing the site into a grid system provides a more realistic representation of the actual site conditions. However, the existing applications of grid system have two major problems. First, the calculation of haul distance in earthworks has been long established through using Euclidean distances between any two cell centroids in the grid system (Son et al. 2005). Euclidean distances, representing the resource transit path between a source and a destination, are similar to the earthmoving operations, but without factoring in a temporary haul road network on a construction site they are inaccurate and insufficient. Second, the grid size defined in previous literatures mainly considered the overall accuracy of the model in terms of site specific constraints, truck size, and actual haul distances between cells. As a typical case, the grid size was selected to be 9m x 9m considering the length of the truck and space between two trucks in a row (Pradhananga and Teizer 2014). However, if grid size is so small that the field is divided into a large number of cells, the road network design based on the grid system tends to be impractical.

Three-Dimensional (3D) Block Model. Given the limited capability for 2D grid system in modelling the vertical stratification of soil and the changing terrain that occurs during construction, a much more comprehensive 3D block model was proposed in recent years (Burdett and Kozan 2014; Lamghari and Dimitrakopoulos 2012; L'Heureux et al. 2013), as shown in Figure 4-2. In the 3D earthmoving site model, each block is a container of earth. It has a specific location in the 3D model and has a common volume of soil. After each cut or fill, the elevation within each block can be updated to account for truck fuel consumption and site constraints updates, providing the potentials to accurately evaluate the real cost of haulage. In addition, the 3D block model enables the consideration of soil or rock types in each and every cut and fill block, for the practical concerns that (1) not all of the excavated soil can be used for fill by engineering design specification; and (2) different soil type excavated from cut block should be fill in a sequence to the perspective of geotechnical engineering (e.g. hard rocks need to be fill to bottom stratification).

Despite of the claimed advantages of 3D block model in modelling the earthmoving site, the earthmoving tasks obtained by optimizing the constantly updating terrain condition iteratively and successively will unavoidably result in non-optimal solution with computational burden and modelling complexity significantly increase. The expensive modelling time and requirement for professional technician results in very limited practical application of 3D modelling based operational planning and estimating. In addition, planning cut and fill assignments considering different soil types in the cut blocks is nearly unrealistic; based on limited borehole information, the accurate soil stratifications could hardly be readily available. In order to obtain relatively accurate soil strata, exhaustive ground investigation needs to be conducted, which will lead to prohibitively high investment. This practical issue further hinders the application of 3D block model for earthmoving site modelling.

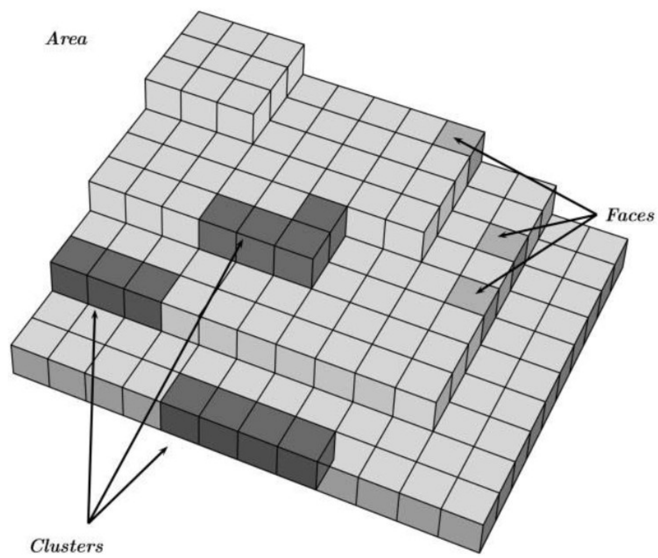


Figure 4-2: Block system (L'Heureux et al. 2013)

Geographical Information based Model. In reality, locating cut or fill areas on the site is not limited to a grid or block system; they can be located anywhere on the earthmoving site. The geometry of an earthmoving site is not a two-dimensional (2D) coordinate plane at bird's view. In addition, the optimal path between a cut cell and a fill cell is not always determined by the shortest distance or shortest haul time calculated by using the Pythagorean theorem, because the location vectors of the paths consisting of a haul route and the geological features of the job site surface change dynamically during earthwork operations (Burdett and Kozan 2014). Therefore, a geographical information-based model was applied to model the earthmoving site and plan haul path between cut and fill, as shown in Figure 3-4. This approach offers an increased flexibility by allowing to plan the areas and haul paths anywhere on the site and without being limited to grid lines or predetermined locations. However, compared to the previous two approaches, it makes the search process more complicated and requires more sophisticated algorithms to identify and resolve conflicts.

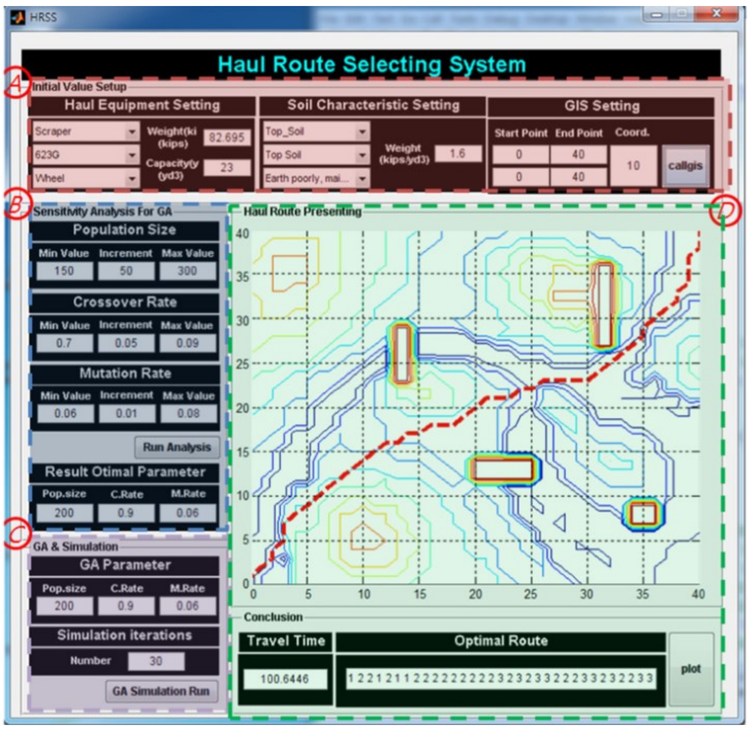


Figure 4-3: Geographical Information based model (Gwak et al. 2015)

4.1.2 Selection of 2D Grid Model

This thesis selected a two-dimensional grid model for mass earthworks in large site grading project for not only its wide applications in both research community and professional practice (Son et al. 2005; Kang et al. 2013; Burdett and Kozan 2014; Pradhananga and Teizer 2014; Liu and Lu, 2015; Li and Lu 2016) for earthworks assignment, but also its potential capability to model temporary haul road network. Certainly, the size of the grid is crucial to the following two aspects:

(1) Practicability of the temporary haul road design

Generally, the grid size should not be too small that the field is divided into a large number of cells, where the temporary haul road design based on the grid system tends to be impractical. Practically, the lower bound of grid size is determined by the minimum allowable distance between two access roads to the main haul road, where in current grid model this distance equals to the grid size. In transportation guideline by Alberta Infrastructure and Transportation (1999), this distance is regulated as no shorter than 150 meters. On the other hand, if the grid size is too big, the grid model may no longer be valid for the reason that modelling of the temporary haul road layout would be oversimplified, leading to insufficient design. In a recent study, Liu and Lu (2015) conducted sensitivity analysis with different grid sizes from 150 m to 300 m (with 50m interval), and proved that 150 m grid size is most effective in modelling temporary haul road layout design in terms of average unit haul time, haul duration, total cost, and etc.

(2) Accuracy of modelling the earthmoving operation

As introduced in previous chapter that bulldozers are typically used for site grading project with average haul distance within 150 meters. Therefore, if grid size is smaller than 150 m, the intra-grid haul effort of truck can be neglected based on current modelling approach. In addition, from the perspective of modelling earthmoving operations, the grid size should never be too big, or the detailed earthmoving operations within large grids would be ignored, which is unrealistic in real world project settings. For example, when dividing the field into 300 m cells, the truck haul effort within this grid would hardly be neglected, or operation modeling is deemed as oversimplified.

Having stated above, a grid network structure for haul road design consists of 150 m ×150 m square grids (or cells) is used in this thesis. The conceptual model of a possible haul road layout design is demonstrated in Figure 4-4. For each cell, the centroid is simplified to be the cell's geometric center; thus, the potential road layout design can be denoted by road links, each connecting the centroids of two adjacent cells with straight-line sections. The road type of each link can be distinguished by a dot line for "rough ground" by default and by a solid line for "gravel surfaced", as shown in Figure 4-4. It should be noted that the "road links" are segments between the centroids of any two adjacent cells, instead of between any two cell centroids; two cells are deemed adjacent only if they are ''immediately adjacent'' or ''diagonally adjacent''.

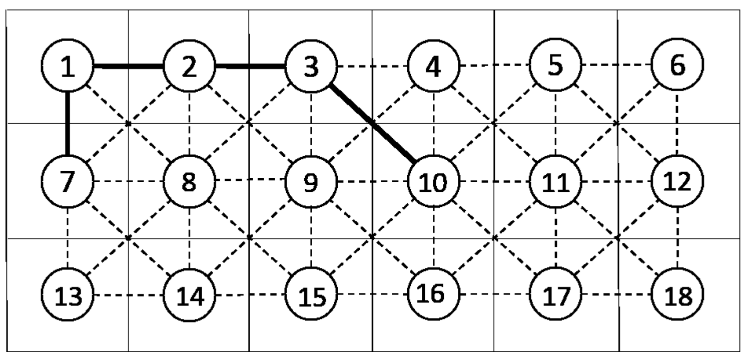


Figure 4-4: Grid model to represent site partitioning strategy and road links

4.2 Graph Theory and Flow Network Model

In the domain of Operation Research, a directed graph is called a network, where the vertices and arcs in the graph are entitled as nodes and edges, respectively. Based on Graph Theory, a flow network is a directed graph written as $G = (V, E)$, meaning that G consists of node-set V and edge-set E. We use v to represent a node and (i,j) to represent an edge of a network. Note ∀ v ∈ V, and all ∀ (i,j) ∈ E where i and j are end nodes of edge (i,j). A flow must satisfy the restriction that the amount of flow into a node equals the amount of flow out of it, unless it is a source, which has only outgoing flow; or sink, which has only incoming flow. Generally, a network can be used to model traffic in a road system, fluids in pipes, currents in an electrical circuit, or anything similar in which something travels through a network of nodes.

In this thesis, a node represents the cell centroid in the grid model. For each node v ∈ V, a variable w_i denoting the quantity of supply or demand is assigned. Typically, the node can be classified into three categories according to the value of variable w_i. In graph theory, if $w_i > 0$, node i is defined as a source node (i.e. cut cell) with supply quantity of w_i; if $w_i < 0$, node i is defined as a sink node (i.e. fill cell) with demand quantity of w_i; or if If $w_i = 0$, node i is defined as a transshipment node with quantity of 0.

Similarly, an edge represents the haul road links between any two adjacent cell centroids in the grid model. For each edge (i,j), two attributes were assigned: f_{ij} and $x_{(i,j)}$. f_{ij} denotes the quantity of earth to be hauled on edge (i, j). The type of haul road is denoted by a Boolean parameter $x_{(i,j)}$, which equals to "0" given "rough ground" haul road; equals to "1" given "gravel surfaced" haul road. A base network model is shown in Figure 4-5.

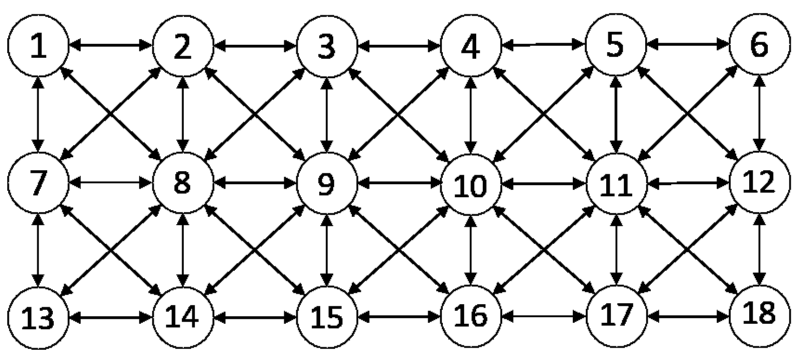


Figure 4-5: Base flow network model

On top of the base network flow model, more site constraints, such as cell accessibility can be further modelled based on practical site conditions. In this thesis, three types of accessibility related site constraints are defined, as illustrated below:

Flow-in only. In some areas on the earthmoving site, trucks are not allowed to haul through for the reasons that subsequent construction tasks (e.g. ground beam) by a third-party contractor or the general contractor will begin immediately after the site grading is finished; or the graded areas will be used as temporary facilities such as parking zone, laydown area, and etc. If the area is denoted by a sink node, all the bilateral edges connecting the sink node are constrained to be unilateral edges, pointing to the sink node only. The sink node and unilateral edges connecting to the sink node are denoted in Figure 4-6. Area B is a reserved area prohibiting truck passing once site grading is finished; node 18 is a sink node; edges (11,18) and (17,18) are unilateral edges pointing to node 18.

Flow-out only. Same to flow-in only constraint, flow-out only constraint exists under the circumstances that graded areas does not allow truck passing. If the area is denoted by a source node, all the bilateral edges connecting the source node are constrained to be unilateral edges, pointing from the source node only. The source node and unilateral edges connecting to the source node are denoted in Figure 4-6. Area A and Area C are reserved areas prohibiting truck passing once site grading is finished; node 6 and node 13 are sink nodes; edge (13,14) and edge (6,11) are unilateral edges pointing to node 14 and node 11, respectively.

Block. The block refers to natural blocks (e.g. rivers) and existing structures that blocks truck passing. The blocks can be simply modeled by removing edges, as shown in Figure 4-6. edges (1,8), (2,7), (7,13), (7,14), (8,13), (5,6), (5,12), (6,12), (12,17), (12,18) are greyed to denote the removal.

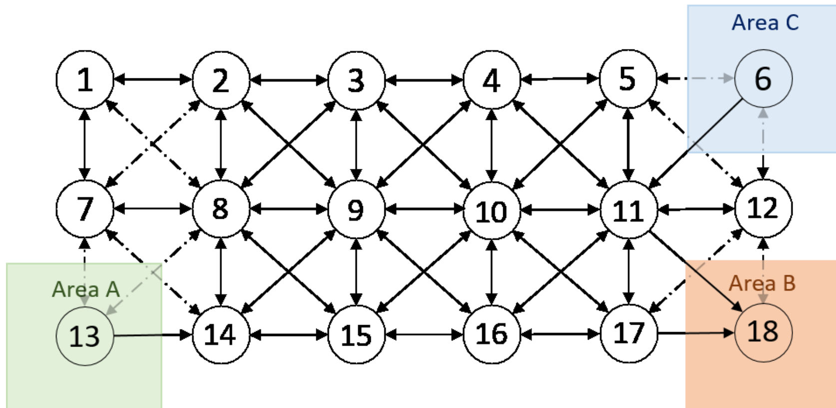


Figure 4-6: Upgraded network flow model based on accessibility related site constraints

4.3 Optimizing Temporary Haul Road Design and Earthmoving Operation Planning

4.3.1 Problem Overview

As stated in research objectives, this thesis is intended to overcome the identified challenges and address field application needs by developing an optimization approach to design temporary haul road layout and plan earthmoving operations on rough grading projects in an integrated fashion.

In the following sections, mathematical formulation and optimization procedures are illustrated step by step with examples. Relevant factors and assumptions considered in the problem definition are summarized as follows:

1. The site grading design is already completed and remains unchanged. It is common practice that civil engineering professionals apply civil information modeling software (such as Autodesk Civil 3D) to achieve a cut-fill balanced grading design with zero net volume of earthworks with or without extra borrow/dump at offsite location.

2. All the temporary haul roads are ready for truck hauling prior to earthmoving operations. It is not uncommon that temporary haul roads are designed and built before the crew start to execute earthmoving jobs.

3. To streamline the mathematical formulation, the average speed of a truck hauling empty on a particular haul road section would be the same as that of a truck hauling a full load. In other

words, in the present research, the truck hauling speed only depends on the type of haul road being of higher grade (gravel surfaced) or of lower grade (rough ground), irrespective of truck's load state, rolling resistance, slope resistance.

4. Truck loading and unloading plus waiting time is generally considered in earthmoving cost estimating and fleet balancing studies; nonetheless, it is not considered in the formulation of the present problem, as the effect of such time is not as relevant as the truck haul time in the context of temporary haul road layout design and earthmoving operation planning.

4.3.2 Input and Output

Model Input. The input data as needed for implementing the optimization methodology include cut and fill volume data of each cell in the site area, average haul speeds of trucks on haul road of different grades, and project-specific parameters or field data, as listed below:

(1) Construction and removal cost of the gravel-surfaced road ($/km). This input includes all the labor, equipment and material costs relating to construction and removal of the gravel-surfaced haul road, in the measurement of $/km. This input can be derived from benchmarking database such as RS Means or directly from earthworks contractor.

(2) Truck volume capacity and truck quantity. It is assumed truck model is selected and total truck quantity to be employed is estimated in the planning stage. Once truck model is determined, its capacity can be easily referred from manufacture handbook.

(3) Mean truck-haul speed on "gravel-surfaced" road (km/hr). This input will be derived from manufacture's handbook once truck model is identified. Note, the mean speed value on "gravel-surfaced" road referred to the truck speed under the context of level ground without slope, rolling resistance value in the category of "Moderately packed gravel" in Chapter 2, and truck being full loaded.

(4) Mean truck-haul speed on "rough ground" road (km/hr). This input will be derived from manufacture's handbook as well. Note, the mean speed value on "rough ground" road referred to the truck speed under the context of level ground without slope, rolling resistance value in the category of "Muddy rutted material" in Chapter 2, and truck being full loaded.

(5) Hourly rate of crew and overhead ($/hr). This input includes all the labor and equipment employed in earthmoving operations, in the measurement of $/hr. This input can be derived from benchmarking database such as RS Means or directly from earthworks contractor.

(6) Working efficiency factor. This input will use the industry rule of thumb value at 45-min per hour, i.e. 0.75, to account for crew non-productive time in the field such as warming up the equipment in the morning, greasing, oiling, lunch and coffee breaks etc.

(7) Maintenance cost on "gravel-surfaced" road ($/km). This input includes all the labor, equipment and material costs relating to routine maintenance service for the gravel-surfaced haul road, in the measurement of $/km. This input can be derived from benchmarking database such as RS Means or directly from earthworks contractor.

(8) Maintenance cost on "rough ground" road ($/km). This input includes all the labor, equipment and material costs relating to routine maintenance service for the rough ground haul road, in the measurement of $/km. This input can be derived from benchmarking database such as RS Means or directly from earthworks contractor.

(9) Cut and fill volumes (m^3). This input specifies the soil volumes to cut or fill in each cell of the site grid model. This is typically done by site surveying and computing software.

(10) Site constraints. This input includes possible reserved areas, natural block, existing structures and site access(es).

Model Output. Basically, the model outputs include temporary haul road layout design and earthmoving operation plans. To be more specific, the temporary haul road layout design will outline the layout of the high grade haul road on the earthmoving site; the earthmoving operation plans will include all the haul jobs in terms of source, destination, earth volume, and haul path to guide field executions.

4.3.3 Mathematical Formulations

With more high-grade road links, the earthmoving duration is reduced at the expense of potentially increasing the cost of building and maintaining the temporary haul road network on site. Hence, the optimization of temporary haul road design becomes a tradeoff problem: how to achieve a balance between project-duration-dependent cost and road construction plus maintenance cost. The objective is to minimize the total cost by combining the two cost items and identifying the optimum equilibrium between them. In this thesis, a complete series of formulations for earthmoving costs are made.

The total cost is given as Eq. (4-1).

$$C_{total} = C_{duration} + C_{road} \tag{4-1}$$

The project duration dependent cost is estimated by Eq. (4-2)

$$C_{duration} = \alpha \cdot T \tag{4-2}$$

where α stands for the sum of hourly rates of the hauling crew (including costs for equipment and operators). T is the total project duration estimated by Eq. (4-3):

$$\mathrm{T} = \frac{2 \cdot \sum_{(i,j)\in A}[f_{(i,j)} \cdot (t_{(i,j)} - x_{(i,j)} \cdot \Delta t_{(i,j)})]}{f \cdot n \cdot c} \tag{4-3}$$

The haul time is calculated simply as $t_{tk(i,j)} = s_{(i,j)}/v_{(i,j)}$, where $t_{(i,j)}$ is the truck haul time per truck load on edge (i, j); $s_{(i,j)}$ is the distance of edge (i, j); $v_{(i,j)}$ is haul speed of a truck on edge (i,j); $\Delta t_{(i,j)}$ is the time saving per truck load on edge (i,j) if a truck travels on "gravel-surfaced" road in contrast with "rough-ground" road; $x_{(i,j)}$ is a Boolean input parameter. Assuming truck returns on the same path in each cycle, '2' is applied to account for the round trip effect; n is the number of trucks (fleet size), c is the volume capacity of one truck in cubic meters, f is the operations efficiency factor (commonly taken as 45-min hour or 0.75 in construction estimating. Eq. (4-3) is given to determine the total duration, which allows for multiple trucks to work concurrently.

Then combined with Eq.(4-2), the project duration dependent cost can be further simplified to Eq. (4-4) where φ is the combined duration-dependent cost parameter.

$$C_{duration} = \varphi \cdot \sum_{(i,j)\in A}[f_{(i,j)} \cdot (t_{(i,j)} - x_{(i,j)} \cdot \Delta t_{(i,j)})] \qquad (4\text{-}4)$$

where

$$\varphi = \frac{2\cdot\alpha}{f\cdot n\cdot c} \qquad (4\text{-}5)$$

Eq. (4-4) can be further transformed by denoting "traffic scenario" on rough-ground haul road and gravel-surfaced haul road separately, as in Eq. (4-6):

$$C_{duration} = \varphi \cdot \sum_{(i,j)\in A}(f^{(1)}_{(i,j)} \cdot t^{(1)}_{(i,j)} + f^{(2)}_{(i,j)} \cdot t^{(2)}_{(i,j)}) \qquad (4\text{-}6)$$

$f^{(1)}_{(i,j)}$ is the allocated earthwork quantity in connection with rough ground haul road, while $f^{(2)}_{(i,j)}$ is the allocated earthwork quantity associated with sections of gravel-surfaced haul road. Note the existence of two extreme cases: (1) if there is no temporary gravel-surfaced haul road to be built, then $f^{(2)}_{(i,j)} = 0$; (2) if trucks haul on gravel-surfaced haul road across the entire site, then $f^{(1)}_{(i,j)} = 0$.

The haul road construction plus maintenance cost is defined by Eq. (4-7):

$$C_{road} = C_{construction} + C_{maintenance} \tag{4-7}$$

The haul road construction cost is proportional to the length of high-grade road as given in Eq. (4-8), where β is the unit construction plus removal cost of the gravel-surfaced road. Note the construction and removal cost of the rough-ground road is insignificant hence ignored.

$$C_{construction} = \beta \cdot \sum_{(i,j)\in A}(s_{(i,j)} \cdot x_{(i,j)}) \tag{4-8}$$

Despite much lower construction cost, rough-ground road is much more expensive to maintain due to safety-related risks and high wear and tear on tires and trucks. Note in a previous study the maintenance cost was simply defined as a function of the proportion of the length of gravel-surfaced haul road over the total length of haul road in the field (Liu and Lu 2015). As the maintenance cost vary with truck traffic volumes, the haul road to carry lesser traffic volumes generally incurs lower maintenance cost. As the earthwork quantity on each road link is treated as variable to be solved out by algorithms to be introduced in subsequent section, the maintenance cost of haul road is given as in Eq. (4-9) factoring in the traffic volume and per km maintenance cost for rough-ground road and gravel-surfaced road, respectively.

$$C_{maintenance} = \sum_{(i,j)\in A}(\sigma_1 \cdot s_{(i,j)} \cdot \frac{f_{(i,j)}^{(1)}}{TH_1}) + \sum_{(i,j)\in A}(\sigma_2 \cdot s_{(i,j)} \cdot \frac{f_{(i,j)}^{(2)}}{TH_2}) \tag{4-9}$$

σ_1 is the per km haul road maintenance cost for rough ground; similarly, σ_2 is the per km haul road maintenance cost for gravel-surfaced haul road; TH_1 is the threshold earthwork quantity for maintenance on rough ground haul road given typical haulers (e.g. CAT 735); TH_2 is the threshold earthwork quantity for maintenance on gravel-surfaced haul road given typical haulers.

Combine Eq.(4-6), Eq.(4-8), and Eq.(4-9), the cost function is finally given as Eq. (4-10):

$$C_{total} = \varphi \cdot \sum_{(i,j)\in A}(f_{(i,j)}^{(1)} \cdot t_{(i,j)}^{(1)} + f_{(i,j)}^{(2)} \cdot t_{(i,j)}^{(2)}) + \beta \cdot \sum_{(i,j)\in A}(s_{(i,j)} \cdot x_{(i,j)}) + \sum_{(i,j)\in A}(\sigma_1 \cdot s_{(i,j)} \cdot \frac{f_{(i,j)}^{(1)}}{TH_1}) + \sum_{(i,j)\in A}(\sigma_2 \cdot s_{(i,j)} \cdot \frac{f_{(i,j)}^{(2)}}{TH_2}) \tag{4-10}$$

4.3.4 Mixed-integer Linear Programming (MILP) Model

Decision Variables

A combinatorial optimization problem is formulated factoring the decision variable as of whether to construct temporary haul road of high grade, as given in Eq.(4-11).

$$x_{(i,j)} = \begin{cases} 0 & \text{"rough ground" link} \\ 1 & \text{"gravel surfaced" link} \end{cases} \tag{4-11}$$

Two additional variables are declared as $f_{(i,j)}^{(1)}$ and $f_{(i,j)}^{(2)}$. The subscript "(i,j)" indicates the edges (i.e. road links) on the graph. The superscripts "(1)" and "(2)" indicate traffic volume being allocated on either rough ground haul road or gravel-surfaced haul road, respectively.

Objective Function

The proposed model in this study is intended to directly minimize the total cost based on the proposed cost function in Eq. (4-10). Then the objective function can be given in Eq. (4-12).

$$Min \quad Z = \varphi \cdot \sum_{(i,j)\in A}(f_{(i,j)}^{(1)} \cdot t_{(i,j)}^{(1)} + f_{(i,j)}^{(2)} \cdot t_{(i,j)}^{(2)}) + \beta \cdot \sum_{(i,j)\in A}(s_{(i,j)} \cdot x_{(i,j)}) + \sum_{(i,j)\in A}(\sigma_1 \cdot s_{(i,j)} \cdot \frac{f_{(i,j)}^{(1)}}{TH_1}) + \sum_{(i,j)\in A}(\sigma_2 \cdot s_{(i,j)} \cdot \frac{f_{(i,j)}^{(2)}}{TH_2}) \tag{4-12}$$

Z = objective function; $\varphi \cdot \sum_{(i,j)\in A}(f_{(i,j)}^{(1)} \cdot t_{(i,j)}^{(1)} + f_{(i,j)}^{(2)} \cdot t_{(i,j)}^{(2)})$ is to summarize the time-dependent project cost including labor, equipment and miscellaneous overhead expenses; note, α is related with haul efficiency, unit rates, number of trucks in the fleet, and truck capacity [referring to Eq. (3-5)]. Similarly, $\beta \cdot \sum_{(i,j)\in A}(s_{(i,j)} \cdot x_{(i,j)})$ is to represent the high-grade haul road construction cost, depending on the per km construction cost β and the distance of haul road of high grade to be built (gravel-surfaced). In addition, $\sum_{(i,j)\in A}(\sigma_1 \cdot s_{(i,j)} \cdot \frac{f_{(i,j)}^{(1)}}{TH_1}) + \sum_{(i,j)\in A}(\sigma_2 \cdot s_{(i,j)} \cdot \frac{f_{(i,j)}^{(2)}}{TH_2})$ is to denote the haul road maintenance cost, which depends on per km maintenance cost parameters (σ_1 or σ_2), the distance of road sections of particular type, the earth volume flow passing each road section, and maintenance thresholds for respective road grade.

By formulating the objective function in a mix-integer linear programming (MILP) format with both material flow ($f_{(i,j)}^{(1)}$ and $f_{(i,j)}^{(2)}$) and the quality grade of haul road ($x_{(i,j)}$) being variables, the research is intended to integrate the three critical earthmoving planning tasks in optimization analysis, thus simultaneously generating (1) the quantity of earth to be moved, (2) the haul route to move the earth, and (3) the layout plan of high-grade haul road.

Constraints

$f^+(v)$ is the earthwork quantity flowing into node v; $f^-(v)$ is the earthwork quantity flowing out of node v; D_v is the earth demand (cut or fill) as per cut and fill design of node. Thus, Eq.(4-13) is given to constrain the earth flow conforming to the cut and fill design.

$$f^+(v) - f^-(v) = D_v \tag{4-13}$$

The earthwork quantity being allocated on rough ground haul road or on gravel-surfaced haul road are real numbers, as demonstrated in Eq.(4-14) and Eq.(4-15).

$$f_{(i,j)}^{(1)} \in R^* \tag{4-14}$$

$$f_{(i,j)}^{(2)} \in R^* \tag{4-15}$$

Eq.(4-16) and Eq.(4-17) maintain that the earthwork quantity being allocated on rough ground haul road or on gravel-surfaced haul road is non negative.

$$f_{(i,j)}^{(1)} \geq 0 \tag{4-16}$$

$$f_{(i,j)}^{(2)} \geq 0 \tag{4-17}$$

4.3.5 Cutting Plane Method

The cutting plane method is an integer programming technique which is intended for iteratively refining the feasible solution set by introducing linear inequalities (termed *cuts*) (Vaughan 1986). In this temporary haul road layout design and earthmoving operation planning problem, the solution obtained from the formulated MILP-based mathematical model does not address constraints of road connectivity and field accessibility introduced in Chapter 2. In this thesis, the cutting plane method is integrated into MILP so as to impose appropriate *cutting-planes* to the MILP model. Those cutting planes are defined as valid inequalities derived based on the concept of *connected components*.

In Graph Theory, a *connected component* is a subgraph belonging to the main graph in which any two nodes are connected by edges; note a solo node with no connected edges can also be characterized as a special case of connected component, which is shown in Figure 4-7(1). In current problem settings, a node corresponds to the center point of each cell while an edge represents a potential road link connecting two cells. A connected component can be defined as *node set*, in which any node is connected to at least another node in the same set to form an edge. If the node set has only one node, the solo node does not connect with any other node in the system.

In this study, the connected component is defined as per Eq. (4-18), where all v in V_m are initially assigned with a unique label $L_{m,(v)}$ which belongs to a *label set* L_m; m is the label set number, (e.g. the initially assigned label is expressed as $L_{1,(v)}$); $X(E)$ is the edge set containing all the high-grade road links; Then, connected components are further defined as sub-sets of nodes where nodes in each set has the same label, all $(i, j) \in X(E)$.

$$L_{m,(i)} = L_{m,(j)} \tag{4-18}$$

By applying Eq. (4-18), Figure 4-7(1) is further updated, shown in Figure 4-7(2).

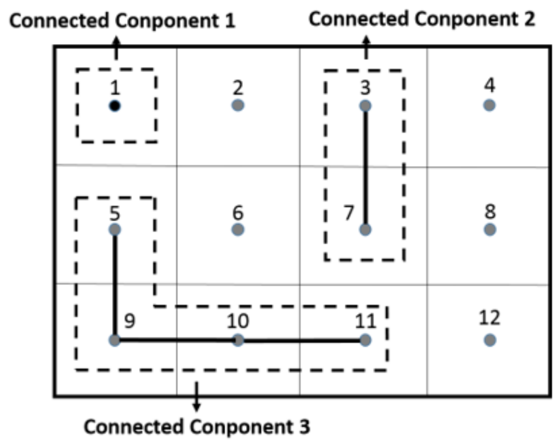


Figure 4-7(1): Original label

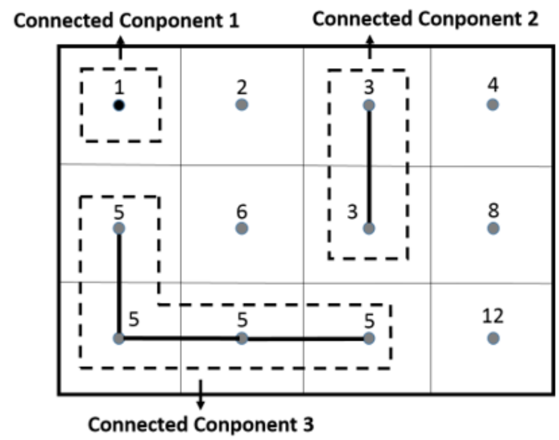


Figure 4-7(2): Updated label

Figure 4-7: Connected components

Then, the connected component(s) with the largest number of nodes [i.e. the longest connected component(s)] is chosen and the particular node set containing these nodes is denoted as the set *S*. Once *S* is selected, *valid inequalities*, as demonstrated in Eq. (4-19), are added to the mathematical model as part of the constraints, where $S \in x(V)$. $x(V)$ is the node set of high-grade road links; the *edge cut* of a node set include those edges that do not belong to the current node set but can be immediately linked with a node in the current set. For example, the edge cut of *connected component 2* in Figure 3-8(1) includes eleven edges, namely: (3, 2), (3, 4), (3, 6), (3, 8), (7, 2), (7, 4) (7, 6) (7, 8) (7,10) (7, 11) (7, 12). $\delta(S)$ is used to denote the edge cut set of S; $x_m(\delta(S))$ is to add up the road type variable (0/1) associated with each edge in $\delta(S)$. Thus, $x_m(\delta(S)) \geq 1$ means that at least one edge in the *edge cut* of S is included in S in the next generation of the solution. With valid inequalities added, the updated haul road layout design can be obtained by solving the mathematical model.

$$x_m(\delta(S)) \geq 1 \tag{4-19}$$

It is important to mention that site accessibility can be guaranteed by adding a valid inequality in connection with a solo node set, defined as the *entrance set*. The node itself is a connected component, which is also referred to as *the entrance component*.

A flowchart to help interpret the algorithmic process is given in Figure 4-8.

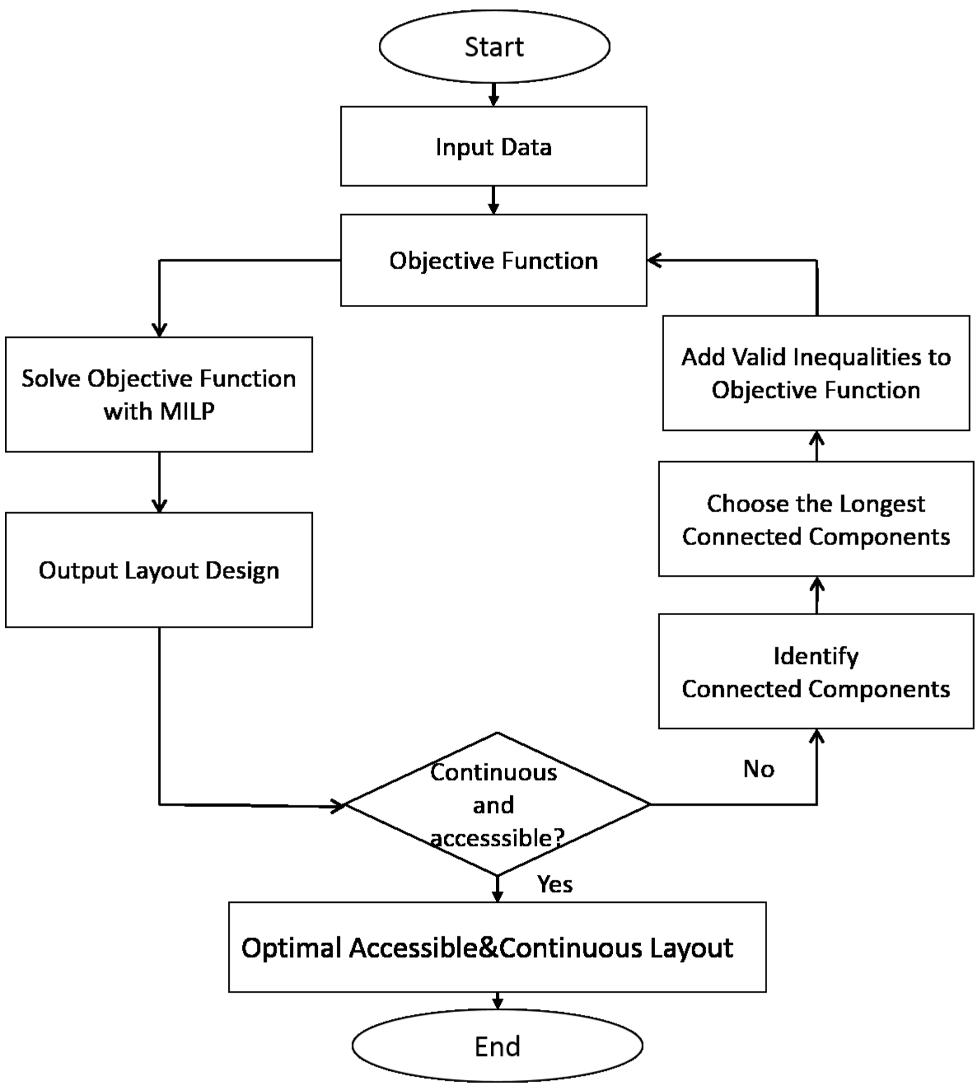


Figure 4-8: Flowchart of integrating a cutting plane method into MILP

4.3.6 Cutting Plane Method Demonstration Case

As the main purpose is to demonstrate how the cutting plane method is applied, parameters φ and β in the objective function are arbitrarily set in the case study. Each node is initially assigned a label from 1 to 12, defined as the label set $L_1 = \{1,2, \dots 12\}$.

Solving the proposed MILP-based mathematical model (identified as Model No.1), the haul road layout design is generated [Figure 4-9(1)]. Nevertheless, the high-grade haul road layout is neither accessible (at entrance cell 1) nor continuous (road link 3-7 is not connected to the other road links). Following Eq. (4-20), connected components can be identified. The process of defining connected components is shown in Eq. (4-20)

$$L_{1,(9)} = L_{1,(5)},\ L_{1,(10)} = L_{1,(5)},\ L_{1,(11)} = L_{1,(5)},\ L_{1,(7)} = L_{1,(3)} \qquad (4\text{-}20)$$

Then the node set with $L_{1,(v)} = L_{1,(5)}$ has the largest number of nodes and is chosen to be the connected component. Along with the accessibility requirement (trucks access the site from permanent road via entrance at Cell 1), two valid inequalities, given in Eq.(4-21) and Eq.(4-22), are added to the original mathematical model as constraints. The updated mathematical model is identified as Model No.2.

$$x_1\big(\delta(1)\big) = x_1(1-2,1-5,1-6) \geq 1 \qquad (4\text{-}21)$$

$$x_1\big(\delta(\{5,9,10,11\})\big) = x_1(5-1,5-2,5-6,9-6,10-6,11-6,11-7,11-8,11-12) \geq 1 \qquad (4\text{-}22)$$

Where $x_1\big(\delta(1)\big) \geq 1$ means the objective function is subject to the constraint that at least one edge in the edge cut of node set $\{1\}$ should be included in the next generation of solution forming part of the high-grade haul road network. Similarly, $x_1\big(\delta(\{5,9,10,11\})\big) \geq 1$ means the objective function is subject to the constraint that at least one edge in the edge cut of node set $\{5,9,10,11\}$ should be present in the next generation of the solution.

Then, by solving Model No.2, the updated high-grade haul road network is generated [Figure 4-9 (2)]. The solution is accessible but still not fully connected (road link 1-2 is detached from the others). Each node is then assigned a second label from 1 to 12, defined as a set $L_2 = \{1,2, \dots 12\}$. Following Eq. (4-20), new connected components can be identified as given in Eq. (4-23)

$$L_{2,(9)} = L_{2,(5)},\ L_{2,(10)} = L_{2,(5)},\ L_{2,(7)} = L_{2,(5)},\ L_{2,(2)} = L_{2,(1)} \tag{4-23}$$

Then node set with $L_{2,(v)} = L_{2,(5)}$ has the largest number of nodes and hence is chosen to be the connected component. One extra valid inequality, as given in Eq. (4-24), is added to Model No.2 as constraint according to Eq. (4-20). Then the mathematical model is further updated to Model No.3.

$$x_2\big(\delta(\{5,7,9,10\})\big) = x_2(5-1,5-2,5-6,9-6,10-6,7-2,7-3,7-4,7-6,7-8,7-11) \geq 1 \quad (4\text{-}24)$$

The node set with $\mathrm{L}_{2,(v)} = \mathrm{L}_{2,(5)}$ is chosen to be the connected component, which means the updated solution must have at least one edge in the edge cut of the node set with $\mathrm{L}_{2,(v)} = \mathrm{L}_{2,(5)}$. By solving Model No.3, a new high-grade haul road layout is generated, as shown in [Figure 4-9 (3)]. The layout is both accessible and interconnected. The cutting plane method based MILP (C-MILP) optimization process halts and the latest solution is taken as the final optimum design.

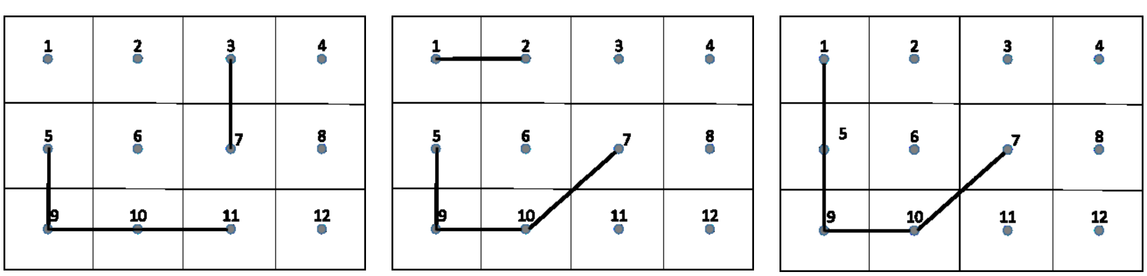


Figure 4-9 (1): First run　Figure 4-9 (2): Second run　Figure 4-9 (3): Third run

Figure 4-9: C-MILP optimization process and solution illustration based on mockup case

Apart from above mockup case, the proposed analytics were applied in a practical application case, which is the preliminary work package of a camp site construction in Fort McMurray, AB, sized at around 120 hectares with a total amount of 335,600 m3 of earth to be handled from cut and fill. Detailed information of the case is presented in Chapter 7.

The Cutting plane method based MILP (C-MILP) model was coded in *Python* Version 3.5 following the proposed optimization procedure (as per Figure 4-8). By running the program, an optimum solution was produced, as shown in Figure 4-10. Throughout the optimization process, a total of 63 solutions (62 intermediate results plus 1 the final result) were generated automatically by computer. The program terminated when both accessibility and continuity of temporary haul road design were achieved. Design layouts for all 63 solutions are shown in Appendix D. The resulting temporary haul road design is smoothly connected to the entrance; on the other hand, the as-designed alignment of temporary haul road in the field consists of two parallel straight-line sections, interconnected by a road link in the middle.

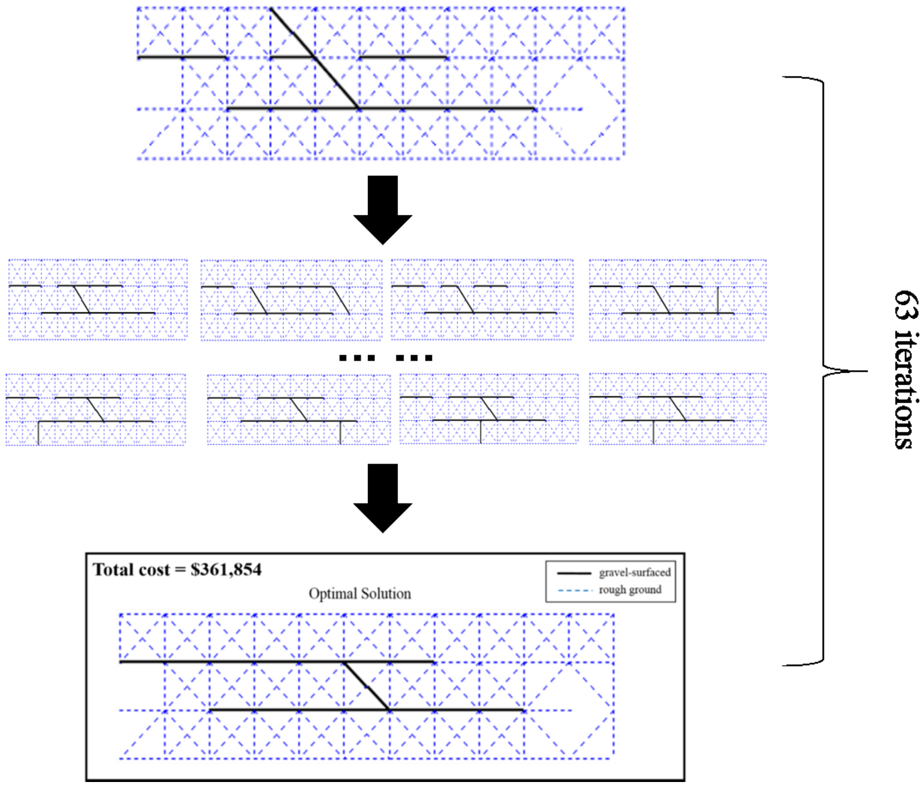


Figure 4-10: C-MILP optimization process and solution illustration based on practical case

Chapter 5. SENSITIVITY ANALYSIS FOR MIXED-INTEGER LINEAR PROGAMMING

In the Mixed-integer Linear Programming (MILP) application in this thesis, deterministic data representing the most likely or average values of input parameters are used to generate optimum solutions. Yet, input data in reality may differ from the deterministic settings in MILP optimization. This chapter formalizes an MILP based methodology for analytically determining the stability region for each input parameter, over which the optimum solution can be retained irrespective of the variation in an input parameter away from its nominal value.

5.1. Role of Sensitivity Analysis in Current Research

In previous chapter, the mathematical model in the form of MILP was developed to generate the optimum temporary haul road layout plan and earthmoving work plan in typical site grading projects. With deterministic parameter values (e.g. "high grade temporary haul road construction and removal cost" set at $17500/km), the resulting optimum solution has been obtained. Note, the inputted deterministic parameter values are termed nominal values, representing the most likely values of input parameters with which the optimum solution to the MILP model is realized. In reality, input data can not be precisely specified due to incomplete knowledge and uncertainty (Blacud et al. 2009). Simply relying on the solution generated by parameters' nominal values without justifying assumptions on model input data would be an act with high risk in applying optimization analysis (Du and Bormann 2012). As a matter of fact, the optimum solution can be irrelevant to the actual engineering application when input settings in reality differ from those ones considered in optimization. In short, to promote MILP in engineering applications, I conducted a post-optimization sensitivity analysis over the optimum solution resulting from MILP in order to address three questions: what happens to the derived optimality when input data values are changed from their nominal values? Does it just fall off the cliff? Or to what extent the optimum solution to MILP is able to tolerate such changes and still holds valid?

Post-optimization sensitivity analysis focuses on studying how the output of a mathematical model is affected in consideration of the uncertainty in its inputs. As stated by Greenberg (1998), one of the most important issues in post-optimization sensitivity analysis of mathematical programming is to identify the stability region of parameters, where the optimum solution stays unchanged subject to a range of parameter values around nominal values. Nonetheless, stability region identification for MILP is a difficult undertaking. The primary reason is that the domain of the MILP objective function is not continuous by definition (Wolsey 1981). Despite the fact that solution techniques for MILP are probably the best researched area in computing, post-optimization analysis has received far less attention and effective methods to identify stability regions on MILP models are yet to be formalized (Arkadiusz 2010).

This research is intended to answer a critical question on an MILP optimization model: what is the stability region of an input parameter over which the optimum solution is retained irrespective of the variation in the input parameter away from its nominal value? In the ensuing sections, the generic MILP sensitivity analysis model and the one-at-a-time (OAT) method are described. The subsequent section of "One-dimensional Line Search Method" describes the proposed technique for tackling the MILP sensitivity analysis problem.

5.2 MILP Sensitivity Analysis Model

In this thesis, the generic form of MILP is applied to generalize sensitivity analysis model (Wolsey and Rinaldi 1993), as shown in Eq.(5-1) - Eq.(5-4),

$$\text{Minimize} \qquad f = \sum_{i=1}^{n} a_i x_i + \sum_{j=1}^{n} b_j x_j \tag{5-1}$$

$$\text{Subject to} \qquad \sum_{i=1}^{n} c_{ki} x_i + \sum_{j=1}^{n} d_{kj} x_j = e_k \tag{5-2}$$

$$x_i \geq 0;\ x_j \geq 0 \tag{5-3}$$

$$x_i \in R^*;\ x_j\ is\ integer \tag{5-4}$$

Where subscript $i\ and\ j$ stand for the serial number of variables from 1 to n; subscript k stands for a series of circumstances by the nature of the problem from 1 to m (e.g. resources, periods); f stands for the objective function formulated according to a specific purpose (e.g. minimize project cost) under current project settings; x_i stands for real number variables, while x_j stands for integer variables to be solved; a_i stands for the coefficient in front of real number variable in objective function; b_j stands for the coefficient in front of integer variable in the objective function; c_{ki} stands for the coefficient in front of real number variables in constraint equations on the left hand side under circumstance k; d_{ki} stands for the coefficient in front of integer variables in constraint equations on the left hand side under circumstance k; e_k stands for the coefficient in constraint equations on the right hand side under circumstance k.

Eq.(4-1) shows the objective function in the form of linear equations consisting of coefficients and variables. Eq.(5-2), Eq.(5-3), and Eq.(5-4) are practical constraints in the form of linear equations/inequalities specific to problem definition.

Generally, coefficients in MILP are termed independent variables (or input parameters), while the objective value is termed dependent variable (or output). By characterizing the relationship between the dependent variable and independent variables, a sensitivity model is generalized in Eq.(5-5).

$$Y = f(X_1, X_2, \dots, X_t) \tag{5-5}$$

Where t stands for the serial number of coefficient; X_t stands for coefficients in MILP formulations; Y stands for the dependent variable. $f(X_1, X_2, \dots, X_t)$ shows that dependent variable is subject to the variations of independent variables factored in MILP.

5.3 One-at-a-time (OAT) Method

As commonly applied in sensitivity analysis, one-at-a-time (OAT) method entails analyzing one input parameter at a time, while keeping others at their nominal values. More specifically, parameter sensitivity can be measured by monitoring changes in the output while altering input parameter values; as such, parameter stability region can be determined by approaching the upper/lower boundaries of an input parameter upon which the optimum solution would considerably alter. Once sensitivity analysis for the current input parameter is finished, all the input parameter values are restored to their respective nominal values. Then, the above procedure is repeated for each of the remaining input parameters. The general process of OAT method is shown in Figure 5-1.

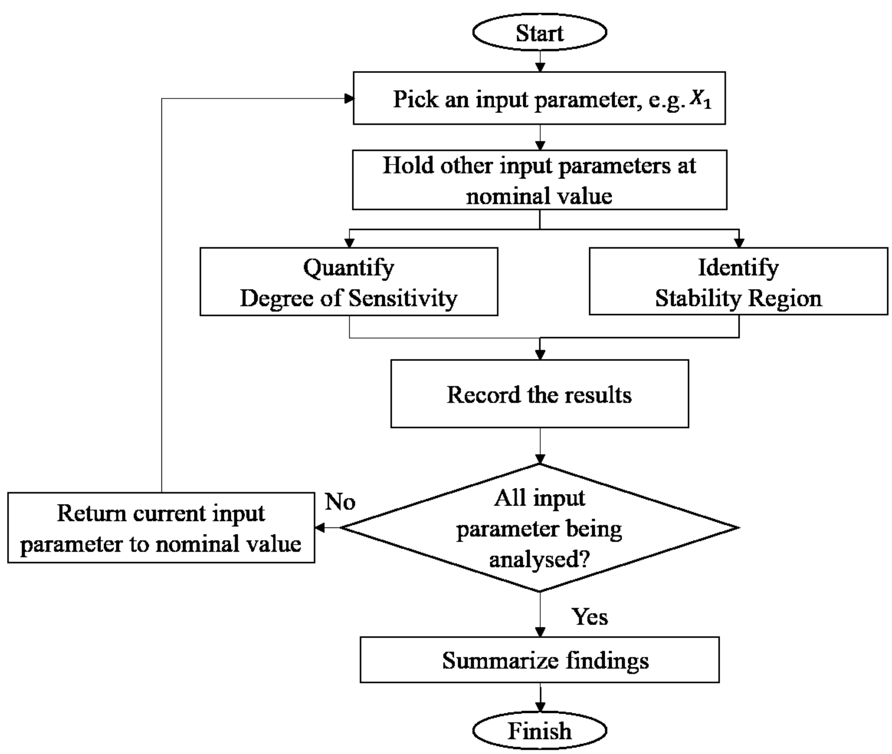


Figure 5-1: OAT method flowchart

It is worth mentioning all the ‘effects’ on the solution are characterized with reference to the same nominal point in the input space –which is the current optimum solution of the MILP model being studied. In addition, the parameter stability region generated in this way provides decision makers with insight on how the variability in the parameter would affect the optimum solution.

5.4 One-dimensional Line Search Method

The one-dimensional line search method is designed to determine the minimizer (the point that attains the minimum) as a function over a closed interval by evaluating the objective function at different points in the interval. Classic one-dimensional line search methods aim to approximate the minimizer in the least number of iterations, including Bisection method, Newton’s method, Golden section search method, Fibonacci search method etc. (Chong and Zak 2013). To put simply, in solving unconstrained optimization problems, the strategy of one dimensional search is to gradually reduce the search step length and progressively narrow the range until the minimizer is “boxed in” with sufficient accuracy. A conceptual demonstration of one-dimensional line search is given in Figure 5-2.

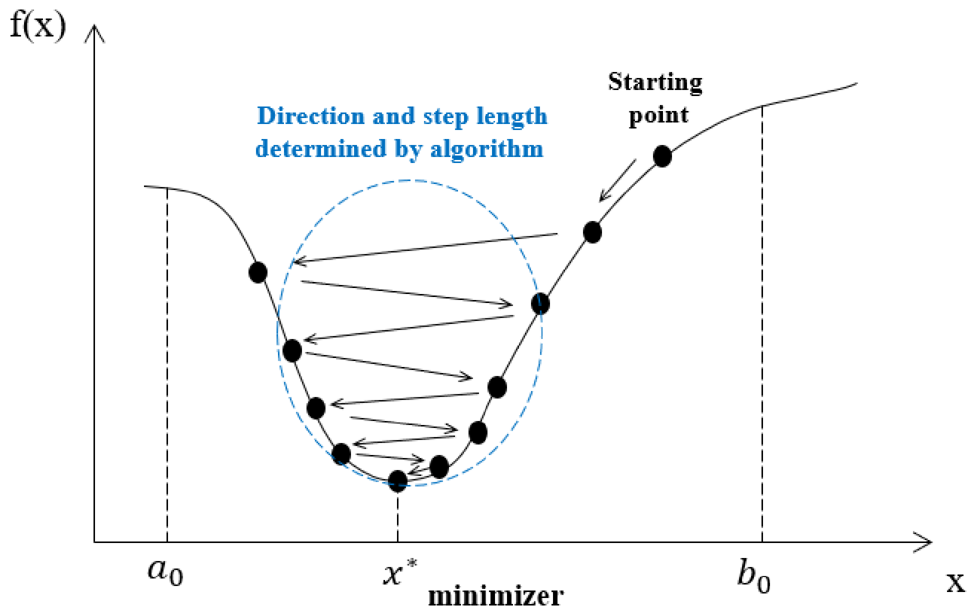


Figure 5-2: Concept of one-dimensional line search

The strategy similar to the one-dimensional line search method is followed in the proposed MILP sensitivity analysis, which determines the lower and upper bounds of the stability region; over the region, variation in a specific parameter would not change the optimality of the current MILP solution. The range boundary determination process is illustrated in Figure 5-3, where Δl is step length, selected as the smallest number in the order of magnitude of the input parameter. For instance, if the input parameter equals to 5200, its order of magnitude ranges from 1000 to 9999, then the initial step length is set as 1000. t is the tolerance which is set as 4/10000 times the nominal value of input parameter. i denotes iterations, with initial number being 0. Note the selection of 4/10000 times the nominal value of input parameter as the tolerance is based on trial and error through numerical tests. By design, the tolerance is not too small to produce insignificant variations in the resulting solution, while it is not too large to miss the optimum solution in the search process.

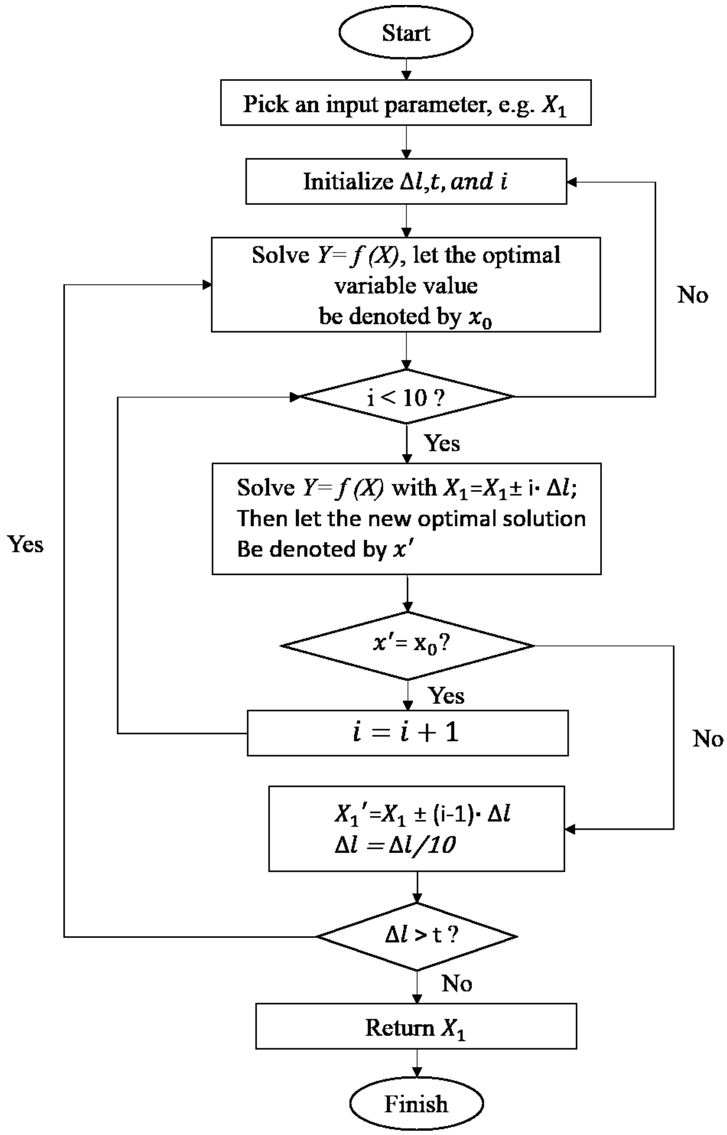


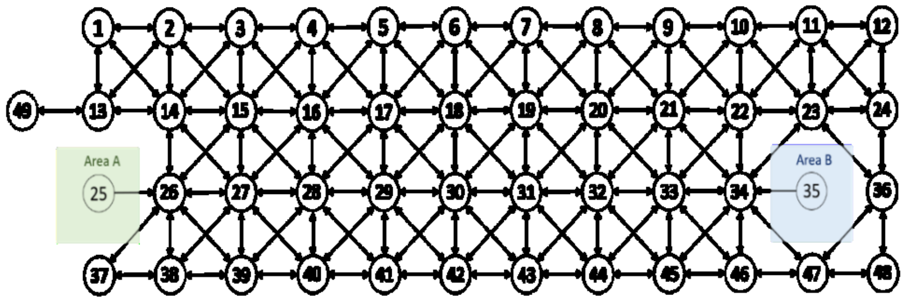
Figure 5-3: Flowchart to calculate upper/lower bound of parameter stability region

To calculate the upper or lower bound of a parameter's stability region, first an input parameter is selected and Δl, t and i are initialized. Then over the iterations, adding or deleting Δl to the parameter under analysis only if the model solution remains unchanged. It is expected the model solution would change within ten iterations; otherwise, the algorithm (as per Figure 5-3) automatically terminates and the value of Δl is re-initialized. If the model solution differs from the initially optimized one, the input parameter is then reset as $X_1' = X_1 \pm$ (i-1)$\cdot$ Δl and step length is also reset as $\Delta l = \Delta l/10$. If Δl is greater than the tolerance t, which means the solution accuracy is not yet sufficient, then the iteration continues by using the updated parameter value and step length; or if Δl is equal to or smaller than the tolerance t, the procedure terminates. The current parameter value is recorded as upper or lower bound of the stability region.

5.5. Stability Region Identification Demonstrative Case

A demonstrative case of how to determine the stability region as per Figure 5-3 is presented in this session. The case used to demonstrate the proposed parameter stability region identification methodology is the same as the practical application case as presented in Chapter 7. The site grading project is the preliminary work package of a camp site construction in North Alberta, Canada. The site layout, input parameter values, and the optimum temporary haul road layout design is shown in Figure 5-4. In light of the possible variations on the values of parameters in reality (e.g. the road construction cost increases due to the higher gravel cost), the site manager requires information on the sensitivity of each of the eight parameters in order to keep the temporary haul road layout design and deliver the minimum total earthmoving cost.

Input



Network flow model based on accessibility related site constraints

Model Inputs		
Parameters	**Value**	**Description**
σ_1	\$1200/km	unit maintenance cost (rough ground)
σ_2	\$500/km	unit maintenance cost (gravel-surfaced)
α	\$5200/hour	the sum of hourly rates of the hauling crew
β	\$17500/km	road unit construction and removal cost
TH_1	5000 m^3	maintenance threshold (rough ground)
TH_2	15000 m^3	maintenance threshold (gravel-surfaced)
n	4 trucks	truck number
c	15 m^3	truck capacity

Nominal values of eight input parameters

Output

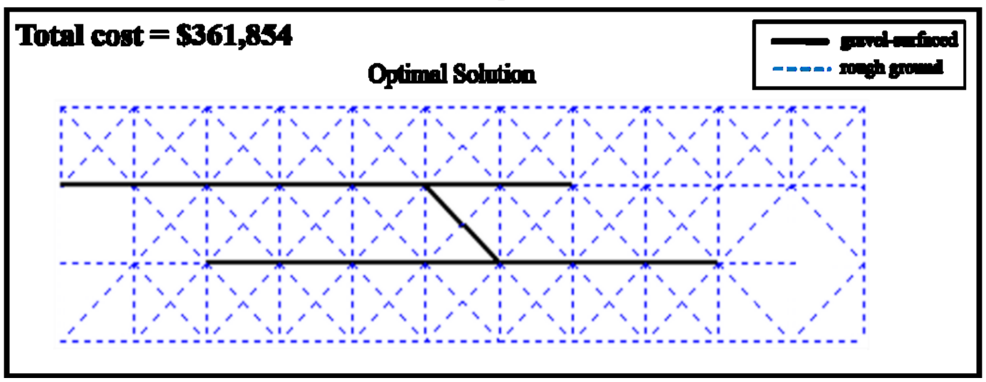


Figure 5-4: Model inputs and optimum output

The calculation process of the upper bound for “road construction and removal cost β” is given as an example to illustrate the one-dimensional line search method. The nominal parameter value of β is 17500 \$/km; step length Δl is set as 10000 \$/km (the order of magnitude ranges of the nominal parameter value is from 10000 to 99999, then the initial step length is set as the smallest number defining the order of magnitude, i.e. 10000); tolerance is 7 \$/km (4/10000 of the nominal parameter value); x_0 is solved with β = 17500 $/km based on the temporary haul road layout. Detailed calculation process is given in Table 5-1.

Table 5-1: Calculation demo to find upper bound of stability region of parameter β

Loop 1: $\Delta l > t$, continue				
i	β = β+ i· Δl	x'= x_0 ?	β′= β+ (i-1)· Δl	Δl = Δl/10
0	17500	√	-	-
1	27500	×	17500	1000 > 7
Loop 2: $\Delta l > t$, continue				
i	β′ = β′+ i· Δl	x'= x_0 ?	β′′= β′+ (i-1)· Δl	Δl = Δl/10
0	17500	√	-	-
1	18500	√	-	-
2	19500	×	18500	100 > 7
Loop 3: $\Delta l > t$, continue				
i	β′′ = β′′+ i· Δl	x'= x_0 ?	β′′′= β′′+ (i-1)· Δl	Δl = Δl/10
0	18500	√	-	-
1	18600	√	-	-
2	18700	√	-	-
3	18800	√	-	-
4	18900	√	-	-
5	19000	√	-	-
6	19100	√	-	-
7	19200	√	-	-
8	19300	×	19200	10 > 7
Loop 4: $\Delta l < t$, terminate				
i	β′′′ = β′′′+ i· Δl	x'= x_0 ?	β′′′′= β′′′+ (i-1)· Δl	Δl = Δl/10
0	19200	√	-	-
1	19210	√	-	-
2	19220	√	-	-
3	19230	√	-	-
4	19240	√	-	-
5	19250	√	-	-
6	19260	x	19250	1< 7

Calculation terminates at β = $19250/km, as the updated step length is smaller than the tolerance value. Hence, the upper bound of stability region of parameter β is determined at $19250/km. In a similar way, the lower bound of stability region of parameter β is determined at $14670/km.

Chapter 6. OPERATION ANALYSIS FOR EVALUATION AND VALIDATION

Chapter 4 and Chapter 5 apply scientific knowledge in mathematical programming and computer science to address a practical problem in earthworks planning by generating cost-effective solutions and providing practical information on sensitivity of the derived optimization results. As an indispensable feature of science, the findings and results need to be verified in a scientifically rigorous fashion in order to make this endeavor of applied research complete. This chapter presents an earthmoving operation analysis approach to assist in evaluating and validating the optimum solution generated from the proposed analytics in Chapter 4. First, the role of operation analysis in current research. Then, earthmoving operation analysis basics in terms of input data, truck number determination criteria, and equipment selection criteria are introduced. An Earthmoving Operation Analysis Platform (EOAP) tool is devised to facilitate the process of evaluating crew operation cost as well as identifying fleet configuration based on simulation. Then, solutions can be compared in terms of total earthmoving cost by summing up crew operation cost, haul road construction and removal cost, and haul road maintenance cost.

6.1. Role of Earthmoving Operation Analysis

Generally, analytical model gives support to research ideas theoretically and in mathematical equations. To be mathematically solvable, certain linearization of the problem and reasonable assumptions must be made. In practice, the magnitude of linearization of a practical problem is deemed reasonable if the resulting degree of realism is appropriate to characterize the problem. In this thesis, the earthmoving operations are linearized without considering loading/dumping/waiting times. This assumption is reasonable in formulating analytical models because such times remain rather fixed or insignificant, which are not as predominant as the truck haul time in the context of current optimization problem. While analytical methods are effective in abstracting real-world project settings into mathematical models and solving for optimum solutions, their characteristics of abstraction and implicitness generally make it difficult to attract practical applications due to possible misunderstanding, miscommunication and misinterpretation. Hence, there needs be a methodology to bridge the gap between analytical methods and reality.

Ideally, the solution can be applied on practical projects and verified and validated by real data, as practice is the best place for validation. However, CEM research generally lacks time and resource to materialize the validation on real projects. Enlightened by literatures (as reviewed in Section 3.3), I adopted computer simulation in this thesis for two main objectives:

(1) Solution Evaluation. The cost function for MILP formulations (as per Eq. (4-10)) does not include cost associated with truck loading/dumping/waiting. Therefore, the cost generated by optimization is more of theoretical value rather than practical value. The computer-aided earthmoving operation analysis has been proved by many previous literatures on its capability in producing accurate operational duration and cost (Liu et al. 2013). With the computer aided tool, the solution generated by analytical method can be evaluated in a simulated realistic environment in terms of resource use, duration, and cost, providing "Day One" budget for project monitoring, tracking and controlling.

(2) Solution Validation. Generally, computer-aided operation analysis allows practitioners to experiment with different solutions in a sufficient virtual model on computer. Carrying out such analysis could yield better understanding of the process and increased certainty in project delivery (AbouRizk 2010). In this thesis, computer-aided tool is used to evaluate the operation cost for each alternative solution. Further, total earthmoving cost, i.e. the sum of operation cost, road construction and removal cost, road maintenance cost, is evaluated for each solution for comparison. It is worth noting the total earthmoving cost evaluated by computer-aided operation analysis accounts for the truck loading/dumping/waiting time related cost, which is theoretically identical (though might be slightly impacted by the stochastic nature of operation simulation) for all the solutions since the total number of truck loads are the same. So, the comparison is consistent between analytical methods and computer-aided operation analysis. The evaluation and validation process is illustrated in Figure 6-1.

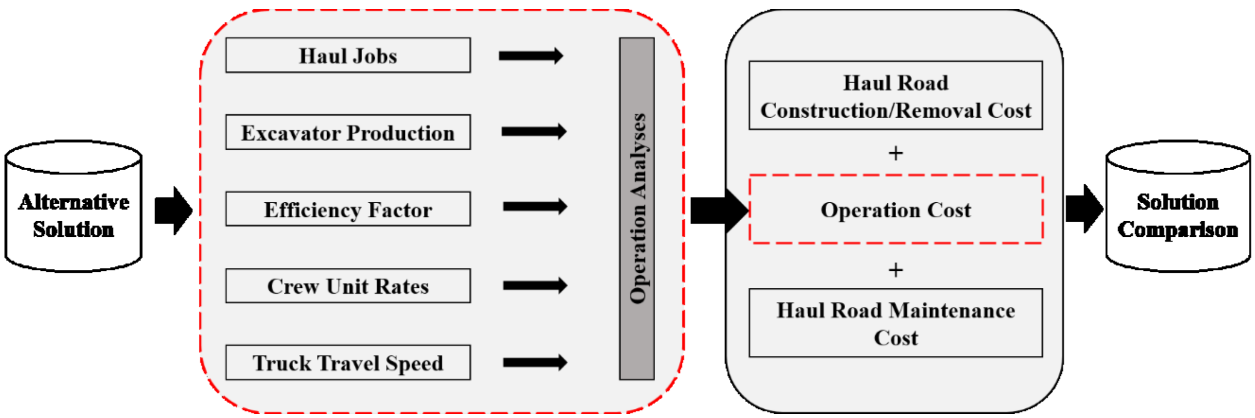


Figure 6-1: Computer-aided operation analysis for solution evaluation and validation

6.2. Earthmoving Operation Analysis Methods

6.2.1 Inputs for Operation Analysis

CAT Handbook. Caterpillar Performance Handbook (Caterpillar 2017) is intended as an aid to assist in estimating machine performance for equipment models manufactured by Caterpillar widely employed in heavy civil construction. In Caterpillar Handbook, tables or curves showing cycle times or hourly production figures for Caterpillar machines under certain conditions are provided. All the machine performance data is based on field testing, computer analysis, laboratory research and experience with every effort made to assure their correctness. In general, “CAT Handbook” provides cycle time data in terms of target values and lower and upper bounds for particular equipment models. The available data in Caterpillar Handbook enables earthmoving operation analysis in current thesis.

Truck Speed and Haul Time. Truck speed is an essential input for earthmoving operation analysis. In general, the factors influencing truck speed include but not limited to truck type, operating weight, rolling resistance, slope resistance and other site-specific regulations (such as speed limit). Firstly, different truck type features different horsepower and gear, leading to different rimpull-speed curve. Different truck models also have different loading capacity and truck weight, leading to different maximum speeds. For rolling resistance and slope resistance, as introduced in Chapter 2, they will have a combined effect on truck hauling speed by adding resistance to truck tires.

Take an example, given effective grade (combined by rolling resistance and slope resistance) as 10%, truck type as Caterpillar 730C, and full loaded, the haul speed can be derived from speed charts in Caterpillar Handbook, as shown in Figure 6-2. So, if road surface material, road slope, truck type and loading status are known, truck speed can be derived accordingly. Changes to any parameters will results in different truck haul speed. The truck haul speeds inputs for simulation of different truck types is attached in Appendix A.

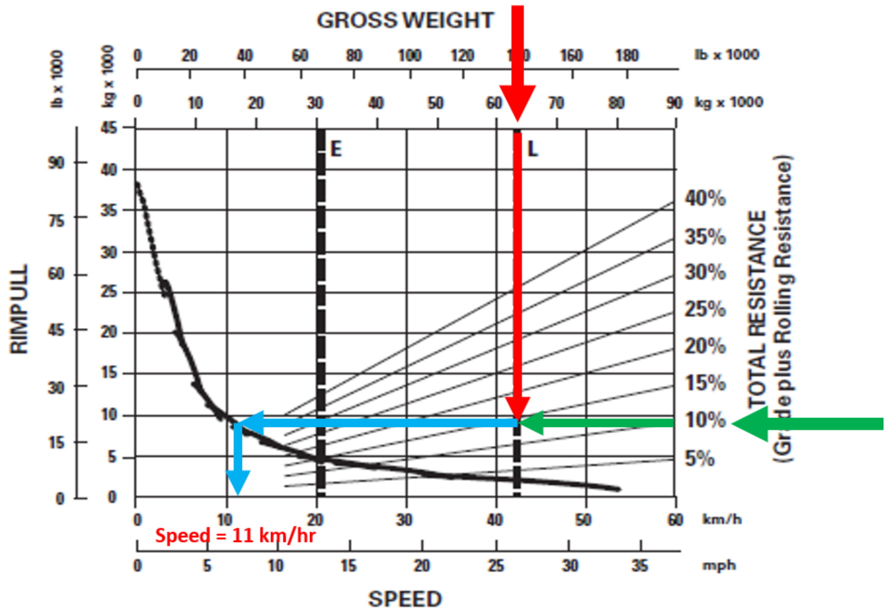


Figure 6-2: 730C Truck speed reference (Caterpillar Handbook 2017)

Haul paths derived from analytics inform the total length of rough ground haul road and gravel-surfaced haul road for trucks to haul back and forth for each haul job. Therefore, with truck speed on respective grade of haul road known, truck cycle time can be derived. In this thesis, the truck cycle time is divided into four parts over the truck hauling cycle, with trucks' speed distinctively defined in Appendix A. The truck haul cycle time is given in Eq.(6-1):

$$t_{h(i,j)} = \frac{d_{r(i,j)}}{v_1} + \frac{d_{r(i,j)}}{v_1'} + \frac{d_{g(i,j)}}{v_2} + \frac{d_{g(i,j)}}{v_2'} \tag{6-1}$$

Where v_1 and v_1' represent the speed of a specific truck hauling on rough ground haul road, being fully loaded or empty, respectively; v_2 and v_2' are the speed of a specific truck hauling on gravel-surfaced haul road, being fully loaded or empty, respectively; for haul job i where the source cell, the destination cell and the haul path are specified, $d_{g(i,j)}$ is the hauling distance on gravel-surfaced haul road while $d_{r(i,j)}$ is the hauling distance on rough ground haul road in a truck hauling cycle.

Excavator Production. Excavator production is critical in the earthmoving cycles, as it may dominate the total haul job duration if excavator production outnumber truck production. In this thesis, the productivity of excavator is measured by cycle time of finishing excavating and loading one bucket of earth, and the size of bucket that mounted on the boom.

Basically, the excavation cycle of the excavator is composed of four processes: load bucket, swing bucket, dump bucket and swing back. Total excavator cycle time is dependent on machine size (small machines can cycle faster than large machines) and job conditions. With favorable job conditions the excavator can cycle fast. As job conditions become more severe (tougher digging, deeper trench, more obstacles, etc.), the excavator slows down accordingly. Also, as the soil gets harder to dig, it takes longer to fill the bucket. For bucket size, each Caterpillar excavator will have a nominal bucket size accordingly. However, different buckets can be mounted to a single excavator if specially required by earthmoving contractor, being out of scope of current research. In Caterpillar Handbook, a Cycle Time Estimating Chart is used to outline the range of total cycle time that can be expected as job conditions range from excellent to poor. As stated in Caterpillar Handbook (2017), "Many variables affect how fast the excavator is able to work. The chart defines the range of cycle times frequently experienced with a machine. Then, users of Cycle Time Estimating Chart can evaluate job conditions and select cycle time appropriately". The Cycle Time Estimating Chart for different Caterpillar excavator models are attached in Appendix B.

Truck Hauling Cycles and Bucket Loads. The number of truck hauling cycles are determined by Eq. (6-2):

$$N_{c(i,j)} = \frac{Q_{ij}}{c} \tag{6-2}$$

Where Q_{ij} is the earthworks volume (m^3) for haul job H_{ij}. c is truck capacity in m^3, listed in Appendix A. $N_{c(i,j)}$ is the number of truck hauling cycles for haul job H_{ij}.

The number of bucket loads are determined by Eq. (6-3):

$$N_b = Roundup(\frac{c}{b}) \tag{6-3}$$

Where b is bucket capacity in m^3; N_b is the number of bucket loads to fully load a truck. N_b is determined once excavator model and truck model are selected. It is essential input to control when the truck is ready to leave loading area.

6.2.2 Determine Truck Number

The number of trucks is determined in order to match up with the production rate of the excavator, which is generally assumed to be the governing resource in earthworks estimating. The number of trucks is determined by achieving the minimum total haul job cost, in terms of the specific excavator being used, the specific truck type being considered, temporary haul road design, and the truck hauling cycle time. The total haul job cost is calculated according to Eq.(6-4):

$$C_{ij} = \frac{T}{f}(U_t N_t + U_{ex} + U_{oh}) \tag{6-4}$$

Where T is the haul job duration from operation analysis; f is the operations efficiency factor; U_t is unit cost of truck plus truck driver in \$/hour; U_{ex} is unit cost of excavator plus excavator operator in \$/hour; U_{oh} is unit cost of field overhead in \$/hour; C_{ij} is the total operation cost of haul job H_{ij}.

The default input for truck quantity is 1 as starting number. Then, the optimal truck number is determined by total operation cost calculated by duration output from computer-aided operation analysis by trying different truck quantities in an incremental fashion from 1 (i.e. add one truck each time). The truck number selection strategy is illustrated in Figure 6-3. It is noted that the termination criterion “Cost N+1 > Cost N” means that employing one more truck will lead to total direct cost increase.

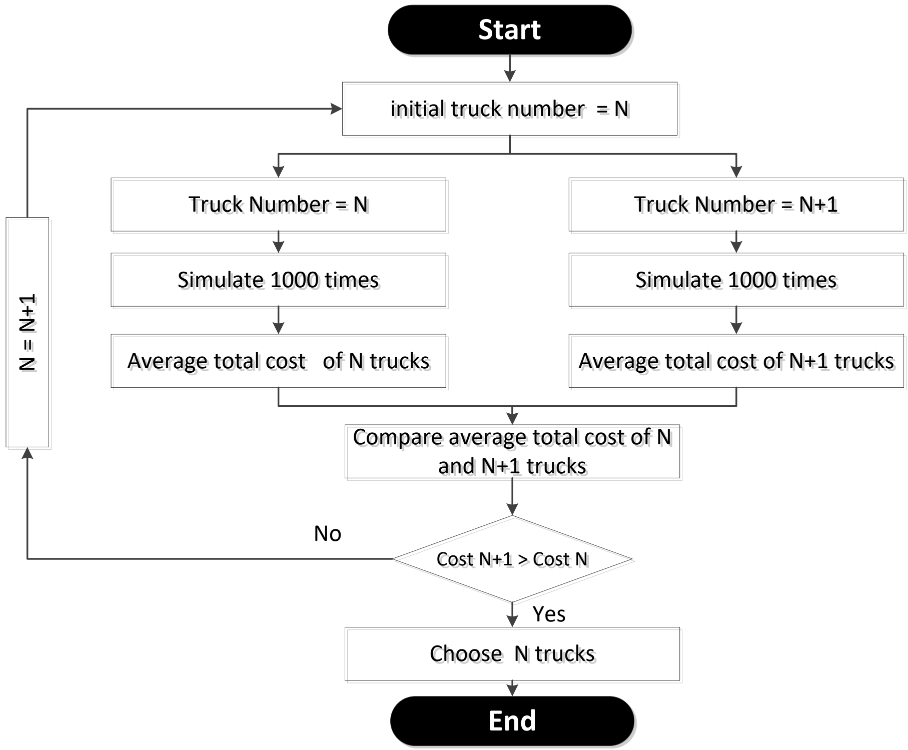


Figure 6-3: Methodology to determine truck number

6.2.3 Determining Equipment Type

Truck/excavator type is determined by adding one more loop by iterating all the possible truck/excavator combinations, as shown in Figure 6-4. The total project cost (consist of multiple haul jobs) under different truck/excavator combinations is calculated and compared to result in the optimal truck/excavator selection in terms of minimum total project cost.

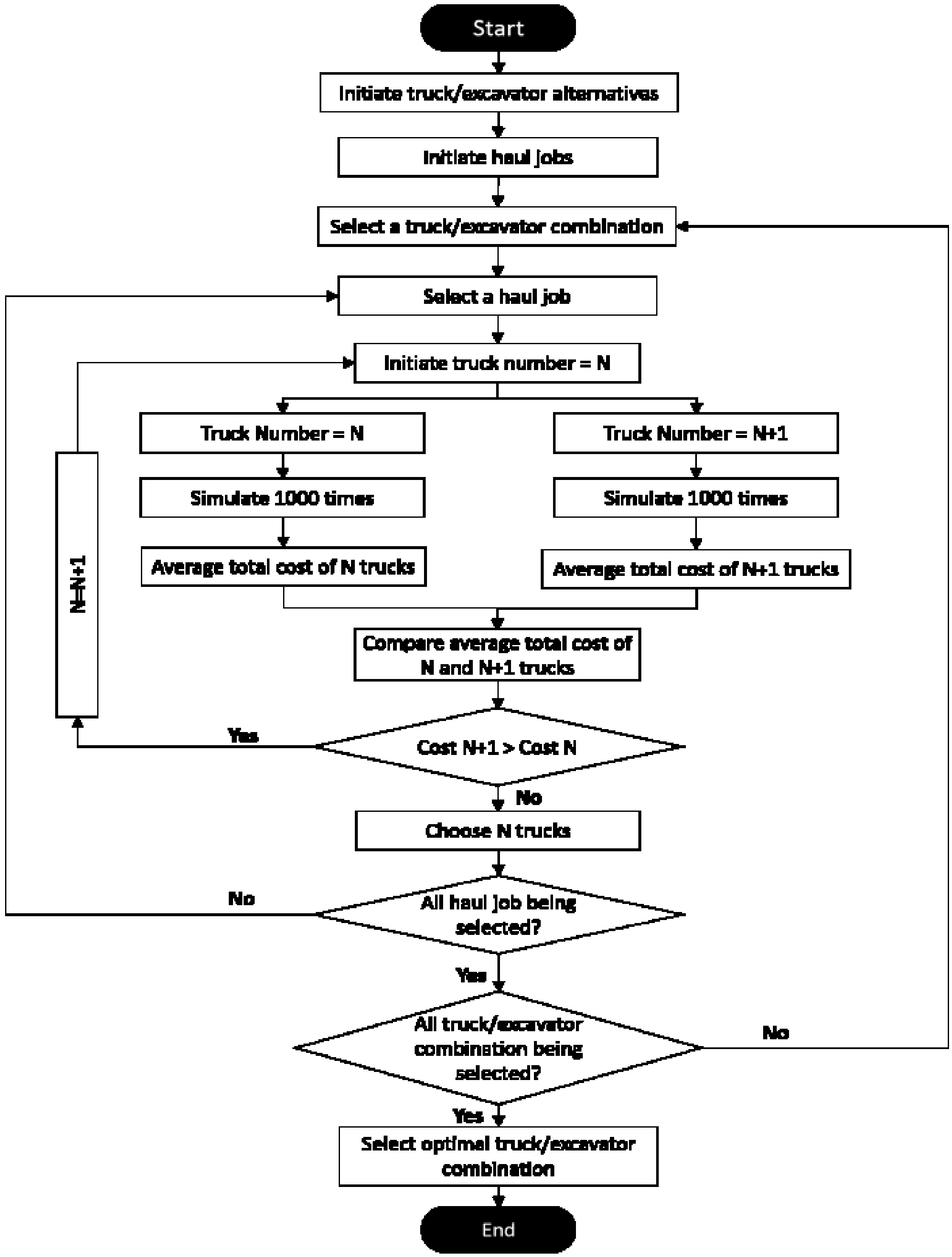


Figure 6-4: Methodology to determine truck/excavator type

6.3 Earthmoving Operation Analysis Platform (EOAP)

With off-the-shelf construction operation analysis software (i.e. construction simulation tool like

Symphony or SDESA), field planners are capable to model the earthmoving operations and generate duration and cost results in either deterministic or stochastic fashion (dependent on input data format). Instead of resorting to the off-the-shelf simulation tools to conduct operation analysis and identify the fleet, I developed an Earthmoving Operation Analysis Platform (*EOAP*) tool instead due to the following two reasons:

(1) **Tedious manually modelling and optimizing process**. The process of determining the optimal truck number in terms of minimum haul job cost is tedious because the modeler needs to manually change the truck number and compare cost for a single haul job. Modeler also needs to update model input for every haul job and conduct the "truck number iteration process" for each haul job. If different truck/excavator combinations exist, modelers need to repeat the manual modelling and optimizing process for every truck/excavator combination. As a typical case, 43 haul jobs and 4 truck/excavator combinations were given to student groups as a graduate course project at University of Alberta. Student groups (with three members each group) were asked to optimize the truck numbers for each haul job and identify the best truck/excavator combination in terms of minimum total operation cost. It took each group nearly 4 weeks to accomplish this task (suppose students need an average of six rounds of trial and error to identify the truck number for each haul job, then they need to establish a total of 1032 (43 haul jobs x 6 trials x 4 equipment combination = 1032) separate simulation models.

(2) **Practical application**. Field planners tend to use average production rates together with their experience for fleet selection at construction stage, due to the lack of professional simulation modelling and optimization training, and haste planning under time constraint. In fact, field supervisors and managers are interested in simulation tools, but hesitate to apply due to prohibitively high time consumption in the fast-paced and profit-chasing construction industry

(Dave et al 2013).

Having stated the challenges, I developed an Earthmoving Operation Analysis Platform (*EOAP*) tool to facilitate the earthmoving operation analysis process through automation to (1) automatically generate the optimal truck numbers for each haul job; and (2) automatically select optimal truck/excavator combination. The EOAP tool is verified by benchmarking with Symphony and SDESA software through numerical investigations in Appendix C.

6.3.1 *EOAP* Main UI Screen

The EOAP tool is programmed based on *SimPy* package in *Python* Version 3.5 (Python Software, 2017), which is an open source process-based discrete-event simulation library based on standard Python. By running the script in Python 3.5 environment, the below User Interface (UI) will pop up for users to (1) input haul job(s) parameters, and (2) select optimization mode.

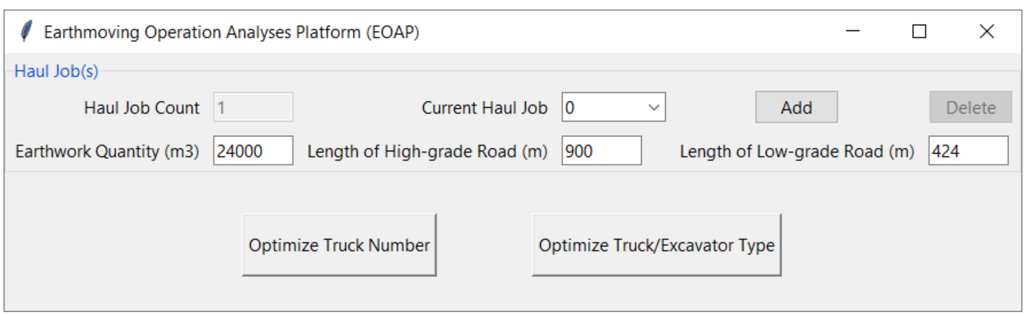


Figure 6-5: *EOAP* User Interface (main)

For each haul job, users need to input “Earthwork Quantity (m^3)”, “Length of High-grade Road (m)” and “Length of Low-grade Road (m)”. The program allows users to input multiple haul jobs by inputting haul job parameters and clicking “Add”. Users are also allowed to check each haul job being inputted by choosing haul job from a dropdown menu in “Current Haul Job”, or delete any haul job by clicking “Delete”.

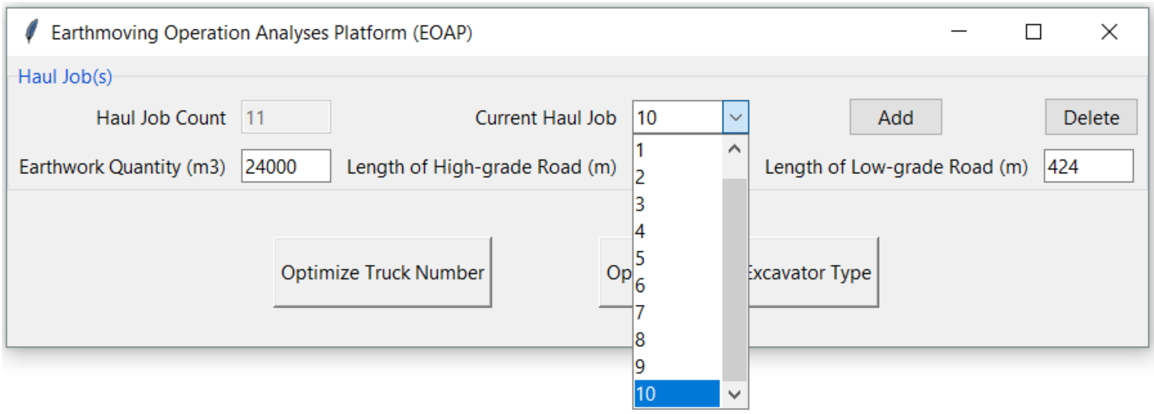


Figure 6-6: Add Multiple Haul jobs

Once haul job(s) information has been inputted, users can choose either to optimize truck number (when truck and excavator type being selected by field planner or no alternatives exist), or to optimize truck/excavator type (when truck and excavator types not determined and multiple alternatives available), by clicking either "Optimize Truck Number" button or "Optimize Truck/Excavator Type" button on the UI screen.

6.3.2 EOAP: Optimize Haul Job Truck Numbers

If users choose to optimize truck numbers, the below UI window will pop up.

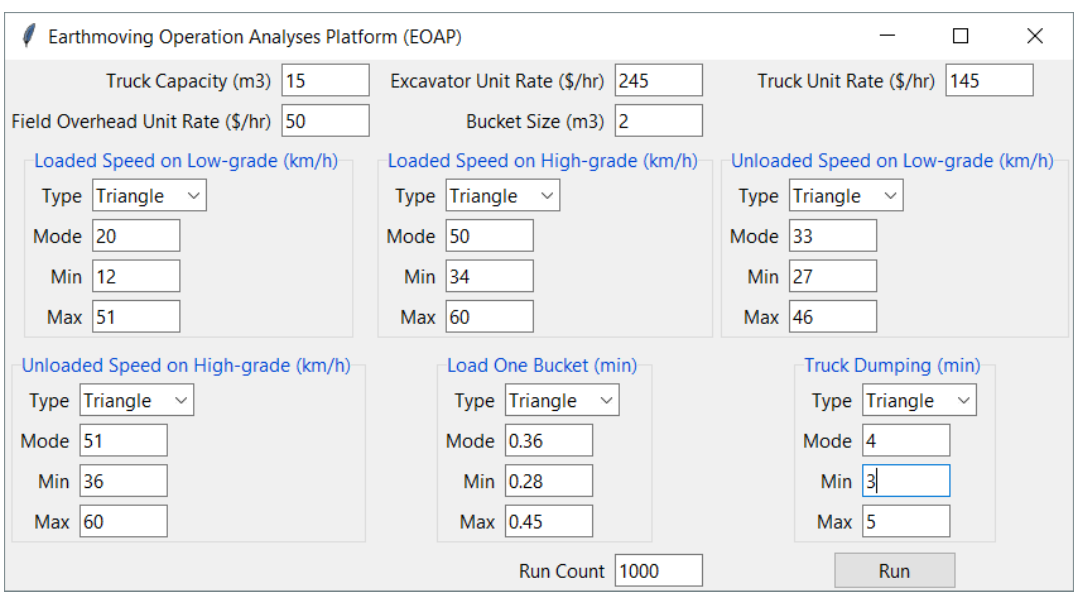


Figure 6-7: *EOAP* User Interface (truck number optimization)

Users need to input "Truck Capacity (m^3)", "Bucket Size (m^3)", "Excavator Unit Rate ($/hr)", "Truck Unit Rate ($/hr)", "Field Overhead Unit Rate ($/hr)", "Loaded Speed on Low-grade (km/h)" , "Loaded Speed on High-grade (km/h)" , "Unloaded Speed on Low-grade (km/h)", "Unloaded Speed on High-grade (km/h)", "Load One Bucket (min)", and "Truck Dumping (min)".

For truck speed and time inputs, users are allowed to input either deterministic values or distributive values by selecting "Constant" or "Distributed" from dropdown menu "Type". For distributive inputs, users are requested to input three values as "Mode", "Min", and "Max". The distribution used in *EOAP* is triangular distribution.

The last input requested is "Run Count", to specify how many run counts the users expect for the program to iterate. Theoretically, the more run counts, the more accurate the final averaged results are (if input are in distributive format). Once all the requested fields have been inputted, users can click "Run" to obtain the optimized truck numbers, duration and cost for each haul job. A sample output from *EOAP* is shown in Figure 6-8 with optimal truck numbers marked with red box.

Optimization Results

```
Simulation Result of Haul Job1:
Truck Num        Time (hr)        Cost ($)
      1            358.03         139631.75
      2            179.07         95801.59
      3            119.49         81254.94
      4             89.67         73975.71
      5             85.50         82938.66
      6             85.50         95336.70
      7             85.50         107734.75
Optimized truck number: 4, Haul job total cost: $73975.71

Total cost: 73975.71428571381
```

Figure 6-8: Optimal Truck Numbers Output (single haul job)

In the output screen, the optimized truck numbers and corresponding total cost are presented to users. The calculation process data (i.e. duration and cost for different truck number scenarios) are also provided for information. If multiple haul jobs are inputted, optimal truck number, duration and cost for each haul job will be listed, and the total operation cost by summing up all the haul job costs can be automatically outputted, as shown in Figure 6-9. This function enables to output optimized total operation cost of a project automatically. Hence, the comparison between alternative site grading design and plan solutions can be materialized with the aid of *EOAP*.

Optimization Results

```
Simulation Result of Haul Job1:
Truck Num       Time (hr)       Cost ($)
      1          358.03         139631.75
      2          179.07         95801.59
      3          119.49         81254.94
      4           89.67         73975.71
      5           85.50         82938.66
      6           85.50         95336.70
      7           85.50         107734.75
Optimized truck number: 4, Haul job total cost: $73975.71

Simulation Result of Haul Job2:
Truck Num       Time (hr)       Cost ($)
      1          164.66         64216.01
      2           82.38         44074.13
      3           55.00         37402.04
      4           49.94         41197.44
      5           49.94         48438.20
      6           49.94         55678.97
Optimized truck number: 3, Haul job total cost: $37402.04

Simulation Result of Haul Job3:
Truck Num       Time (hr)       Cost ($)
      1          401.76         156685.82
      2          200.93         107498.93
      3          134.05         91150.61
      4          113.95         94007.32
      5          113.95         110529.82
      6          113.95         127052.32
Optimized truck number: 3, Haul job total cost: $91150.61

Total cost: 202528.36396728916
```

Figure 6-9: Optimal truck numbers output (multiple haul jobs)

6.3.3 EOAP: Optimize Equipment Types

EOAP is capable to optimize truck/excavator types together with optimal truck numbers for each haul job in a holistic fashion. In *EOAP*, if users choose to optimize truck/excavator type, the below UI window will pop up. The resources pool in EOAP provides limited hydraulic excavator types and articulated truck types (as per Appendix A and Appendix B from Caterpillar Handbook). It is easy to add other equipment types (e.g. Komatsu, Volvo) if it is practically needed and performance data are available.

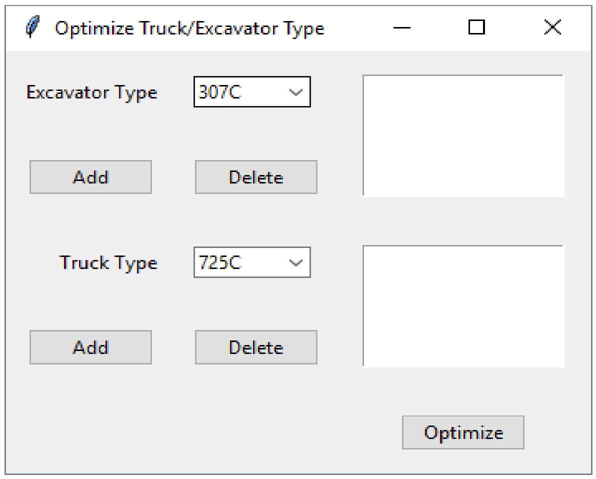


Figure 6-10: *EOAP* User Interface (truck/excavator type optimization)

The program allows users to input multiple excavator and truck alternatives. Users are also allowed to select excavator type by a dropdown menu including all the excavator types in Appendix B. Once excavator type is selected, user need to click "Add" to add the selected excavator type to the excavator pool. Users can delete excavator in the pool by selecting an excavator type in the pool then clicking "Delete". The truck type input functionalities are the same as excavator. Note, the truck and excavator performance parameters are encoded in *EOAP* according to the data in Appendix A and Appendix B. Once alternative trucks and excavators are selected and added to the pools, users click "Optimize" to result in optimal excavator/truck type, together with truck numbers of each haul job and total operation cost.

A demonstrative case is used to show the functionality of truck/excavator type selection. Two haul jobs are inputted in the main screen; Caterpillar 730C and 735C articulated trucks and Caterpillar 320D and 336D hydraulic excavators are available for selection, being inputted in *EOAP* as shown in Figure 6-11.

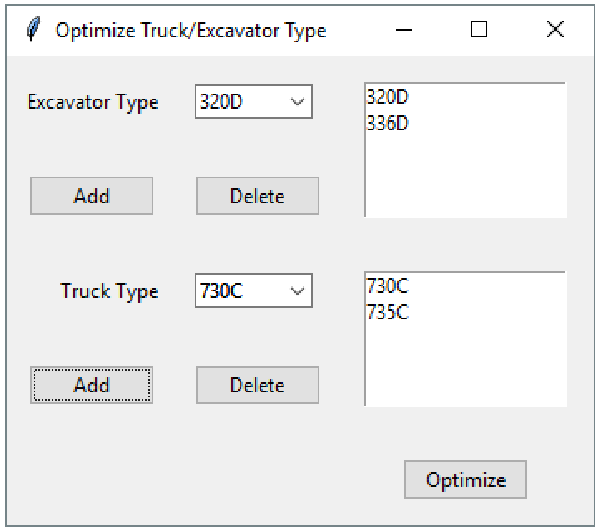


Figure 6-11: Truck/excavator alternatives input

A total of four excavator/truck permutations, i.e. 320D/730C, 320D/735C, 336D/730C, 336D/735C, were automatically generated. Operation analysis results for each excavator/truck permutation were calculated and a final result denoting the optimal excavator/truck in terms of minimum total project cost was generated, as shown in Figure 6-12. It is shown that 320D/735C is the least-cost excavator/truck combination compared to the other three combinations. At haul job level, duration, haul job operation cost and optimal truck number are presented in the outputs.

```
Excavator: 320D, Truck: 730C
===============================

Simulation Result of Haul Job1:
Truck Num        Time (hr)        Cost ($)
       1           436.88         117957.94
       2           219.39         76786.82
       3           172.30         74089.69
       4           172.32         87881.98
       5           172.28         101645.97
Optimized truck number: 3, Haul job total cost: $74089.69

Simulation Result of Haul Job2:
Truck Num        Time (hr)        Cost ($)
       1           170.12         45932.17
       2            85.41         29893.20
       3            71.85         30893.82
       4            71.87         36651.77
       5            71.87         42405.91
Optimized truck number: 2, Haul job total cost: $29893.20
```

```
Excavator: 320D, Truck: 735C
===============================

Simulation Result of Haul Job1:
Truck Num        Time (hr)        Cost ($)
       1           410.24         112815.40
       2           206.84         74462.37
       3           170.72         75969.85
       4           170.68         90462.31
       5           170.67         104963.57
Optimized truck number: 2, Haul job total cost: $74462.37

Simulation Result of Haul Job2:
Truck Num        Time (hr)        Cost ($)
       1           159.81         43947.53
       2            80.76         29073.03
       3            71.19         31679.54
       4            71.24         37755.90
       5            71.20         43786.88
Optimized truck number: 2, Haul job total cost: $29073.03
```

```
Excavator: 336D, Truck: 730C
===============================

Simulation Result of Haul Job1:
Truck Num        Time (hr)        Cost ($)
       1           549.04         178437.33
       2           284.75         115322.04
       3           284.28         137878.19
       4           284.25         160602.84
       5           284.20         183311.52
Optimized truck number: 2, Haul job total cost: $115322.04

Simulation Result of Haul Job2:
Truck Num        Time (hr)        Cost ($)
       1           216.75         70444.68
       2           118.49         47989.58
       3           118.51         57476.48
       4           118.50         66950.79
Optimized truck number: 2, Haul job total cost: $47989.58
```

```
Excavator: 336D, Truck: 735C
================================

Simulation Result of Haul Job1:
Truck Num        Time (hr)        Cost ($)
       1           520.75         171847.31
       2           281.27         116727.51
       3           281.08         140539.29
       4           281.16         164476.36
       5           281.16         188377.50
Optimized truck number: 2, Haul job total cost: $116727.51

Simulation Result of Haul Job2:
Truck Num        Time (hr)        Cost ($)
       1           205.87         67937.83
       2           117.20         48636.76
       3           117.17         58587.36
       4           117.21         68565.14
Optimized truck number: 2, Haul job total cost: $48636.76
```

```
Simulation Result:
        Best excavator: 320D
        Best truck:     735C
        Total cost:     $103535.40
```

Figure 6-12: Optimal excavator/truck combination output

Chapter 7. PRACTICAL APPLICATION

This chapter presented the implementation of the proposed methodology on a real world site grading project. First, with project data being inputted, the program automatically generated optimum temporary haul road layout design and earthmoving operation plans. Then, sensitivity analysis was applied to eight critical input parameters of optimization model to generate stability regions. The optimized solution in terms of temporary haul road layout design and earthmoving operation plans was compared with alternative solutions collected from site manager, field engineers, and graduate students majored in civil engineering. It is concluded that the proposed analytics could assist in delivering cost-effective temporary haul road layout design and earthmoving operation plan.

7.1. Project Background

7.1.1 Site Layout

A real-world site grading project was chosen as test-bed case to illustrate and verify the proposed approaches in optimizing both temporary haul road layout design and earthmoving operation plans. The site grading project is the preliminary work package of a camp site construction in Fort McMurray, Alberta, Canada. The site was around 120 hectares and the site layout of the camp site project is shown in Figure 7-1. Two drainage ponds whose sides were gently sloped were engineered and constructed prior to site grading operations to capture storm water runoff during heavy rainfalls and prevent potential water hazard on construction activities. There was only one site access at west end of the site. A spoil area was located one kilometer north of the site access, to not only allow the piling of construction waste, the extra soil was also planned to be dumped in this area. The offsite road was built gravel-surfaced.

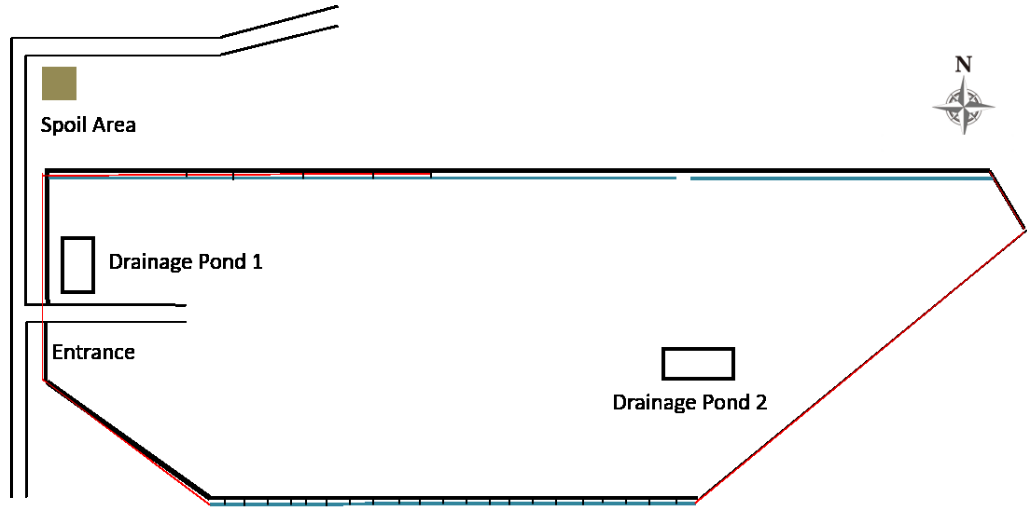


Figure 7-1: Site layout

7.1.2 Cut and Fill Design

According to the site grading design (from client) and site survey results (from survey consultant), it was calculated that the project has around 335,600 m^3 of earth required to be balanced through cut and fill, as shown in Figure 7-2. A cut-fill table illustrating the denotation of colors and corresponding earthwork volumes was provided at the right bottom corner of Figure 6-2. The rough ground (0-2m depth top soil) in the field was mainly composed of sand and glacial till. According to the proposed grid model for site modelling, a total of 48 grids sized at 150 m by 150 m were divided with earth volumes specified for each grid in bank cubic meters (bcm^3), as shown in Figure 7-3. The cut volume is denoted with "-" while fill volumes in "+". Note, the cut and fill was not balanced within the site and an extra of 20,000 m^3 of earth needed to be dumped to the offsite spoil area.

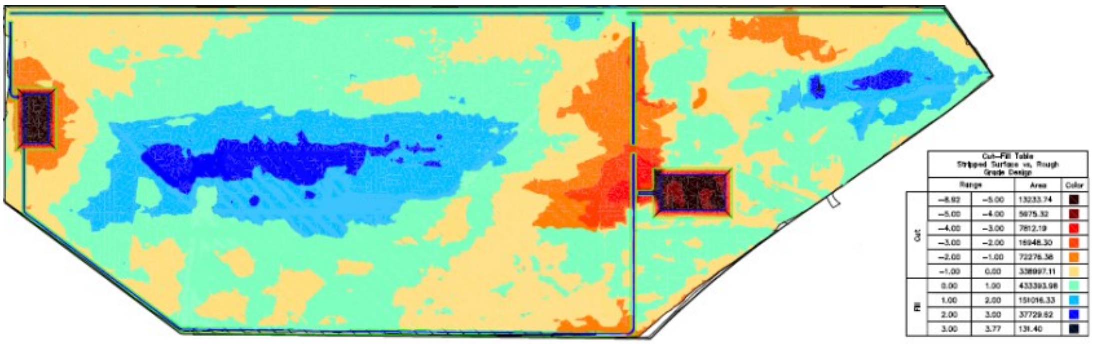


Figure 7-2: Designed cut and fill Areas

Cell 1 -15000	Cell 2 -3700	Cell 3 +3700	Cell 4 +9000	Cell 5 +9000	Cell 6 +8000	Cell 7 -1000	Cell 8 -11200	Cell 9 -2300	Cell 10 -22000	Cell 11 -6900	Cell 12 +11200
Cell 13 -62600	Cell 14 +22500	Cell 15 +23800	Cell 16 +26000	Cell 17 +23000	Cell 18 +22200	Cell 19 +8100	Cell 20 -24800	Cell 21 -9900	Cell 22 -2200	Cell 23 +14300	Cell 24 +7900
Cell 25 -3700	Cell 26 +22500	Cell 27 +28100	Cell 28 +23000	Cell 29 +24300	Cell 30 +14200	Cell 31 -12400	Cell 32 -34400	Cell 33 -72500	Cell 34 -28500	Cell 35 -2500	Cell 36 0
Cell 37 0	Cell 38 1400	Cell 39 +2300	Cell 40 +1200	Cell 41 +9000	Cell 42 -5900	Cell 43 -9900	Cell 44 -2700	Cell 45 +2300	Cell 46 -100	Cell 47 0	Cell 48 0

Figure 7-3: Designed cut and fill volumes onsite

7.1.3 Site Representation by Network Flow Model

The "rough ground" haul road in the current case would lead to slower hauling speed, higher maintenance cost and potential safety hazard. To ensure operations safety and control project cost, the contract stipulated that temporary haul roads be constructed at the cost of the contractor.

Based on flow network model, the site grid model is further represented by a list of nodes, with edges connecting adjacent nodes horizontally, vertically and diagonally, as shown in Figure 7-4. A dummy node (node 49) was used to represent the spoil area with a demand valued at 20,000 m^3. The dummy node is programmed to be 1,000m to the entrance node (node 13) while high grade temporary haul road is constructed between the node 13 and node 49 ($x_{13,49} = 1$).

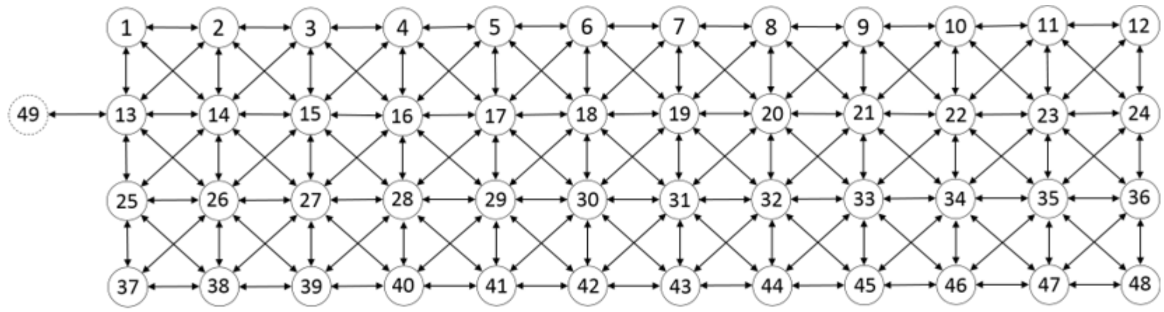


Figure 7-4: Base network flow model

On top of the base network flow model, accessibility related site constraints were further added. The dry pond areas (area A and area B) do not allow truck passing once site grading is finished. Therefore, edge (25,26) and edge (34,35) are modified to be unilateral, together with all the other edges connecting to node 25 and node 35 being removed.

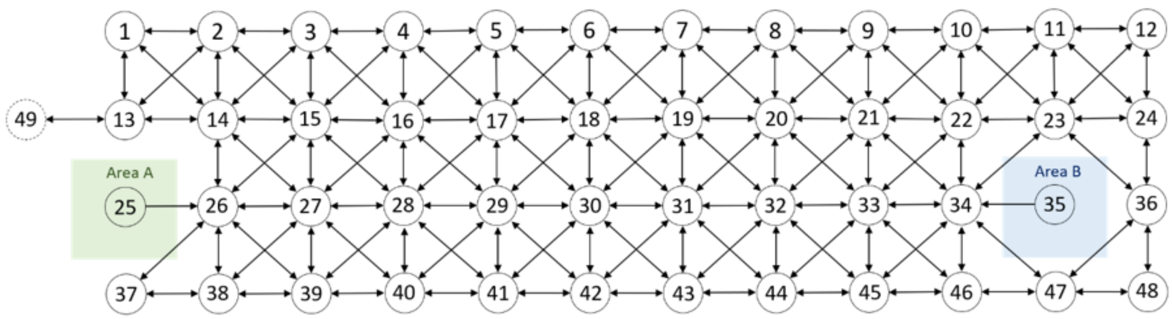


Figure 7-5: Upgraded network flow model based on accessibility related site constraints

7.1.4 Input Data

The data relevant to the mathematical programming model formulations were evaluated based on field data and empirical data with the help of the project manager of the contract company. The construction plus removal cost of gravel-surfaced temporary haul road was \$17500/km; the maintenance costs for gravel-surfaced temporary haul road and rough ground temporary haul road was \$600/km and \$150/km, respectively; the threshold earthwork quantity for maintenance on rough ground haul road was 5000 m^3; the threshold earthwork quantity for maintenance on gravel-surfaced haul road was 15000 m^3. Caterpillar 735 articulated trucks were selected as haulers for this project. The mean truck-haul speed on gravel-surfaced haul road was 36 km/h;

the mean haul speed on rough ground haul road was 24 km/h; the truck volume capacity was 15 m^3; Caterpillar 336D excavator was selected. The mean excavator travel speed on gravel-surfaced haul road was 15 km/h; the mean excavator travel speed on rough ground haul road was 10 km/h; the hourly rate for all the earthmoving crew was $5000/h (including articulated trucks, excavator, crew trucks, water trucks, rollers, highway tractor and trailer, equipment operators and drivers, field supervisor, QA/QC, field engineers, surveyor, spotter, and etc.); the hourly rate for field overhead (including advertising, insurance, labor burden, rent, repairs, supplies, telephone bills, travel expenditures, utilities, and etc.) was $200/h; the operation efficiency factor was 0.75; 3 trucks of the same type made up the fleet.

The data relevant to operation analysis were from Caterpillar Handbook (2017) in Appendix A and Appendix B. The hourly rate for CAT 735C articulated truck plus driver was $120/hr; the hourly rate for CAT 336D hydraulic excavator plus operator was $245/hr; the hourly rate for truck/excavator related field overhead was $50/hr.

7.2. Optimization Application and Outputs

The mathematical programming formulations and algorithms for optimizing (1) temporary haul road layout; and (2) earthmoving operation plans were coded in *Python* Version 3.5 with a Python module integrated with *CPLEX* Version 12.61. The computer platform used in running the optimization code had the following configurations: Intel Core i7-5500U CPU, up to 3.00 GHz; Memory: 8.0 GB; System type: 64-bit Operating System.

7.2.1 Temporary Haul Road Layout Design

By running the C-MILP optimization algorithms, a total of 63 solutions (62 intermediate results plus 1 the final result) were generated automatically by computer. The program terminated when both accessibility and connectivity of temporary haul road design were achieved. Design layouts for all 63 solutions are shown in Appendix D.

The resulting temporary haul road layout design is shown in Figure 7-6. The high grade temporary haul road is denoted by solid black line. The high-grade temporary haul road network smoothly connected to the entrance; on the other hand, the as-designed alignment of temporary haul road in the field consists of two parallel straight-line sections, interconnected by a road link in the middle.

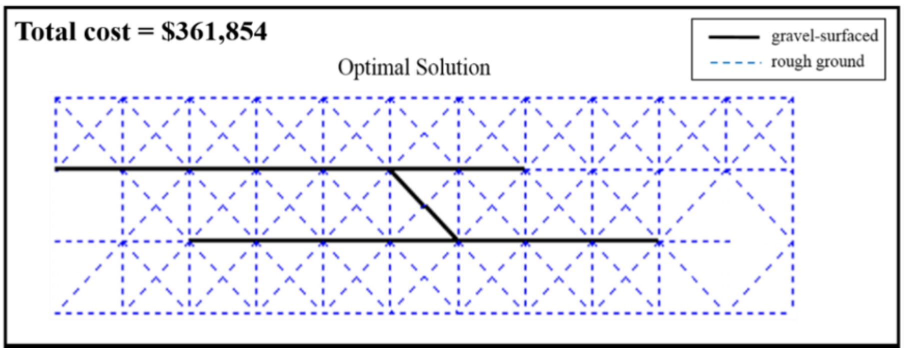
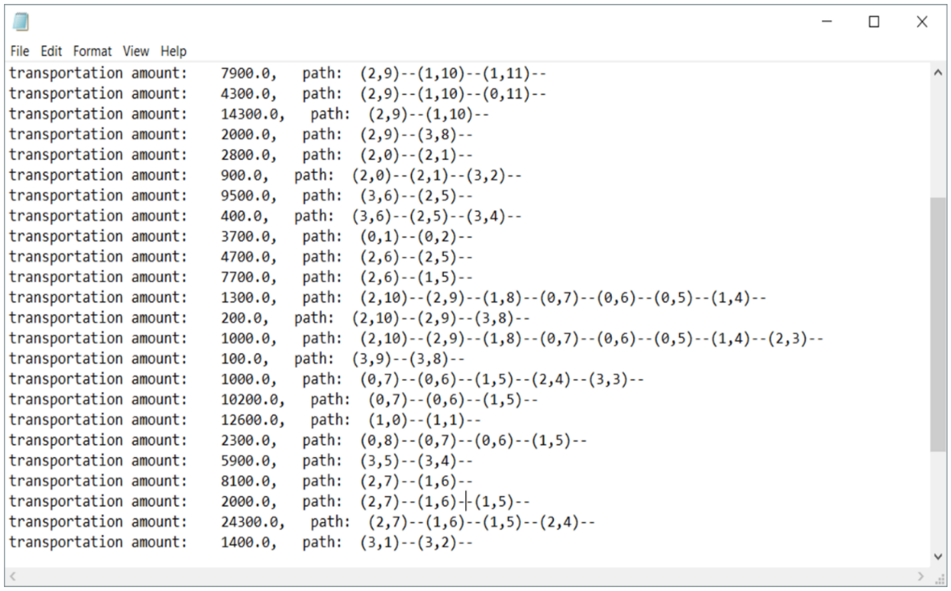


Figure 7-6: Optimized temporary haul road layout design

7.2.2 Earthmoving Operation Plan

As introduced in previous chapter, the proposed analytics are capable of outputting all the haul jobs in terms of source, destination, haul path, and earth volume. A sample software output screen is shown in Figure 7-7. The two numbers in the bracket is the coordinate of a node, with top left node in the flow network model being (0,0) in program. As an example, node (2, 9) in program denotes node 34 in flow network model.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```
transportation amount:    7900.0,   path:  (2,9)--(1,10)--(1,11)--
transportation amount:    4300.0,   path:  (2,9)--(1,10)--(0,11)--
transportation amount:    14300.0,   path:  (2,9)--(1,10)--
transportation amount:    2000.0,   path:  (2,9)--(3,8)--
transportation amount:    2800.0,   path:  (2,0)--(2,1)--
transportation amount:    900.0,   path:  (2,0)--(2,1)--(3,2)--
transportation amount:    9500.0,   path:  (3,6)--(2,5)--
transportation amount:    400.0,   path:  (3,6)--(2,5)--(3,4)--
transportation amount:    3700.0,   path:  (0,1)--(0,2)--
transportation amount:    4700.0,   path:  (2,6)--(2,5)--
transportation amount:    7700.0,   path:  (2,6)--(1,5)--
transportation amount:    1300.0,   path:  (2,10)--(2,9)--(1,8)--(0,7)--(0,6)--(0,5)--(1,4)--
transportation amount:    200.0,   path:  (2,10)--(2,9)--(3,8)--
transportation amount:    1000.0,   path:  (2,10)--(2,9)--(1,8)--(0,7)--(0,6)--(0,5)--(1,4)--(2,3)--
transportation amount:    100.0,   path:  (3,9)--(3,8)--
transportation amount:    1000.0,   path:  (0,7)--(0,6)--(1,5)--(2,4)--(3,3)--
transportation amount:    10200.0,   path:  (0,7)--(0,6)--(1,5)--
transportation amount:    12600.0,   path:  (1,0)--(1,1)--
transportation amount:    2300.0,   path:  (0,8)--(0,7)--(0,6)--(1,5)--
transportation amount:    5900.0,   path:  (3,5)--(3,4)--
transportation amount:    8100.0,   path:  (2,7)--(1,6)--
transportation amount:    2000.0,   path:  (2,7)--(1,6)--(1,5)--
transportation amount:    24300.0,   path:  (2,7)--(1,6)--(1,5)--(2,4)--
transportation amount:    1400.0,   path:  (3,1)--(3,2)--
```

Figure 7-7: Optimized earthmoving operation plan

The haul job information derived from analytics are further summarized in Table 7-1. The haul job in terms of source, destination, haul path, and earth volume are presented in the table.

Table 7-1: Optimized haul jobs

Job No.	Volume (Bm3)	Haul Path	Haul Distance (m)	
			d_{gravel}	d_{rough}
1	20000	13-49	1000	0
2	15400	13-14-27	150	212
3	19700	13-14-26	150	150
4	7500	13-14	150	0
5	15000	1-14	0	212
6	3700	2-3	0	150
7	1000	7-6	0	150
8	4200	8-19-18-17-16-27	450	424
9	7000	8-7-6	0	300
10	2300	9-8-19-18-17-16-27	450	574
11	7900	10-11-24	0	362
12	4300	10-11-12	0	300
13	9800	10-23	0	212
14	6900	11-12	0	150
15	2200	22-23	0	150
16	2500	35-34-33-32-31-18-17-16	962	150
17	15100	34-33-32-31-18-17-16-15	1112	0
18	8900	34-33-32-31-18-5	662	212
19	2300	34-23	0	212
20	2200	34-45	0	212
21	100	46-45	0	150

22	3500	33-32-31-18-17-16-27	812	212
23	9000	33-32-31-18-17-4	662	212
24	6800	33-32-31-18-17-16	812	0
25	100	33-32-31-18-5	512	212
26	3100	33-32-31-30-41	450	212
27	23000	33-32-31-18-17	662	0
28	4800	33-32-31-30-29	600	0
29	22200	33-32-31-18	512	0
30	8700	21-32-31-18-17-16-15	812	212
31	1200	21-32-31-30-29-40	450	424
32	16700	20-19-18-17-16	600	0
33	8100	20-19	150	0
34	12400	31-30-29	300	0
35	20200	32-31-30-29-28	600	0
36	14200	32-31-30	300	0
37	2700	44-31-18-17-16-27	512	424
38	2800	43-30-29-28	300	212
39	7100	43-30-29	150	212
40	5900	42-41	0	150
41	1400	38-39	0	150
42	900	25-26-39	0	362
43	2800	25-26	0	150

7.3. Sensitivity Analysis Application and Outputs

7.3.1 Parameter Stability Region

The proposed one-dimensional line search method is applied to determine the stability regions of the input parameters. In particular, for every selected parameter X_t in $(\sigma_2, \alpha, \beta, TH_1, TH_2, n, c)$, step length Δl and tolerance t are specified at the beginning. Next, the parameter sensitivity model is established by iteratively searching for the optimum solution to the MILP formulation until the optimum solution changes. Once change is observed, input parameter value and step length are updated prior to further search. If the updated step length Δl is greater than the tolerance value, program starts a new iteration with updated input parameter value and step length to further approach the boundaries of the stability region. Otherwise, if the updated step length Δl is smaller than the tolerance value, program terminates and the latest updated input parameter value is fixed as the lower or upper bound of the stability region.

The search for the stability region in all the eight parameters is performed automatically by computer programming. The computational time for outputting the stability region of one parameter is around six hours in total, with an average of three hours to calculate one bound. The input parameters' stability regions are summarized in Table 7-2.

Table 7-2: Parameter stability region

Parameter	Unit of Measure	Lower Bound	Total Cost Optimized ($)	Upper Bound	Total Cost Optimized ($)
σ_1	$/km	155	357842	1390	363483
σ_2	$/km	78	362584	1070	382450
α	$/hour	4598	332154	5309	391246
β	$/km	14670	359857	19250	382685
TH_1	m^3	14316	361548	18709	369426
TH_2	m^3	2846	365549	7009	367854
n	-	3	379902	4	301584
c	m^3	14.69	378425	16.96	315879

7.3.3 Numerical Investigation

To prove the effectiveness of the proposed one-dimensional line search method in determining the parameter stability region, a numerical experiment is performed by evaluating a total of fifty-six investigation scenarios. For each parameter, two experiments are designed, namely: (1) a total of five parameter values within respective stability regions are randomly generated for assessing whether the optimum solution remains unchanged; (2) two arbitrarily selected "outlier" parameter values outside of the stability region (one slightly greater than upper bound, one slightly lesser than lower bound) are used for assessing whether the optimum solution is changed. Hence, a total of seven input settings are designed and each setting is assessed independently by applying the MILP algorithms to solve the rough grading problem.

As an example, the stability region of parameter σ_1(the per km haul road maintenance cost for rough ground in $/km) is [155,1390] as per Table 7-3. Five parameter values were randomly generated within the stability region as 315, 547, 864, 1002, and 1235. The MILP model was solved five times by changing the value of σ_1 while holding all other parameter constant at their nominal values. The generated optimum haul road layout solutions keep unchanged as given in Figure 7-6. A sample output when σ_1 is at 547 \$/km is shown in Figure 7-8. Though the objective function (total earthmoving cost) slightly drops (<1%) because σ_1 decreases from 1200 \$/km (nominal value) to 547 \$/km, the optimum haul road layout solution remains the same as shown in Fig 7-6.

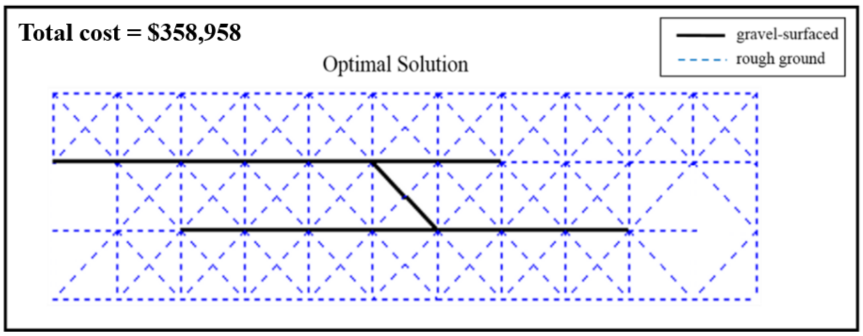


Figure 7-8: Optimum output when σ_1 at 547 \$/km: total cost lowered marginally; the haul road network remains

A parameter value slightly smaller than the lower bound (σ_1 = 154 \$/km) and a parameter value slightly greater than the upper bound (σ_1 = 1391 \$/km) were evaluated, respectively. The outputs from MILP are shown in Figure 7-9 and Figure 7-10. It is clearly evidenced that the optimum solutions have changed once the parameter value is out of the stability region.

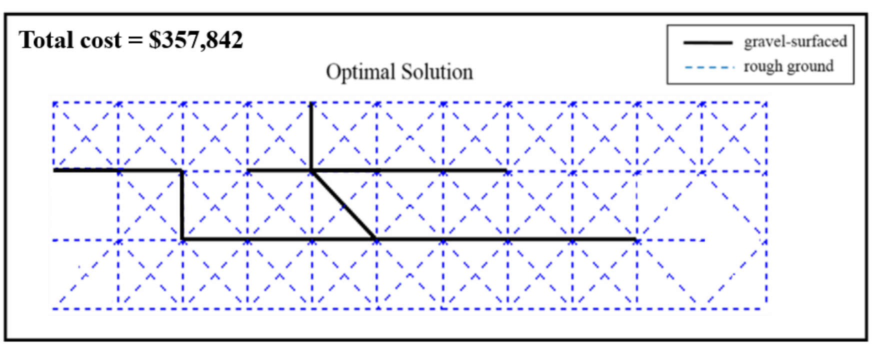


Figure 7-9: Optimum output when σ_1 at 154 \$/km: total cost lowered; the road network changed

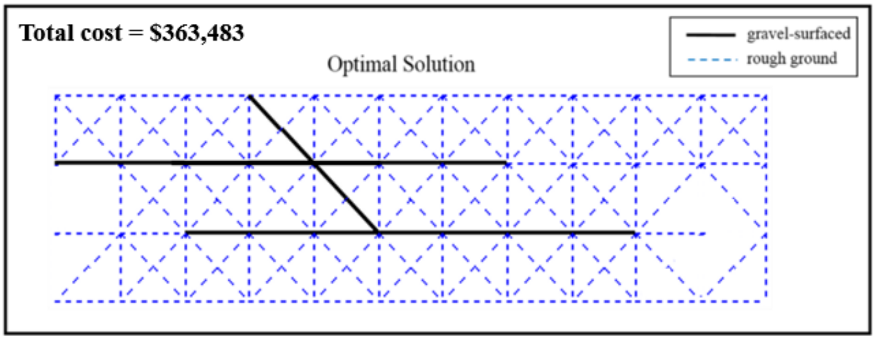
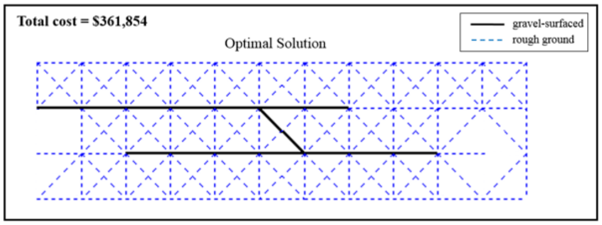


Figure 7-10: Optimum output when σ_1 at 1391 \$/km: total cost increased; the haul road network changed

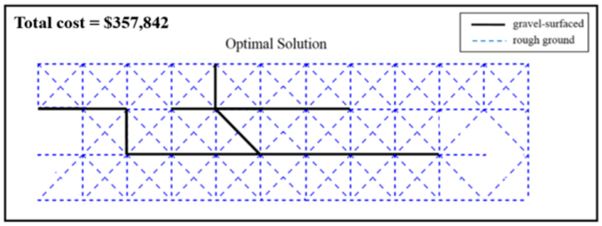
The experiment for all the eight input parameters is presented in three parts. Part I gives the parameter settings in the original optimum solution as in Table 7-3; Part II presents alternative layout variations pertaining in the experiment, as shown in Figure 7-11. Note Layout 0 is the optimum solution for the haul road layout as in the original MILP solution. Part III summarizes the investigation findings as given in Table 7-4.

Table 7-3: Parameter Settings for Designing Stability Region Validation Scenarios

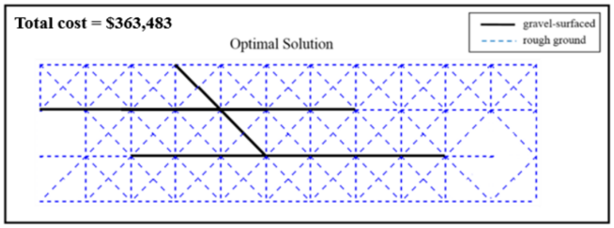
Setting ID	Parameter in focus	Unit of Measure	Nominal Value	Stability Region
1	σ_1	$/km	1200	[155,1390]
2	σ_2	$/km	500	[78,1070]
3	α	$/hour	5200	[4598,5309]
4	β	$/km	17500	[14670,19250]
5	TH_1	m^3	5000	[14316,18709]
6	TH_2	m^3	15000	[2846,7009]
7	n	-	3	[3,4]
8	c	m^3	15	[14.69,16.96]



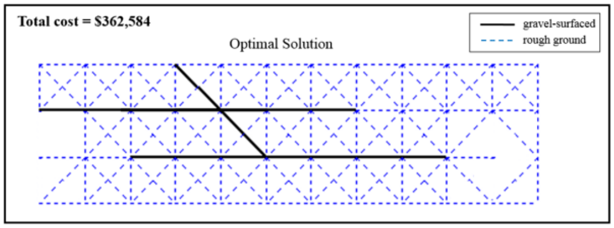
Layout 0



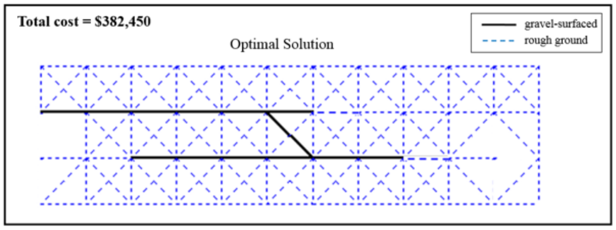
Layout 1



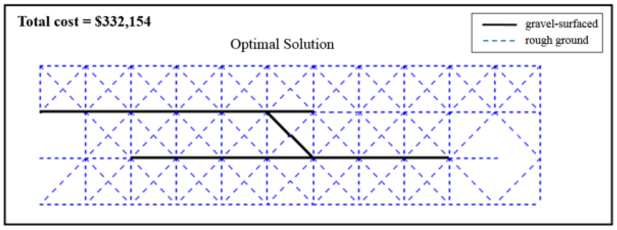
Layout 2



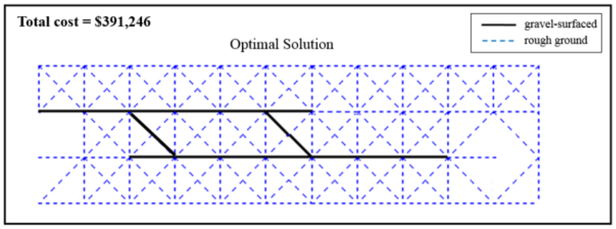
Layout 3



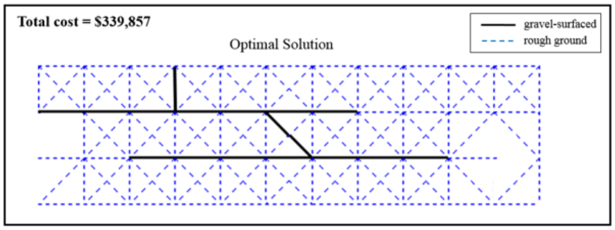
Layout 4



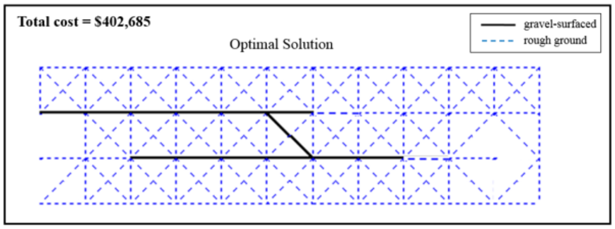
Layout 5



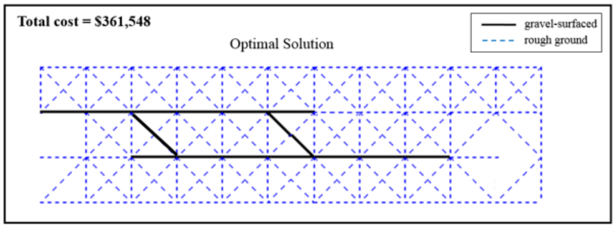
Layout 6



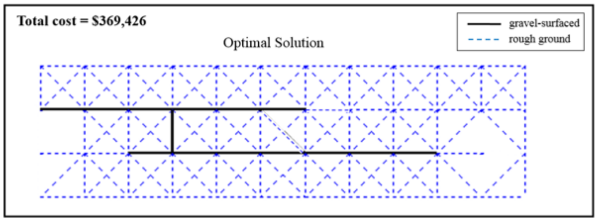
Layout 7



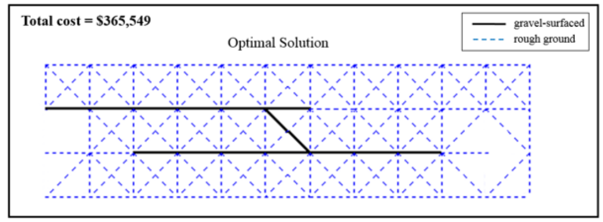
Layout 8



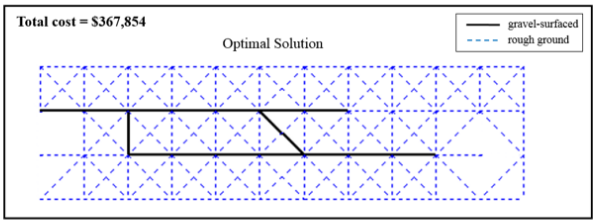
Layout 9



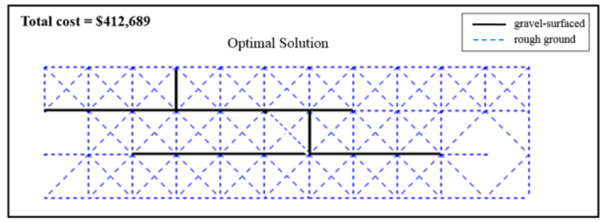
Layout 10



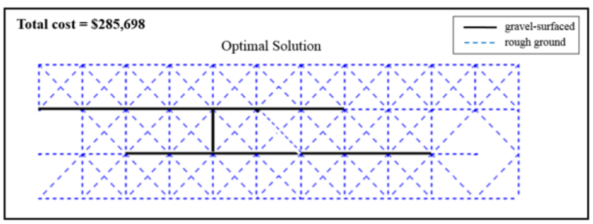
Layout 11



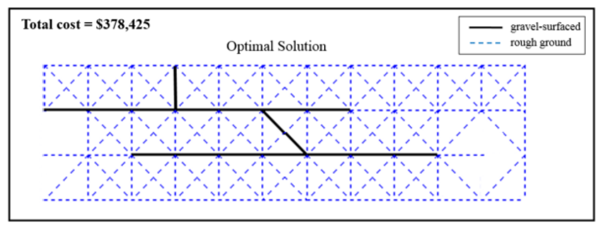
Layout 12



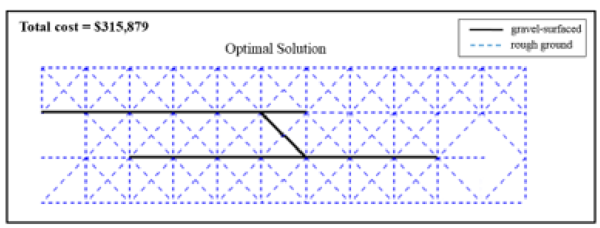
Layout 13



Layout 14



Layout 15



Layout 16

Figure 7-11: Haul road layout alternatives resulting from MILP optimization in various investigative scenarios

Table 7-4: Summary of fifty-six investigation scenarios along with updated MILP optimization results

Investigation ID	Parameter Setting ID	Adjusted Value One At a Time	Optimized Gravel Road Layout ID	Optimum Solution for Gravel Road Length (m)	Total Cost Optimized ($)
1	1	154	1	2162	357842
2		315	0	2312	358219
3		547			358958
4		864			359326
5		1002			360328

6		1235			362536
7		1391	2	2524	363483
8		77	3	2524	362584
9		213			359684
10		456			361384
11	2	627	0	2312	362846
12		748			363902
13		904			365239
14		1071	4	2012	382450
15		4597	5	2162	332154
16		4694			325896
17		4920			348265
18	3	5038	0	2312	354824
19		5210			361458
20		5298			395156
21		5310	6	2374	391246
22		14660	7	2462	339857
23		15746			358648
24		16493			359526
25	4	17500	0	2312	361854
26		18128			363012
27		19032			385649
28		19260	8	2012	402685
29		14315	9	2374	361548
30		15326			358365
31		16524			357458
32	5	16987	0	2312	357158
33		17548			356782
34		18026			356318
35		18710	10	2100	369426
36		2845	11	2162	365549
37		3025			363587
38		3958			360458
39	6	4587	0	2312	359318
40		5698			356685
41		6325			354328
42		7010	12	2462	367854
43		2	13	2400	412689
44		3.2			356895
45		3.4			346985
46	7	3.5	0	2312	336859
47		3.7			326598
48		3.9			315879
49		5	14	2250	285698
50		14.68	15	2462	378425
51		15.03			360268
52		15.24			352687
53	8	15.68	0	2312	342615
54		16.32			332684
55		16.82			321659
56		16.97	16	2162	315879

It is observed from the experiment that the optimum solution in terms of the haul road layout design remains unchanged for those scenarios in which parameter values are altered within the identified stability regions; the updated total cost stays lower than the original value in the base case (i.e. $361,854). This implies the optimum solutions derived in the base case scenario are still valid despite the changes to the input parameters. In contrast, the optimum haul road layout design has significantly changed and the total cost value increased for those scenarios in which parameter values are outside of the identified stability regions. Hence, it is proven that the identified stability region for the MILP model by applying the proposed one-dimensional line search method is valid.

7.3.3 Results Discussion

To cross validate the results against the common wisdom and guide the practitioners in making the most informed decisions, the patterns of variation in optimum solutions in regards to individual parameters (such as unit cost for constructing and maintaining haul road, the volume capacity of truck, the number of truck) are further discussed based on results of selected investigation scenarios, as follows:

Investigation ID:7; Parameter Setting ID: 1, Layout ID:2

If the unit maintenance cost on rough ground σ_1 ($/km) increases (e.g. rise of labour and equipment cost), the cost associated with operating on rough ground haul road increases accordingly, which justifies the construction of more gravel-surfaced haul road. As shown in Table 7-4, given Investigation ID 7, when unit maintenance cost on rough ground increases over $1390/km, the optimum haul road layout changes with an additional 212 meters of gravel-surfaced haul road constructed.

Investigation ID:1; Parameter Setting ID: 1, Layout ID:1

On the contrary, when the unit maintenance cost on rough ground decreases, the cost associated with operating on rough ground haul road is reduced, hindering construction of more gravel-surfaced haul roads. The total length of gravel-surfaced haul road reduces to 2162 meters once unit maintenance cost on rough ground is below \$154/km.

Investigation ID:14; Parameter Setting ID: 2, Layout ID:4

As opposed to unit maintenance cost on rough ground, if the unit maintenance cost on gravel-surfaced haul road σ_2 (\$/km) increases, it would be less cost-effective to construct gravel-surfaced haul road. As shown in Table 7-4, given Investigation ID 14, when unit maintenance cost on gravel-surfaced haul road increases over \$1071/km, the total length of gravel-surfaced haul road reduces by 300 meters.

Investigation ID:8; Parameter Setting ID: 2, Layout ID:3

On the contrary, when the unit maintenance cost on gravel-surfaced haul road decreases below \$77/km, it is justifiable to construct 212 meters more gravel-surfaced haul road as per Table 7-4.

Investigation ID:21; Parameter Setting ID: 3, Layout ID:6

In practice, it is likely that the sum of hourly rates of the hauling crew α (\$/hour) increases due to significant increase in fuel price and labour shortage. In this scenario, the savings on operation with regards to the construction of gravel-surfaced haul road increases accordingly. This justifies the construction of more gravel-surfaced haul roads. As shown in Table 7-4, in Investigation ID 21, when α rises over \$5309/hour, 62 meters more gravel-surfaced haul roads are built.

Investigation ID:15; Parameter Setting ID: 3, Layout ID:5

By contrast, in Investigation ID 15, when α decreases below \$4597/hour (e.g. economic depression or less competitive market environment), the total length of gravel-surfaced haul road reduces to 2162 meters since less saving can be made to compensate for haul road construction and removal cost.

Investigation ID:28; Parameter Setting ID: 4, Layout ID:8

In practice, the road construction and removal cost β (\$/km) may increase due to the increase in raw material cost, high shipping cost, or a new environmental bylaw (e.g. imposition of carbon tax). This would directly undermine the benefit of constructing more gravel-surface haul road. As a result, in Investigation ID 28, when the road construction and removal cost increases over \$19250/km, 300 meters of gravel-surfaced haul roads are reduced.

Investigation ID:22; Parameter Setting ID: 4, Layout ID:7

On the contrary, if the road construction and removal cost decreases, the construction of more gravel-surfaced haul road is justified. As demonstrated in Table 7-4, in Investigation ID 22, when the road construction and removal cost decreases under \$14660/km, 150 meters more of gravel-surfaced haul roads are added.

Investigation ID:29,36; Parameter Setting ID: 5,6 Layout ID:9,11

In situations such as inclement weather or poor soil condition in roadbed, more frequent maintenance is required for both rough ground haul road and gravel-surfaced haul road, thereby decreasing the maintenance threshold on rough ground TH_1 (m3) as well as the maintenance threshold on gravel-surfaced haul road TH_2 (m3). Similar to the change patterns of unit maintenance costs, for rough ground haul road, more frequent maintenance requirement increases maintenance cost, thus justifying building more gravel-surfaced haul road; while for gravel surfaced haul road, the more frequent maintenance requirement impedes the construction of gravel-surfaced haul road. As reflected in Table 7-4, 62 meters more of gravel-surfaced haul road and 150 meters less of gravel-surfaced haul road are suggested as per optimization results once TH_1 and TH_2 decreases below the lower bound of the stability region, respectively.

Investigation ID:35,42; Parameter Setting ID: 5,6, Layout ID:10,12

Conversely, when less frequent maintenance is required for both rough ground haul road and gravel-surfaced haul road (e.g. road becomes stiff in winter and is less likely to be rutted or potholed), 212 meters less of gravel-surfaced haul road and 150 meters more of gravel-surfaced haul road are suggested as per optimization results in Table 7-4 once TH_1 and TH_2 increases beyond the upper bound of the stability region, respectively.

Investigation ID:43; Parameter Setting ID: 7, Layout ID:13

When fewer than the planned number of trucks are available for execution due to inadequate equipment allocation, longer total project duration is expected. In this regards, higher hauling efficiency is needed in order to expedite the project towards the objective of lowering total earthmoving cost. This justifies the construction of more gravel-surfaced haul road. As presented in Table 7-4, in Investigation ID 43, when truck number n drops to two, 88 meters of more gravel-surfaced haul road is added.

Investigation ID:49; Parameter Setting ID: 7, Layout ID:14

On the contrary, when extra truck(s) are added, project is likely to be completed within a shorter timeframe. The savings from building gravel-surfaced haul road will be reduced, thus less gravel-surfaced haul road is needed. This is demonstrated as per results in Table 7-4, in Investigation ID 49, 62 meters less of gravel-surfaced haul road is added when five trucks are utilized, compared to the original optimum solution which employs 4 trucks.

Investigation ID:56; Parameter Setting ID: 8, Layout ID:16

It is not uncommon that the site manager changes the truck type prior to execution due to resource availability constraint or other practical concerns (e.g. unique site condition that requires larger or smaller rimpull). On one hand, if truck with larger volume capacity c (m3) is chosen, fewer number of truck loads would be required, undermining the advantage of building gravel-surfaced haul road in terms of saving truck hauling time. As per Table 7-4, in Investigation ID 56, the total lengths of gravel-surfaced haul road decreases to 2162 meters (against 2312 meters) when truck capacity exceeds 16.96 m3.

Investigation ID:50; Parameter Setting ID: 8, Layout ID:15

On the other hand, if truck with smaller volume capacity is chosen, more total number of truck loads would be required, thus justifying the construction of more gravel-surfaced haul road to potentially reduce truck hauling time. This is adequately reflected in the results in Table 7-4. In Investigation ID 50, once truck capacity decreases under 14.69 m3, a 150 meters more gravel-surfaced haul road is added through optimization.

Having analysed above, it is concluded that if a parameter value falls out of its stability region, the optimum solution will change by following a certain logic pattern that is compatible with the common wisdom in the problem domain. It is pointed out, all the results and analysis in the current paper are based on the assumption that only one parameter value will change each time and the possible combined variability on all input parameters is not considered. If multiple parameter values are changed it is suggested that practitioners apply the optimization tool to analyse case by case, scenario by scenario in order to guide decision makings. In short, this case study is conducive to illustrating how the proposed approach can be effectively used to fix the stability region of a MILP parameter. Planners are suggested to take full advantage of the resulting information and the insight gained from the parameter stability regions in connection with implementing the MILP suggested optimum solution.

7.4. Solution Evaluation

In order to validate the optimality of the computer-generated solution, it was benchmarked with layout design alternatives and earthmoving plan alternatives collected from site manager, field engineers, and graduate students majored in civil engineering. The anonymized providers of alternative temporary haul road layout designs or earthmoving operation plans were acknowledged in the thesis.

7.4.1 Optimized Haul Road Design vs. Empirical Haul Road Design

Facilitated by the site manager, comparison was made for four layout options (include the optimized layout) with varied total length and design configuration of gravel-surfaced haul roads, as demonstrated in Figure 7-12, Figure 7-13, and Figure 7-14. The alternative layout options were empirically designed by field engineers.

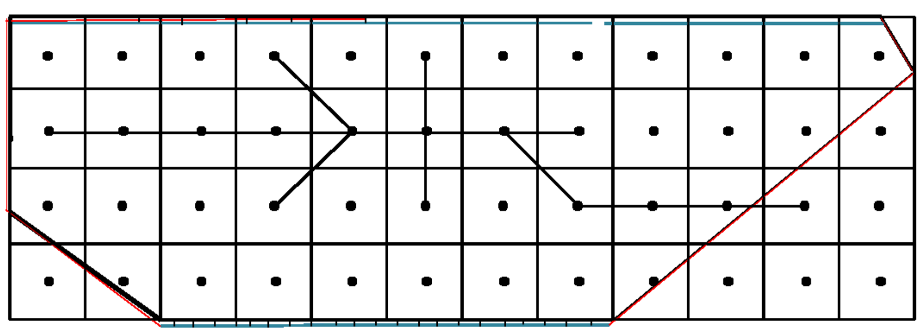


Figure 7-12: Layout option 1

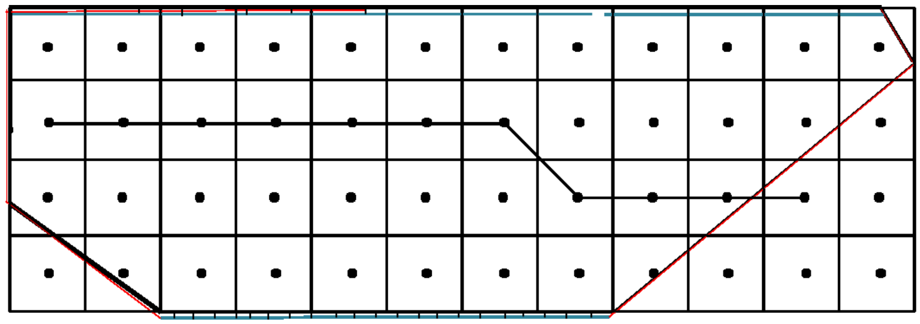


Figure 7-13: Layout option 2

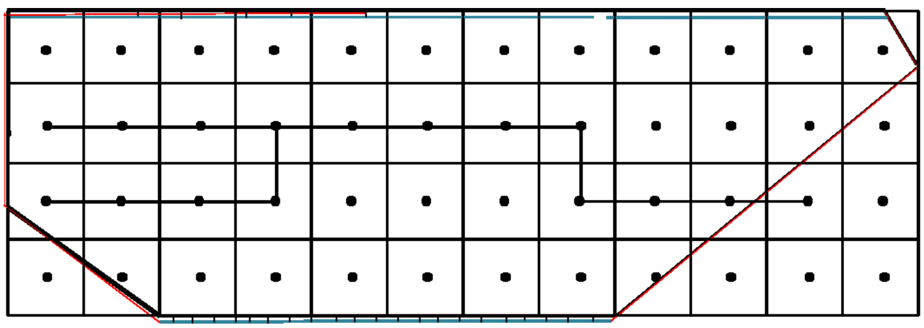


Figure 7-14: Layout option 3

For each layout option, the earthmoving operation plans remain the same as the optimum solution derived in Table 7-1. It is practically assumed that a Caterpillar 329D excavator is released from other project prior to the execution of the earthmoving project. So, there are two excavator/truck combinations (i.e. 329D and 735C, 336D and 735C) for the site manager to select. Detailed operation analysis results are presented in Table 7-5, Table 7-6, Table 7-7, and Table 7-8.

Table 7-5: Earthmoving operation analysis results (optimum layout)

Job No.	Volume (Bm3)	Haul Path	Haul Distance (m)		No. of Trucks	Duration (hour)	Cost ($)
			d_{gravel}	d_{gravel}			
336D Excavator + 735C Truck							
1	20000	13-49	1000	0	3	83.07	47764.10
2	15400	13-14-27	150	212	3	60.55	34814.38
3	19700	13-14-26	150	150	3	77.48	44550.73
4	7500	13-14	150	0	3	29.54	16984.68
5	15000	1-14	0	212	3	58.96	33901.09
6	3700	2-3	0	150	3	14.61	8398.77
7	1000	7-6	0	150	3	4.02	2311.45
8	4200	8-19-18-17-16-27	450	424	3	18.28	10513.70
9	7000	8-7-6	0	300	3	27.58	15856.04
10	2300	9-8-19-18-17-16-27	450	574	3	10.66	6126.68
11	7900	10-11-24	0	362	3	31.23	17954.69
12	4300	10-11-12	0	300	3	17.01	9781.25
13	9800	10-23	0	212	3	38.56	22173.81
14	6900	11-12	0	150	3	27.16	15614.49
15	2200	22-23	0	150	3	8.72	5011.74
16	2500	35-34-33-32-31-18-17-16	962	150	3	10.99	6319.20
17	15100	34-33-32-31-18-17-16-15	1112	0	3	55.36	31830.40
18	8900	34-33-32-31-18-5	662	212	3	33.50	19264.78
19	2300	34-23	0	212	3	9.12	5245.90
20	2200	34-45	0	212	4	8.81	6034.13
21	100	46-45	0	150	2	0.59	274.43
22	3500	33-32-31-18-17-16-27	812	212	3	15.22	8751.62
23	9000	33-32-31-18-17-4	662	212	3	29.39	16899.41
24	6800	33-32-31-18-17-16	812	0	3	27.32	15707.91
25	100	33-32-31-18-5	512	212	3	0.52	301.10
26	3100	33-32-31-30-41	450	212	3	12.54	7212.10
27	23000	33-32-31-18-17	662	0	3	51.23	29459.05
28	4800	33-32-31-30-29	600	0	3	18.95	10895.41
29	22200	33-32-31-18	512	0	3	48.01	27603.48
30	8700	21-32-31-18-17-16-15	812	212	3	37.71	21685.01
31	1200	21-32-31-30-29-40	450	424	3	5.31	3051.71
32	16700	20-19-18-17-16	600	0	3	39.37	22635.42
33	8100	20-19	150	0	3	31.93	18361.26
34	12400	31-30-29	300	0	3	48.77	28043.07
35	20200	32-31-30-29-28	600	0	3	79.41	45663.42
36	14200	32-31-30	300	0	3	55.87	32126.78
37	2700	44-31-18-17-16-27	512	424	3	11.93	6862.26
38	2800	43-30-29-28	300	212	3	11.13	6398.89
39	7100	43-30-29	150	212	3	28.03	16117.18
40	5900	42-41	0	150	3	23.25	13369.59
41	1400	38-39	0	150	3	5.59	3214.95
42	900	25-26-39	0	362	3	3.66	2103.20
43	2800	25-26	0	150	3	11.08	6368.26
Total						**1222.02**	**703558.12**

Table 7-6: Earthmoving operation analysis results (layout option 1)

Job No.	Volume (Bm3)	Haul Path	Haul Distance (m)		No. of Trucks	Duration (hour)	Cost ($)
			d_{gravel}	d_{rough}			
336D Excavator + 735C Truck							
1	20000	13-49	1000	0	3	82.68	47359.48
2	15400	13-14-27	150	212	3	60.19	34839.18
3	19700	13-14-26	150	150	3	77.87	44595.48
4	7500	13-14	150	0	3	29.07	16915.98
5	15000	1-14	0	212	3	57.15	33485.68
6	3700	2-3	0	150	3	14.61	8398.77
7	1000	7-6	0	150	3	4.86	2325.68
8	4200	8-19-18-17-16-27	450	424	3	18.57	10513.70
9	7000	8-7-6	0	300	3	27.58	15816.04
10	2300	9-8-19-18-17-16-27	450	574	3	10.65	6126.64
11	7900	10-11-24	0	362	3	31.14	17954.57
12	4300	10-11-12	0	300	3	17.24	9783.27
13	9800	10-23	0	212	3	38.24	22178.12
14	6900	11-12	0	150	3	26.58	15648.35
15	2200	22-23	0	150	3	8.72	5011.74
16	2500	35-34-33-32-31-18-17-16	600	512	3	12.57	7536.75
17	15100	34-33-32-31-18-17-16-15	750	362	3	58.36	34830.40
18	8900	34-33-32-31-18-5	300	574	3	34.35	19785.78
19	2300	34-23	0	212	3	9.12	5245.90
20	2200	34-45	0	212	4	8.81	6034.13
21	100	46-45	0	150	2	0.59	274.43
22	3500	33-32-31-18-17-16-27	450	574	3	16.35	9758.62
23	9000	33-32-31-18-17-4	300	574	3	30.39	17548.41
24	6800	33-32-31-18-17-16	450	362	3	28.35	16485.91
25	100	33-32-31-18-5	150	574	3	0.68	321.04
26	3100	33-32-31-30-41	150	512	3	13.64	7854.10
27	23000	33-32-31-18-17	300	362	3	56.23	31684.05
28	4800	33-32-31-30-29	300	300	3	19.35	11524.41
29	22200	33-32-31-18	150	362	3	49.24	28568.48
30	8700	21-32-31-18-17-16-15	450	574	3	38.71	22685.01
31	1200	21-32-31-30-29-40	0	974	3	5.68	3258.71
32	16700	20-19-18-17-16	600	0	3	39.37	22635.42
33	8100	20-19	150	0	3	31.93	18361.26
34	12400	31-30-29	0	300	3	50.35	28785.07
35	20200	32-31-30-29-28	0	600	3	80.15	47586.14
36	14200	32-31-30	0	300	3	56.35	33865.25
37	2700	44-31-18-17-16-27	400	636	3	12.52	7584.26
38	2800	43-30-29-28	0	512	3	12.57	6785.58
39	7100	43-30-29	0	362	3	29.63	17584.52
40	5900	42-41	0	150	3	23.21	13369.48
41	1400	38-39	0	150	3	5.68	3218.35
42	900	25-26-39	0	362	3	3.85	2108.52
43	2800	25-26	0	150	3	11.32	6370.42
Total						**1254.5**	**752603.36**

Table 7-7: Earthmoving operation analysis results (layout option 2)

Job No.	Volume (Bm3)	Haul Path	Haul Distance (m)		No. of Trucks	Duration (hour)	Cost ($)
			d_{gravel}	d_{rough}			
336D Excavator + 735C Truck							
1	20000	13-49	1000	0	3	83.15	47748.10
2	15400	13-14-27	150	212	3	60.55	34814.24
3	19700	13-14-26	150	150	3	77.14	44550.15
4	7500	13-14	150	0	3	29.38	16984.68
5	15000	1-14	0	212	3	58.96	33901.09
6	3700	2-3	0	150	3	14.10	8398.24
7	1000	7-6	0	150	3	4.08	2311.87
8	4200	8-19-18-17-16-27	450	424	3	18.17	10513.34
9	7000	8-7-6	0	300	3	27.24	15856.24
10	2300	9-8-19-18-17-16-27	450	574	3	10.48	6126.35
11	7900	10-11-24	0	362	3	31.17	17954.24
12	4300	10-11-12	0	300	3	17.17	9781.16
13	9800	10-23	0	212	3	38.37	22173.24
14	6900	11-12	0	150	3	27.28	15614.01
15	2200	22-23	0	150	3	9.01	5011.71
16	2500	35-34-33-32-31-18-17-16	600	512	3	10.24	6319.37
17	15100	34-33-32-31-18-17-16-15	750	362	3	55.80	31830.46
18	8900	34-33-32-31-18-5	300	574	3	33.86	19264.38
19	2300	34-23	0	212	3	9.45	5245.78
20	2200	34-45	0	212	4	8.07	6034.37
21	100	46-45	0	150	2	0.67	274.70
22	3500	33-32-31-18-17-16-27	450	574	3	15.86	8751.15
23	9000	33-32-31-18-17-4	300	574	3	29.75	16885.53
24	6800	33-32-31-18-17-16	450	362	3	27.14	15707.86
25	100	33-32-31-18-5	150	574	3	0.52	301.10
26	3100	33-32-31-30-41	150	512	3	12.88	7235.86
27	23000	33-32-31-18-17	300	362	3	51.75	29475.68
28	4800	33-32-31-30-29	300	300	3	18.58	10895.41
29	22200	33-32-31-18	150	362	3	48.01	27603.48
30	8700	21-32-31-18-17-16-15	450	574	3	37.71	21685.01
31	1200	21-32-31-30-29-40	0	974	3	5.31	3051.15
32	16700	20-19-18-17-16	600	0	3	39.37	22635.42
33	8100	20-19	0	150	3	0.24	18361.87
34	12400	31-30-29	0	300	3	48.77	28043.07
35	20200	32-31-30-29-28	0	600	3	79.41	45663.42
36	14200	32-31-30	0	300	3	55.24	32126.78
37	2700	44-31-18-17-16-27	400	636	3	11.93	6862.26
38	2800	43-30-29-28	0	512	3	11.13	6398.35
39	7100	43-30-29	0	362	3	28.25	16782.35
40	5900	42-41	0	150	3	25.68	13358.75
41	1400	38-39	0	150	3	5.38	3158.65
42	900	25-26-39	0	362	3	3.54	2153.27
43	2800	25-26	0	150	3	11.24	6345.32
Total						**1312.63**	**754034.85**

Table 7-8: Earthmoving operation analysis results (layout option 3)

Job No.	Volume (Bm3)	Haul Path	Haul Distance (m)		No. of Trucks	Duration (hour)	Cost ($)
			d_{gravel}	d_{rough}			
329D Excavator + 735C Truck							
1	20000	13-49	1000	0	3	83.72	47796.10
2	15400	13-14-27	150	212	3	60.69	34884.79
3	19700	13-14-26	150	150	3	77.94	44601.40
4	7500	13-14	150	0	3	29.85	17064.17
5	15000	1-14	0	212	3	59.36	33977.51
6	3700	2-3	0	150	3	14.80	8461.49
7	1000	7-6	0	150	3	4.49	2351.41
8	4200	8-19-18-17-16-27	450	424	3	18.61	10514.62
9	7000	8-7-6	0	300	3	27.44	15860.82
10	2300	9-8-19-18-17-16-27	450	574	3	11.24	6207.54
11	7900	10-11-24	0	362	3	31.29	18041.55
12	4300	10-11-12	0	300	3	17.37	9877.62
13	9800	10-23	0	212	3	38.73	22261.26
14	6900	11-12	0	150	3	27.62	15699.84
15	2200	22-23	0	150	3	9.06	5032.38
16	2500	35-34-33-32-31-18-17-16	600	512	3	10.86	6413.46
17	15100	34-33-32-31-18-17-16-15	750	362	3	56.42	31857.71
18	8900	34-33-32-31-18-5	300	574	3	34.52	19304.53
19	2300	34-23	0	212	3	10.18	5336.74
20	2200	34-45	0	212	4	8.58	6131.31
21	100	46-45	0	150	2	0.72	334.32
22	3500	33-32-31-18-17-16-27	450	574	3	16.60	8838.98
23	9000	33-32-31-18-17-4	300	574	3	29.84	16897.58
24	6800	33-32-31-18-17-16	450	362	3	27.97	15744.12
25	100	33-32-31-18-5	150	574	3	0.89	324.83
26	3100	33-32-31-30-41	150	512	3	13.63	7281.02
27	23000	33-32-31-18-17	300	362	3	52.51	29511.35
28	4800	33-32-31-30-29	300	300	3	19.12	10927.44
29	22200	33-32-31-18	150	362	3	48.69	27654.15
30	8700	21-32-31-18-17-16-15	450	574	3	37.99	21745.27
31	1200	21-32-31-30-29-40	0	974	3	6.18	3114.07
32	16700	20-19-18-17-16	600	0	3	39.50	22710.68
33	8100	20-19	0	150	3	1.09	18421.13
34	12400	31-30-29	0	300	3	49.21	28128.58
35	20200	32-31-30-29-28	0	600	3	80.08	45685.75
36	14200	32-31-30	0	300	3	56.16	32218.44
37	2700	44-31-18-17-16-27	400	636	3	12.14	6947.06
38	2800	43-30-29-28	0	512	3	11.69	6437.35
39	7100	43-30-29	0	362	3	28.88	16865.44
40	5900	42-41	0	150	3	26.34	13418.90
41	1400	38-39	0	150	3	5.89	3184.73
42	900	25-26-39	150	212	3	10.84	5903.23
43	2800	25-26	150	0	3	3.56	2050.47
Total						**1356.36**	**742856.39**

KPIs including gravel-surfaced road length, road construction and removal cost, road maintenance cost, total operation cost, and total project cost for each layout option were calculated, as shown in Table 7-9. In specific, total operation cost is derived by computer-aided operation analysis described in Chapter 6. Note the total operation cost shown in Table 7-9 is for cost estimating purpose; thereby only the most likely value (i.e. average) is used in deriving the cost estimate. The uncertainty inherent in total operation cost due to variations in earthmoving operation analysis inputs (e.g. truck speed and cycle time per bucket) is not addressed in the current thesis but worthy of investigation in the immediate future based on the optimization and simulation models resulting from the current research. Road construction and removal cost is calculated as per Eq.(4-8) while road maintenance cost is calculated as per Eq. (4-9). Total earthmoving cost is defined as the sum of total operation cost, road construction and removal cost, and road maintenance cost.

Table 7-9: Layout option comparison

Layout options	**Total operation cost ($) (1)**	**Gravel-surfaced road length (m)**	**Road construction &removal cost ($) (As per Eq.(4-8)) (2)**	**Road maintenance cost ($) (As per Eq.(4-9)) (3)**	**Total earthmoving cost (1)+(2)+(3)**
1	752603	2436	42630	62136	857369
2	754035	1562	27335	78403	859773
3	742856	2250	39375	64930	847161
4 (optimum)	703558	2312	40460	61250	**805268**

According to Table 7-9, among the four layout options, option 4 which is the optimized layout design achieved lowest total project cost and total project duration, owing to the effective temporary haul road layout design and efficient earthmoving operation plan. On average, the optimized temporary haul road layout could potential save 6% of total earthmoving cost. In short, the layout comparison has validated the proposed approaches in current thesis and proven that building a well-designed temporary haul road network in support of site grading operations can potentially save considerable budget for earthmoving contractors.

7.4.2 Computer Automated Earthmoving Plan vs. Manually Determined Earthmoving Plans

A total of three earthmoving plans were collected from graduate students majored in Civil Engineering in University of Alberta. The three students have had an average of six years engineering trainings in university plus two years working experience in industry as either field engineer or project coordinator. Each student was provided the project background and input data (same crew unit rates, truck speeds, truck volume, bucket size, efficiency factor, dumping time as in session 7.1). The optimum temporary haul road layout (same as Figure 7-6) was given to the students while the optimum earthmoving operation plans were not provided.

Each student was asked to plan the haul jobs by trying to minimize the operation cost based on their knowledge and experience. Students were allowed to use discrete event simulation (DES) tool to do trials and error on analyzing each haul job to identify truck numbers, and calculate haul job duration and cost accordingly. In particular, followed by the criterion in Figure 6-3, for each haul job, student need to set up simulation model (e.g. activity times, total number of truck loads). Student starts by assigning one truck for the simulation model, run the simulation for 1000 times, record the average duration and calculate operation cost; then student repeat the process by assigning on more truck each time; the iteration terminates when the cost of N+1 trucks scenario is greater than the cost of N trucks scenario. The truck number, duration and cost of N truck scenario is recorded for each haul job.

Three requests were sent out and three earthmoving plans were collected. The manually generated plans submitted by the students were carefully verified with the following three criteria:

(1) **Haul job quantity and total cut volume**: This is to check the total number of haul jobs and the total amount of excavation as high-level verifications.

(2) **Haul path and haul road distance**: This is to check whether the haul road distances match with the planned haul paths for each haul job.

(3) **Cost for each haul job**: The planned haul jobs for each manual solution are inputted into EOAP tool to generate costs. Comparison is made between each haul job cost generated by EOAP tool and students' calculations.

First, the plans produced by the three graduate students have exact 43 haul jobs and a total volume at 335,600 m^3. No errors were found in haul job assignment in terms of earthworks volumes.

Second, the haul distances on respective haul road grades followed by haul paths for each haul job were carefully examined. No errors were found in haul distance calculations.

Third, costs for each haul job provided by the three graduate students were carefully checked. More or less, the provided plans have calculation errors in cost for haul jobs. This finding highlights the "human factor" in manual cost estimating endeavors if they are not carefully examined. Then, I corrected the erroneous costs based on EOAP outputs to have error-free plans for comparison in this thesis. The students' plans with updated haul job costs are presented in Table 7-10, Table 7-11, and Table 7-12.

Table 7-10: Alternative earthmoving operation plan 1.

Job No.	Volume (Bm3)	Haul Path	Haul Distance (m)		No. of Trucks	Duration (hour)	Cost ($)
			d_{gravel}	d_{rough}			
1	22500	13-14	150	0	3	88.45	53492.14
2	22500	13-26	0	212	3	88.38	53470.11
3	17600	13-14-15	300	0	3	69.16	41855.24
4	15000	1-14-15	150	212	3	59.02	35704.91
5	3700	2-3	0	150	3	14.63	8848.27
6	1200	25-13-14-15	300	150	3	4.82	2921.31
7	2500	25-13-14-15-16	450	150	3	9.99	6045.97
8	1400	38-39	0	150	3	5.60	3386.62
9	12400	31-30-29-28-27	600	0	3	48.81	29530.30
10	15700	32-31-30-29-28-27	750	0	4	62.30	37691.41
11	18700	32-31-30-29-28	600	0	3	73.53	44484.93
12	5900	42-41	0	150	3	23.25	14066.74
13	3100	43-42-41	0	300	3	12.27	7422.91
14	1200	43-42-41-40	0	450	3	4.82	2968.28
15	900	43-42-41-40-39	0	600	3	3.89	2354.46
16	4700	43-30	0	212	3	18.54	11217.20
17	500	44-31-30	150	212	3	2.07	1252.15
18	2200	44-45	0	150	3	8.74	5290.72
19	4300	33-32-31-30-29-28	750	0	3	17.14	10369.18
20	24300	33-32-31-30-29	600	0	3	95.56	57815.02
21	9000	33-32-31-30	450	0	3	35.42	21431.16
22	23000	33-32-31-30-17	662	0	3	90.59	54804.67
23	11900	33-32-31-30-17-16	812	0	4	47.66	28836.81
24	21600	34-33-32-31-30-17-16	962	0	4	85.12	61713.51
25	6900	34-33-32-31-30-17-4	812	212	3	29.89	18086.09
26	19900	20-19-18	300	0	3	87.24	52783.09
27	2100	20-19-18-17-4	450	212	3	8.55	5171.93
28	500	20-19	150	0	2	2.56	1241.04
29	1000	7-6	0	150	3	4.01	2425.09
30	7000	8-7-6	0	300	3	27.61	16703.68
31	4200	8-7-6-5	0	450	3	16.93	10241.63
32	2300	9-20-19-18-5	300	424	3	9.73	5889.22
33	4800	21-20-19-18-5	300	362	3	19.83	11995.33
34	5100	21-20-19	150	150	3	20.11	12164.68
35	2300	9-20-19	150	212	3	9.14	5527.52
36	200	22-21-20-19	150	300	3	0.90	544.33
37	2000	22-23	0	150	3	7.94	4803.66
38	12300	10-23	0	212	3	48.39	29274.85
39	7900	10-23-24	0	362	3	31.24	18901.51
40	1800	10-23-12	0	424	3	7.26	4393.93
41	6900	11-12	0	150	3	27.19	16452.33
42	2500	35-23-12	0	362	3	9.96	6024.71
43	100	46-45	0	150	2	0.59	286.88
Total						**1250.38**	**819885.63**

Table 7-11: Alternative earthmoving operation plan 2.

Job No.	Volume (Bm3)	Haul Path	Haul Distance (m)		No. of Trucks	Duration (hour)	Cost ($)
			d_{gravel}	d_{rough}			
1	12400	31-30	150	0	3	48.78	29511.12
2	1800	32-31-30	300	0	3	7.17	4335.76
3	24300	32-31-30-29	450	0	3	95.51	57785.06
4	8300	32-31-30-29-28	600	0	3	32.68	19773.55
5	14700	33-31-30-29-28	750	0	3	58.33	35286.72
6	21000	33-31-30-29-28-27	900	0	3	114.19	69085.34
7	22500	33-31-30-29-28-27-14	900	212	3	98.86	59809.33
8	33800	13-14-15	300	0	3	132.81	80349.58
9	28800	13-14-15-16	450	0	3	113.21	68489.19
10	7200	333-32-19	150	212	3	28.37	17161.06
11	900	34-33-32-19	300	212	3	3.66	2211.82
12	23000	34-33-32-31-30-17	812	0	3	92.00	55661.56
13	4600	34-33-32-31-18	450	212	3	18.57	11233.63
14	17600	20-19-18	300	0	3	69.17	41846.18
15	7200	20-19-18-17-16	600	0	3	28.40	17179.29
16	3700	2-3	0	150	3	14.62	8844.10
17	9000	1-2-3-4	0	450	3	36.17	21884.06
18	6000	1-2-3-4-5	0	600	3	25.31	15311.23
19	1000	7-6	0	150	3	4.03	2437.29
20	7000	8-7-6	0	300	3	27.57	16682.07
21	3000	8-7-6-5	0	450	3	12.14	7343.89
22	2200	22-23	0	150	3	8.74	5289.89
23	9900	21-22-23	0	300	3	39.02	23609.55
24	2200	10-23	0	212	3	8.74	5287.23
25	6900	11-12	0	150	3	27.16	16430.58
26	4300	10-11-12	0	300	3	17.01	10288.75
27	7900	10-11-24	0	362	3	31.22	18888.26
28	1200	8-19-30-41	0	626	3	5.21	3151.38
29	2300	9-8-19-30-41	0	786	3	10.45	6325.23
30	5500	10-9-8-19-30-41	0	936	4	21.79	15801.32
31	1200	10-9-8-7-18-29-40	0	1086	4	4.97	3601.06
32	900	10-9-8-7-18-17-16-15-26	750	574	4	3.70	2679.48
33	3700	25-26	0	150	3	15.18	9186.44
34	1400	38-26	0	150	3	5.60	3386.07
35	2300	42-41-40-39	0	450	3	9.31	5634.20
36	3600	42-29-28-27-26	300	362	3	14.85	8985.08
37	9900	43-30-29-28-27-26	450	362	3	41.94	25371.73
38	2700	44-31-30-29-28-27-26	600	362	3	11.94	7223.98
39	300	35-34-33-32-31-30-29-28	1050	300	3	1.52	922.14
40	100	46-45	0	150	2	0.59	287.55
41	2200	35-34-45	0	362	3	8.79	5315.39
42	2300	9-20-19-18-5	300	424	3	9.65	5828.36
43	4800	21-20-19-18-5	300	362	3	19.95	11997.36
Total						**1359.83**	**837712.90**

Table 7-12: Alternative earthmoving operation plan 3.

Job No.	Volume (Bm3)	Haul Path	Haul Distance (m)		No. of Trucks	Duration (hour)	Cost ($)
			d_{gravel}	d_{rough}			
1	2500	13-14	150	0	3	88.44	5961.86
2	3800	13-15	300	0	3	132.81	9096.80
3	22500	13-14-26	150	150	3	88.40	39921.66
4	16200	1-13-26	0	362	3	63.91	31731.69
5	3700	2-3	0	150	3	14.61	15030.80
6	1200	25-26	0	150	3	4.81	4944.73
7	18100	25-27	0	300	3	110.46	62612.93
8	15600	38-27	0	212	3	100.60	52462.32
9	14200	31-30-29-28-27	600	0	3	95.15	46862.52
10	1800	42-30-29-28-27	450	150	3	46.77	14105.12
11	5900	43-30-29-28-27	600	150	3	23.94	17826.98
12	2300	43-30-29-28-27-39	450	362	3	9.87	10149.05
13	1200	43-30-29-28-40	300	362	3	5.02	5166.35
14	9000	43-30-29-41	150	362	3	36.11	20143.74
15	2300	44-45	0	150	3	9.12	9385.05
16	3500	32-31-30-29-41	450	150	3	36.83	12376.15
17	3000	32-31-30-29-28	600	0	3	90.40	11372.32
18	24300	32-31-30-29	450	150	3	96.15	9984.01
19	21400	20-31-30-29	300	212	3	84.47	69876.01
20	14200	20-31-30	150	212	3	57.92	25574.29
21	10800	33-32-31-30	450	0	3	42.52	21631.49
22	6000	33-32-31-30-17-16	812	0	3	143.99	12090.46
23	3000	33-32-31-30-17	962	0	3	94.76	9745.55
24	2200	33-20-19-18	150	212	3	87.26	4745.05
25	19500	34-33-20-19-18	450	212	3	78.33	63558.37
26	8100	34-33-20-19	300	212	3	34.08	18054.62
27	14300	34-23	0	212	3	57.03	24659.94
28	4000	21-20-19-18-17-16-4	600	300	3	38.43	10626.64
29	9000	21-20-19-18-17-5	450	300	3	103.80	4754.61
30	8100	9-20-19-18-17-5	450	300	3	35.12	12664.84
31	8000	8-19-18-6	150	362	3	32.06	12571.29
32	4900	7-6	0	150	3	19.37	9717.54
33	3900	9-20-19-6	150	424	3	15.97	7926.89
34	1600	10-21-20-19-6	300	512	3	7.06	7256.17
35	13400	10-23	0	212	3	52.67	54173.74
36	7900	10-23-24	0	362	3	31.22	32108.13
37	900	22-23-24	0	300	3	3.63	3736.61
38	11200	22-23-12	0	362	3	44.24	28505.26
39	4900	11-12	0	150	3	38.93	9442.71
40	3000	35-23-12	0	362	3	11.91	7150.69
41	500	46-34-23-12	0	512	3	2.16	2217.54
42	900	25-26-39	150	212	3	10.84	3235.49
43	2800	25-26	150	0	3	3.56	5185.79
Total						**1402.33**	**840344.3**

Then, comparison was made for four earthmoving plan alternatives (including the optimized plan) in terms of total project duration, road construction and removal cost, road maintenance cost, total operation cost, and total project cost for each layout option being calculated, as shown in Table 7-13.

Table 7-13: Earthmoving plans comparison

Earthmoving plans	**Total operation cost ($) (1)**	**Road construction &removal cost ($) (As per Eq.(4-8)) (2)**	**Road maintenance cost ($) (As per Eq.(4-9)) (3)**	**Total earthmoving Cost (1)+(2)+(3)**
1	819885	40460	65738	926083
2	837712	40460	74930	953102
3	840344	40460	72290	953094
4 (optimum)	703558	40460	61250	**805268**

According to Table 7-13, among the four earthmoving plans based on the same temporary haul road layout design, earthmoving plan 4 which is optimized by the proposed analytics achieved lowest total operation cost, as well as total earthmoving cost. On average, the optimized earthmoving plan could potentially save 18% of total earthmoving cost. The earthmoving plan comparison, in addition to previous layout design comparison, has further substantiated that a computer-aided earthmoving planning can potentially save considerable amount of budget for earthmoving contractors.

Chapter 8. CONCLUSIONS

This thesis has presented my work on proposing an integrated optimization framework to integrate the three critical earthmoving planning tasks by simultaneously generating (1) the quantity of earth to be moved, (2) the haul route to move the earth, and (3) the layout plan of high-grade haul road in site grading projects, based on mathematical modelling and computing programming, post-optimization sensitivity analysis, and computer simulation. I endeavored to turn the art of earthworks planning into science by taking advantage of latest advances in optimization and automation. Though complex in nature as earthworks is, current research is moving a positive step forward by providing another alternative solution in planning earthworks and realizing the wish of practitioners to a certain extent. The current solution is better than the solution that the practitioners can obtain given the available experience and software (e.g. AutoCAD Civil 3D). This work makes the following specific academic contributions to the domain of construction engineering and management:

- **Integrated optimization for earthworks**
    - **A flow network model to represent earthmoving operations and temporary haul road layout.** In Chapter 4, I described a methodology to model earthmoving operations and temporary haul road layout using a flow network that connects nodes vertically, horizontally, and diagonally. The flow network, as a graph-based approach, not only facilitate communication with the model users on the practical constraints being imposed and the optimized haul road layout design being generated, it also lays a solid basis for modelling various site conditions in practice.
    - **A mixed-integer linear programming (MILP) method based planner.** In

Chapter 4, I formulated current earthworks planning problem in the format of mixed-integer linear programming, capable to represent the earthmoving operation decisions and temporary haul road layout design decisions in real number variables and integer variables, respectively. The MILP model is solved by Branch and Bond algorithms embedded in the up-to-date optimization engine (IBM CPLEX 12.61), to generate solution with minimum combined earthmoving cost, as crew operation cost, road construction and removal cost, and road maintenance cost.

  - **A cutting plane method to ensure haul road accessibility and continuity.** In Chapter 4, I adopted a cutting plane method and blended it into MILP to produce accessible and connected temporary haul road layout while maintaining optimality in minimizing cost. I devised innovative algorithms to iteratively add connected components to allow to program converge to accessible and connected road layout.

- **Post-optimization sensitivity analysis for MILP**
  - **An MILP sensitivity analysis method to identify parameter stability region.** In Chapter 5, I devised an innovative one-dimensional line search approach based on the constrained optimization theory in order to find the boundaries of a stability region around the parameter nominal value for each input parameter of the optimization model. This approach is the first approach to identify stability region of MILP for engineering problems in practical size.

The research also results in several products as practical contributions and can be applied in industry:

- **A prototype software to generate earthmoving operation plan and temporary haul road layout design.** A prototype software for automated earthworks planning is developed. The prototype can be applied for earthworks planning in large civil and industrial site grading projects.
- **An MILP post-optimization sensitivity analysis system to produce input parameter stability regions.** A prototype software to generate parameter stability regions is developed. The prototype is capable to produce sensitivity information conducive to determining a valuable "buffer" on each input parameter so to assist decision makers in assessing risks and coping with changes in reality.
- **A tool to identify crew configurations and evaluate time and cost for haul jobs based on computer simulation.** This software is user-friendly designed to facilitate crew configuration identification and solution evaluations for earthworks planning.

8.1 Research Limitations and Future Work

In this thesis, I have presented an analytical framework based on latest advances in optimization and automation for producing executable cost-effective temporary haul road layout design and earthmoving operation plans. Despite the advantages of the proposed approach, certain limitations of current research should be explained and possible future research endeavors are recommended:

- **Database integration.** In this thesis, the optimization solution is designed to be much correlated with the empirical cost data commonly available from the perspective of practitioners without deriving the cost from systematic composition (e.g. equipment cost comprises of annual depreciation, ownership, midlife overhaul cost, special tooling cost, maintenance cost, and maintenance cost), it is foreseen that there is a need to improve the reliability of cost data in order to achieve better optimized solutions. Full integration and automation of the proposed methodology would be worthy of pursuit by linking the optimization system with databases which track construction cost performances; as such all the empirical cost data used as input parameters in the current model will be replaced with "live" data that are more relevant and accurate.

- **Spatial Conflict.** This thesis assumes all the temporary haul roads are ready to pass at the start of operations without considering the possible "soft blocks" (e.g. some fill areas may need to be filled before truck can pass). Future research may extend current scope by including practical spatial conflict in earthmoving planning to derive block-free earthmoving plans.
- **Fleet Diversity**. This thesis only analysis the temporary haul road layout design and earthmoving operation planning problems for earthworks planning with a pre-defined operating method (i.e. truck and excavator). Future research may increase the scope of the optimization problem by investigating different operating methods, e.g. employing a fleet consisting of loading and hauling units or more independent machines such as wheel loaders and scrapers.
- **Global sensitivity analysis.** The current research only provides MILP sensitivity analysis methodology for one parameter at a time; the study on the interactions with and influences of other input parameters in regard to overall model performance will be desirable. Global sensitivity analysis will shed more light on MILP so to better guide model application and decision making.
- **Dynamic Optimization.** The current optimization system intends to provide earthworks planning solutions at the early planning stage without considering the fact that the

searching space in optimization changes along the course of construction. The site topography (e.g. road grade, blocks) changes during time which renders the optimized operation plans not to be optimal any more. Advanced information technology such as GPS devices, sensors, 3D GIS system are worthy to be integrated with current optimization system for planning earthworks in near-real time, or on a short-term, dynamic basis.

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Appendix A. Articulated Haul Trucks Performances (Caterpillar Handbook, 2017)

Caterpillar articulated trucks basic information including truck model, operating weights (loaded and unloaded) and truck capacity are shown in below Table:

Table A-1: Caterpillar articulated trucks basic information

Truck Model	Operating Weight (Empty) (kg)	Operating Weight (loaded) (kg)	Capacity (m3)
725C	23220	46820	11
730C	24100	52100	13.3
735C	31200	63900	15
740C	35600	73600	18
745C	33400	74400	18.5

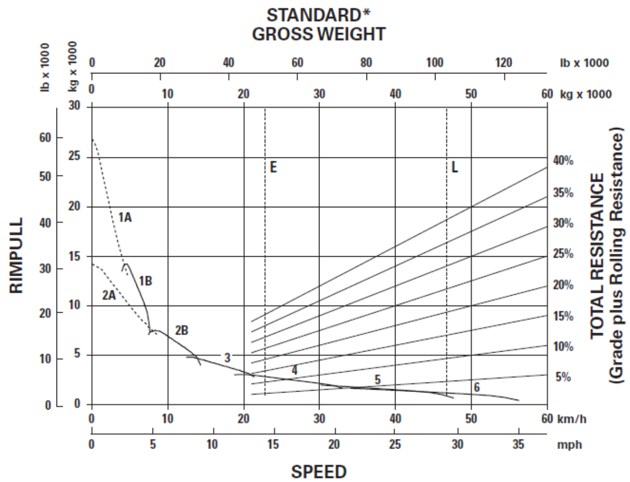
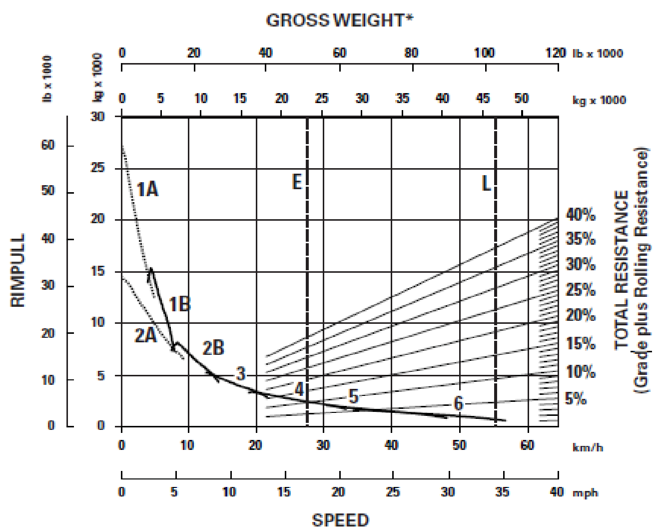
In this thesis, the haul road slope in earthmoving site is given as ±3% without steep slopes on site. Therefore, by referencing Table 2-1, the rolling resistance and total resistance is shown in below Table.

Table A-2: Slope resistance, rolling resistance and total resistance

	Slope Grade (%)	Rolling Resistance (%)	Total Resistance (%)
Rough ground haul road	±3	7.5	7.5 ± 3
Gravel-surfaced haul road		3	3 ± 3

With total resistance and truck operating weight known, truck speed can be referenced according to truck rimpell-speed diagram, as shown in Table A-3.

Table A-3: Truck Performance

<table>
<tr><th>Model</th><th>Caterpillar Articulate Haul Truck Rimpell-speed diagram</th><th>Referenced Speed</th></tr>
<tr><td>725C</td><td>
</td><td>
<table>
<tr><th colspan="5">725C</th></tr>
<tr><td></td><td colspan="2">Loaded</td><td colspan="2">Unloaded</td></tr>
<tr><td>Parameter</td><td>Rough km/h</td><td>Gravel km/h</td><td>Rough km/h</td><td>Gravel km/h</td></tr>
<tr><td>min</td><td>13</td><td>28</td><td>29</td><td>41</td></tr>
<tr><td>mode</td><td>22</td><td>45</td><td>34</td><td>51</td></tr>
<tr><td>max</td><td>33</td><td>56</td><td>49</td><td>56</td></tr>
</table>
</td></tr>
<tr><td>730C</td><td>
</td><td>
<table>
<tr><th colspan="5">730C</th></tr>
<tr><td></td><td colspan="2">Loaded</td><td colspan="2">Unloaded</td></tr>
<tr><td>Parameter</td><td>Rough km/h</td><td>Gravel km/h</td><td>Rough km/h</td><td>Gravel km/h</td></tr>
<tr><td>min</td><td>17</td><td>35</td><td>31</td><td>46</td></tr>
<tr><td>mode</td><td>24</td><td>50</td><td>37</td><td>52</td></tr>
<tr><td>max</td><td>38</td><td>60</td><td>50</td><td>60</td></tr>
</table>
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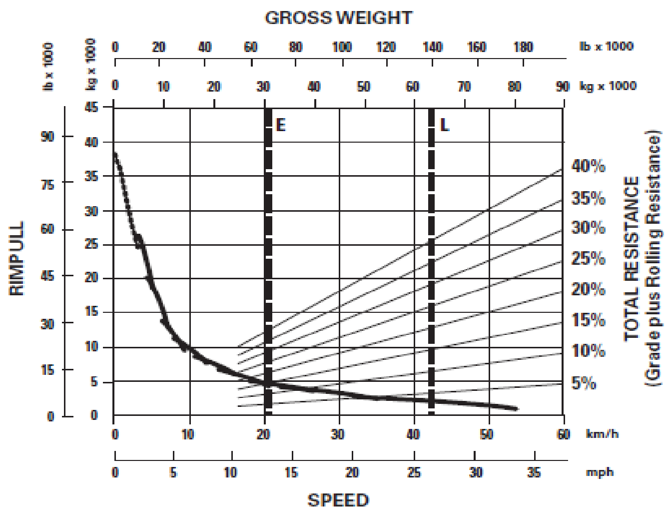
<table>
<tr><th>Model</th><th>Caterpillar Articulate Haul Truck Rimpell-speed diagram</th><th>Referenced Speed</th></tr>
<tr><td>735C</td><td>
</td><td>
<table>
<tr><th colspan="5">735C</th></tr>
<tr><td></td><td colspan="2">Loaded</td><td colspan="2">Unloaded</td></tr>
<tr><td>Parameter</td><td>Rough km/h</td><td>Gravel km/h</td><td>Rough km/h</td><td>Gravel km/h</td></tr>
<tr><td>min</td><td>12</td><td>34</td><td>27</td><td>36</td></tr>
<tr><td>mode</td><td>20</td><td>50</td><td>33</td><td>51</td></tr>
<tr><td>max</td><td>51</td><td>60</td><td>46</td><td>60</td></tr>
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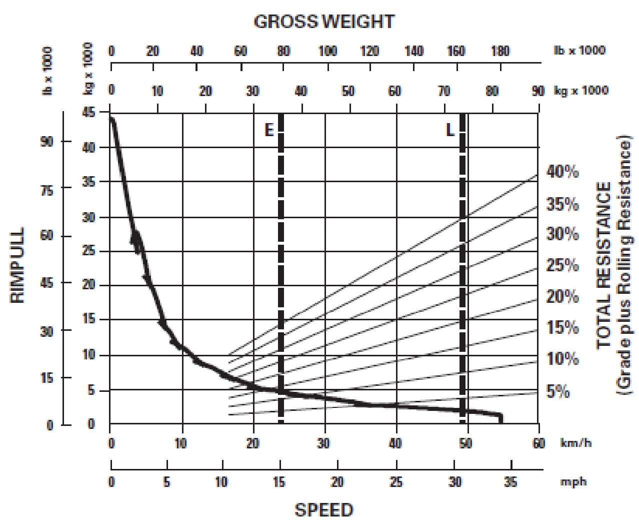
<tr><td>740C</td><td>
</td><td>
<table>
<tr><th colspan="5">740C</th></tr>
<tr><td></td><td colspan="2">Loaded</td><td colspan="2">Unloaded</td></tr>
<tr><td>Parameter</td><td>Rough km/h</td><td>Gravel km/h</td><td>Rough km/h</td><td>Gravel km/h</td></tr>
<tr><td>min</td><td>16</td><td>29</td><td>30</td><td>38</td></tr>
<tr><td>mode</td><td>24</td><td>45</td><td>36</td><td>50</td></tr>
<tr><td>max</td><td>34</td><td>55</td><td>45</td><td>55</td></tr>
</table>
</td></tr>
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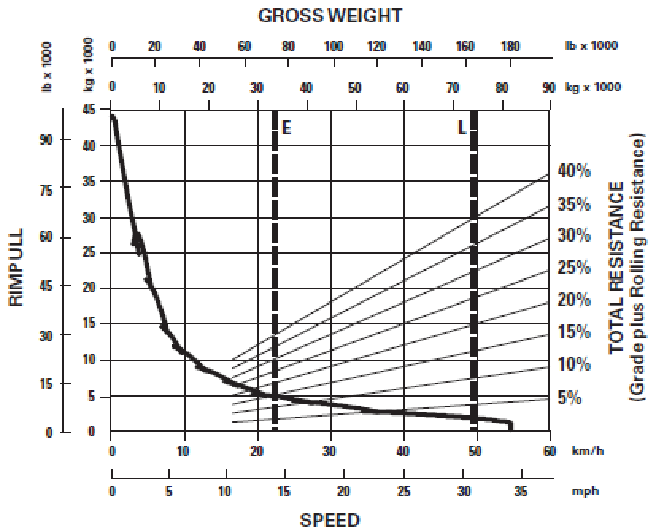
<table>
<tr><th>Model</th><th>Caterpillar Articulate Haul Truck Rimpell-speed diagram</th><th>Referenced Speed</th></tr>
<tr><td>745C</td><td>
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<table>
<tr><th colspan="5">745C</th></tr>
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<tr><td>Parameter</td><td>Rough km/h</td><td>Gravel km/h</td><td>Rough km/h</td><td>Gravel km/h</td></tr>
<tr><td>min</td><td>15</td><td>28</td><td>31</td><td>40</td></tr>
<tr><td>mode</td><td>22</td><td>45</td><td>36</td><td>51</td></tr>
<tr><td>max</td><td>30</td><td>55</td><td>48</td><td>55</td></tr>
</table>
</td></tr>
</table>

Appendix B. Hydraulic Excavator Performances (Caterpillar Handbook, 2017)

Caterpillar excavator Cycle Time Estimating Chart including excavator model, nominal bucket size, soil type, digging depth, load bucket time, swing bucket time, dump bucket time, and swing back time are shown in below tables. The cycle time shown below are deterministic based on average digging condition.

Table B-1: Caterpillar Hydraulic Excavator Cycle Time Deterministic Estimating Chart (1)

Model		308E2 CR SB	311D LRR	312D, 312D L	315D L	319D L, 319D LN	M314F, M315D2	M316F, M317D2, M318F	M320F, M320D2	M322F, M322D2
Bucket Size	L	220	450	520	520	800	610	750	900	1050
	yd³	0.30	0.59	0.68	0.68	1.05	0.80	0.98	1.18	1.37
Soil Type		Packed Earth					Sand/Gravel			
Digging Depth	m	1.8	1.5	1.8	3.0	3.0	3.0	3.0	3.0	3.0
	ft	6'0"	5'0"	6'0"	10'0"	10'0"	10'0"	10'0"	10'0"	10'0"
Load Bucket	min	0.08	0.07	0.07	0.07	0.09	0.05	0.06	0.06	0.08
Swing Loaded	min	0.03	0.06	0.06	0.08	0.09	0.05	0.05	0.06	0.06
Dump Bucket	min	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
Swing Empty	min	0.08	0.05	0.05	0.06	0.07	0.04	0.04	0.05	0.05
Total Cycle Time	min	0.22	0.21	0.21	0.24	0.28	0.17	0.18	0.20	0.23

Table B-2: Caterpillar Hydraulic Excavator Cycle Time Deterministic Estimating Chart (2)

Model		320D2	320D RR, 321D CR, 323D2	324D	328D LCR	329D	336D	349D2, 349E, 349F	365C L	385C
Bucket Size	L	800	800	1000	N/A	1100	1400	2400	1900	3760
	yd³	1.05	1.05	1.31		1.44	1.83	3.0	2.5	5.0
Soil Type		Hard Clay								
Digging Depth	m	2.3	2.3	3.2	N/A	3.2	3.4	4.0	4.2	5.6
	ft	8	8	10		10	11	13	14	18
Load Bucket	min	0.09	0.09	0.09	N/A	0.09	0.09	0.13	0.10	0.19
Swing Loaded	min	0.06	0.06	0.06	N/A	0.06	0.07	0.07	0.09	0.06
Dump Bucket	min	0.03	0.03	0.04	N/A	0.04	0.04	0.02	0.04	0.03
Swing Empty	min	0.05	0.05	0.06	N/A	0.06	0.07	0.06	0.07	0.07
Total Cycle Time	min	0.23	0.23	0.25	N/A	0.25	0.27	0.28	0.30	0.35

Apart from above deterministic cycle time reference, Caterpillar excavator Cycle Time Range Estimating Chart considering contingencies in job condition is also provided in Caterpillar Handbook. Due to the uncertainty of job condition, the cycle time range defined by minimum, average, and maximum cycle time is given in Table B-3 and Table B-4.

Table B-3: Caterpillar Hydraulic Excavator Cycle Time Range Estimating Chart (1)

	Cycle Time (min)						
	Machine Size Class						
	307C 308D CR 308D CR SB	311D	M314F M315D2 312D	M316F M317D2 M318F 315D L	M320F M320D2 319D L 319D LN	322F M322D2 320D 323D	324D
Min	0.21	0.22	0.22	0.22	0.25	0.26	0.27
Avg	0.28	0.28	0.30	0.30	0.33	0.33	0.35
Max	0.38	0.39	0.40	0.40	0.42	0.42	0.43

Table B-4: Caterpillar Hydraulic Excavator Cycle Time Range Estimating Chart (2)

	Cycle Time (min)						
	Machine Size Class						
	328D LCR	329D	336D	349D2 349E 349F	365C L	385C	
Min	-	0.27	0.28	0.27	0.27	0.28	
Avg	-	0.35	0.36	0.35	0.43	0.45	
Max	-	0.44	0.45	0.49	0.60	0.67	

Appendix C. Cross Validation with Established Simulation Software

In order to prove *EOAP* is a valid tool, *EOAP* was contrasted with two other simulation platforms, *SDESA* and *Symphony* (Symphony.NET 4.6 2017), based on different earthmoving cases in terms of the average total durations outputted from simulation software. Note, the simplified discrete-event simulation approach (SDESA) is a simplified, activity-based modeling platform proposed by Lu (2003), aiming to make construction simulation as easy as applying the critical path method (CPM); *Simphony* is a state-of-art construction simulation software consisting of a foundation library as well as specialized computer programs that allows for the development of simulation models in an efficient manner.

A total of five haul jobs were selected for assessing the outputs from the three simulation tools and contrasting them. A summary of simulation inputs and outputs are given in Table C-1 and Table C-2, respectively. For each job, volumes, haul path and equipment are specified, with equipment performance parameters (e.g. speed) referenced from Appendix A and Appendix B. Different truck number scenarios for each test case were simulated and corresponding total durations were recorded. Based on the test results from the five test cases, it showed that three software produced almost the same results given each earthmoving scenario. The trivial difference may come from the use of different random number generator or digital precision of numbers in program.

Table C-1: Inputs for comparison

Job No.	**Volume (m3)**	**Haul Distance (m)**			**Excavator Type**	**Truck Type**
		d_{gravel}	d_{rough}	total		
1	8100	150		150	CAT 336D	CAT 735C
2	16700	300		300		
3	5500	450		450		
4	4400		300	300		
5	9900	150	212	362		

Table C-2: Outputs comparison among *EOAP*, *SDESA*, and *Symphany*

Job No.	# of Trucks	*EOAP*		*SDESA*		*Symphany*	
		Duration (h)	Cost ($)	Duration (h)	Cost ($)	Duration (h)	Cost ($)
1	2	41.82	22374	40.86	21858	40.30	21563
	3	32.80	21484	33.17	21728	32.37	21200
	4	32.67	25319	33.40	25887	33.25	25766
2	2	91.01	48690	91.54	48974	90.78	48569
	3	67.67	44324	68.33	44754	67.65	44314
	4	67.55	52351	67.74	52498	67.66	52438
3	2	31.60	16906	32.05	17145	31.89	17061
	3	22.38	14659	22.78	14923	21.84	14303
	4	22.25	17244	22.87	17724	22.69	17581
4	2	24.65	13188	25.30	13534	25.08	13415
	3	17.86	11698	18.14	11883	17.95	11757
	4	17.86	13842	18.41	14270	17.47	13541
5	2	56.08	30003	56.97	30477	56.74	30357
	3	41.36	27091	42.35	27740	42.32	27720
	4	39.05	30264	39.92	30936	39.85	30884

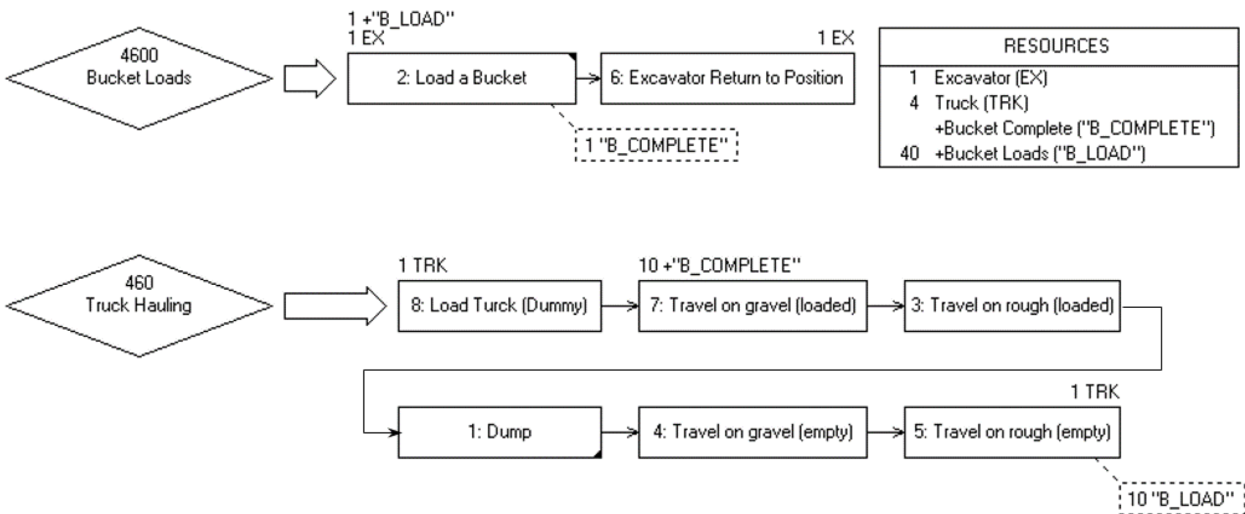


Figure C-1: SDESA earthmoving operation simulation model

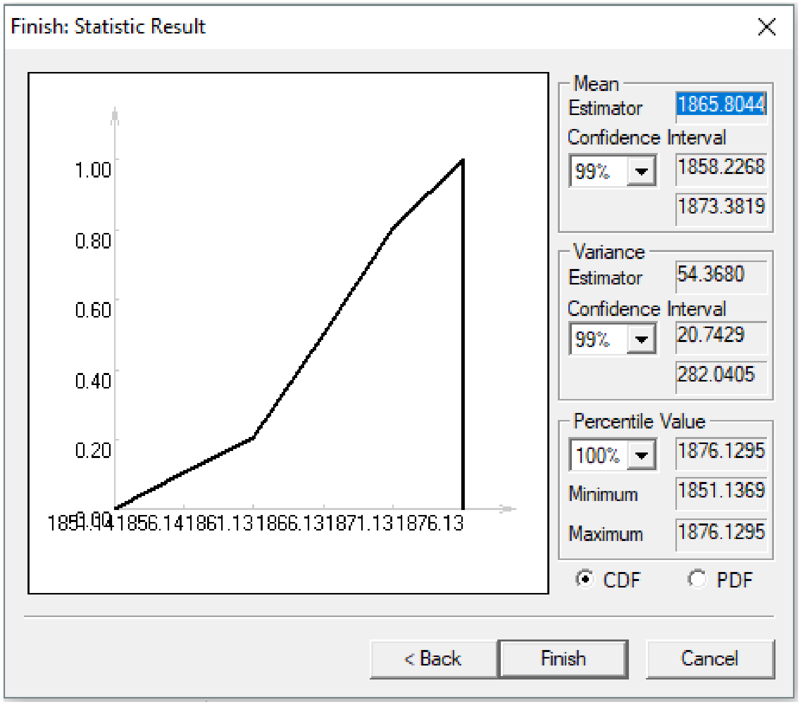


Figure C-2: Sample average duration output from SDESA

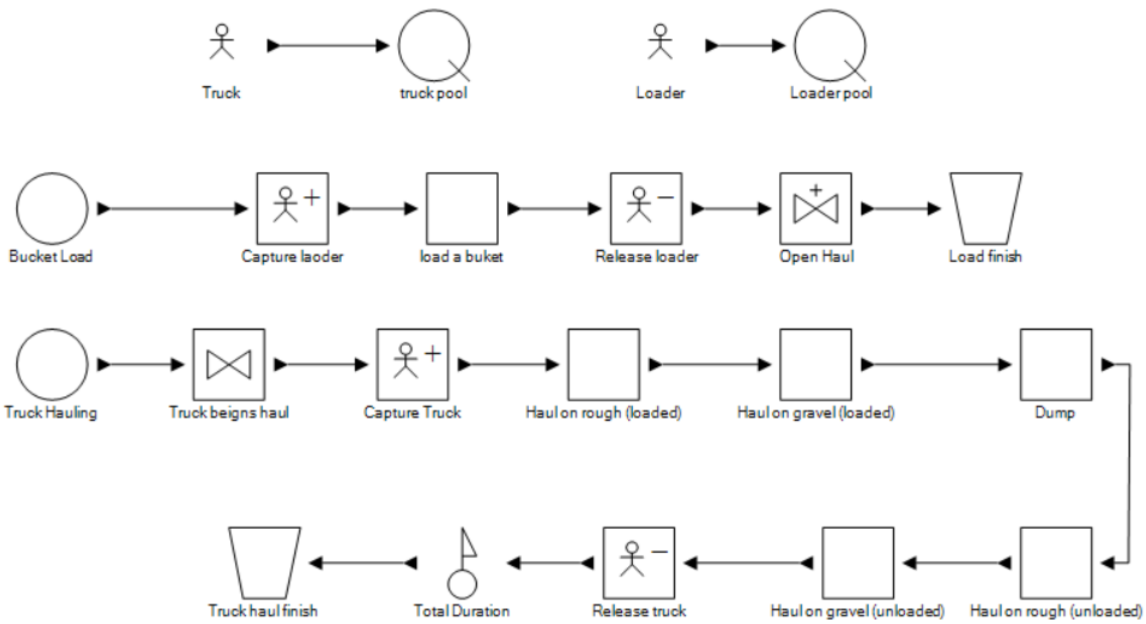


Figure C-3: Simphany earthmoving operation simulation model

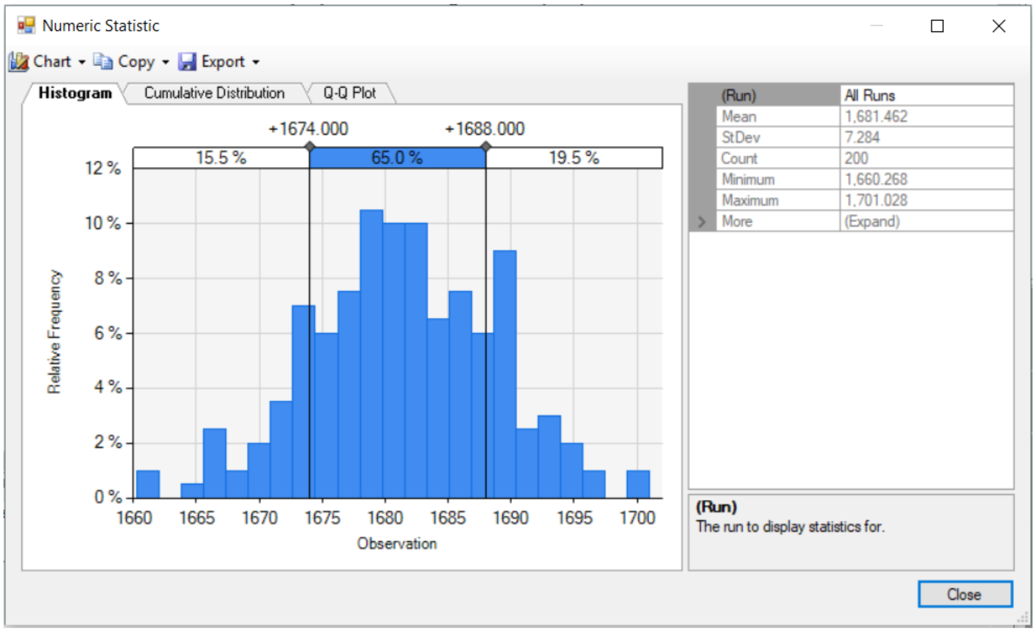
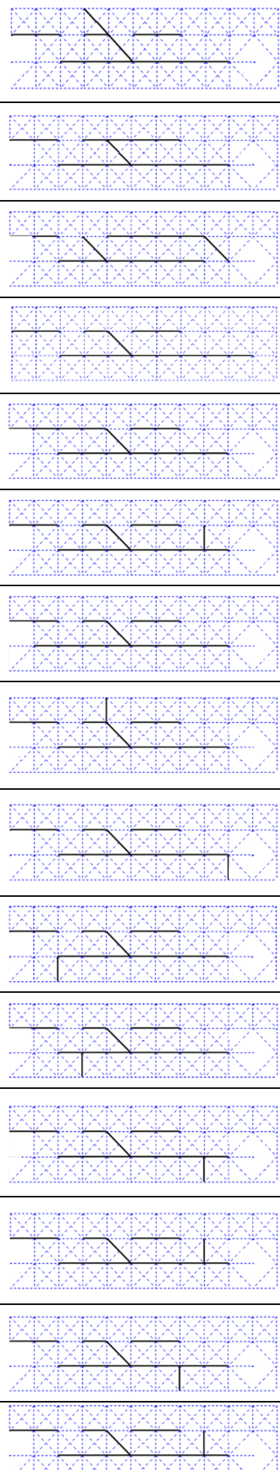
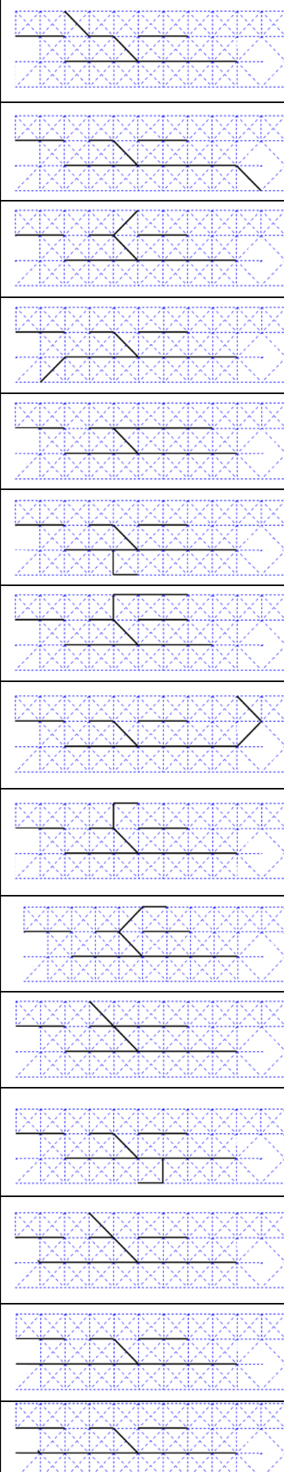
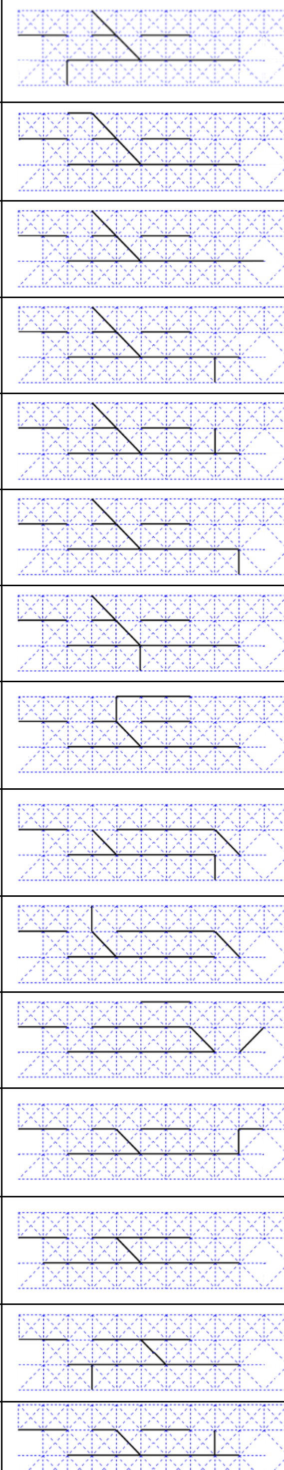
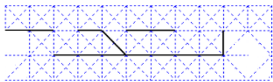
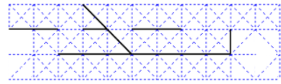
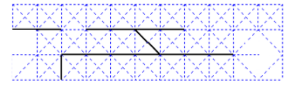
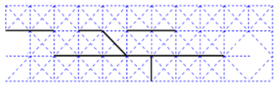
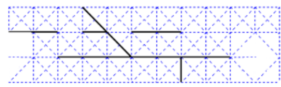
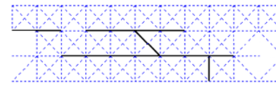
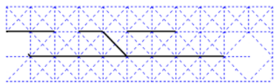
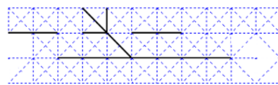
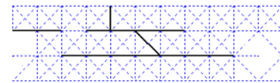
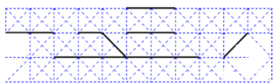
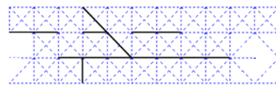
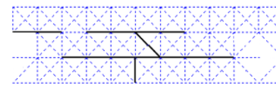
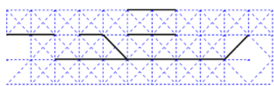
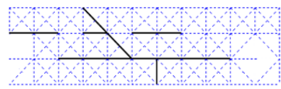
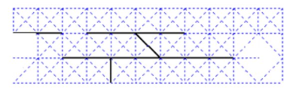
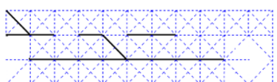
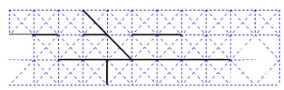
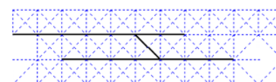


Figure C-4: Sample average duration output from Symphany.NET

Appendix D. Interim Layouts in Optimization Process

Table D-1: Interim layouts in optimization process

Run Number	Intermediate layout	Run Number	Intermediate layout	Run Number	Intermediate layout
1		22		43	
2		23		44	
3		24		45	
4		25		46	
5		26		47	
6		27		48	
7		28		49	
8		29		50	
9		30		51	
10		31		52	
11		32		53	
12		33		54	
13		34		55	
14		35		56	
15		36		57	

Run Number	Intermediate layout	Run Number	Intermediate layout	Run Number	Intermediate layout
16		37		58	
17		38		59	
18		39		60	
19		40		61	
20		41		62	
21		42		63	

Appendix E. Numerical Test Results of C-MILP CPU Time

A total of ten test sets were randomly generated for assessing performances of C-MILP algorithms. A summary of test settings and results are given in Table E-1. The test sets each represent a rough grading project of particular size (i.e. the project size increases with a larger number of cells), with randomly-simulated cut and fill volumes. For each test case, the basic cell in the grid has a constant size, namely: 150 m by 150 m; while, the $m \times n$ site layout means that the site has *m* rows and *n* columns of cells; the total earthwork volume represents the sum of cut volumes, which is equal to the sum of fill volumes in each test case. Performance assessment was conducted by independently applying the proposed C-MILP algorithm to solve each "test set" problem. CPU time for each test was recorded.

Table E-1: A summary of test settings and results

Test No.	Site Layout ($m \times n$)	Total Earthwork Volumes(m^3)	CPU Time (min)
1	4 x 8	1,261,800	0.71
2	4 x 9	1,362,800	1.31
3	4 x 10	1,946,900	1.84
4	5 x 9	2,160,500	7.88
5	5 x 10	2,188,900	8.83
6	5 x 11	2,787,900	9.72
7	6 x 10	2,697,300	13.09
8	7 x 11	2,672,900	62.30
9	8 x 12	3,178,800	202.55
10	9 x 15	3,672,000	540.09

Appendix F. Codes of Cutting Plane Method based Mixed-integer Linear Programming

This appendix provides the codes for optimizing earthmoving operation plans and temporary haul road layout designs, including two major parts: site modelling and C-MILP optimization. The codes were written in Python language in Python Spyder platform.

Import Functional Boxes

```
import math
import matplotlib.pyplot as plt
import networkx as nx
import numpy as np
import matplotlib.lines as mlines
from cplex import *
```

Define Function to Generate Grids

```
def distance(x, y):
    return math.sqrt(pow((x[0] - x[1]), 2) + pow((y[0] - y[1]), 2))

def generate_grid_network(row_num, col_num, demand):
    g = nx.Graph()
    for i in range(row_num):
        for j in range(col_num):
            g.add_node((i, j), d=demand[i][j], pos=[
                (j + 0.5) * 0.15, (-i + 0.5) * 0.15])

    for i in range(row_num - 1):
        for j in range(col_num):
            l = distance(g.node[(i, j)]["pos"], g.node[(i + 1, j)]["pos"])
            g.add_edge((i, j), (i + 1, j), length=l)

    for i in range(row_num):
        for j in range(col_num - 1):
            l = distance(g.node[(i, j)]["pos"], g.node[(i, j + 1)]["pos"])
            g.add_edge((i, j), (i, j + 1), length=l)

    for i in range(row_num - 1):
        for j in range(col_num - 1):
            l = distance(g.node[(i, j)]["pos"], g.node[(i + 1, j + 1)]["pos"])
            g.add_edge((i, j), (i + 1, j + 1), length=l)
            g.add_edge((i + 1, j), (i, j + 1), length=l)
```

```
    g.remove_edges_from([e for e in g.edges_iter((2, 0))])
    g.add_edge((2, 0), (2, 1), length=math.sqrt(2) * 0.15)
    g.remove_edges_from([e for e in g.edges_iter((2, 10))])
    g.add_edge((2, 10), (2, 9), length=math.sqrt(2) * 0.15)

    return g
```

Define Function to Generate Haul Road

```
def draw_solution(g=nx.Graph(), x={}, count=0):
    edge_list = []
    for a in g.edges_iter():
        if x[a].x > 0.9:
            edge_list.append(a)
    fig = plt.figure(figsize=(20, 8))
    ax = fig.add_subplot(111, aspect='equal')
    nx.draw_networkx_nodes(g, pos=nx.get_node_attributes(
        g, "pos"), node_size=50, with_labels=False)
    nx.draw_networkx_edges(g, pos=nx.get_node_attributes(
        g, "pos"), with_labels=False, style="dashdot", alpha=0.2, arrows=False)
    nx.draw_networkx_edges(g, pos=nx.get_node_attributes(g, "pos"),
                           edgelist=edge_list, width=3, edge_color="b",
                           arrows=False)
    plt.xlim(-0.15, 1.8)
    plt.subplots_adjust(top=0.95, bottom=0.005, left=0.005, right=1.0)
    solid_line = mlines.Line2D(
        [], [], color='b', linewidth=5, linestyle="solid", label='temporary road')
    dash_line = mlines.Line2D(
        [], [], color='k', linewidth=1, linestyle="dashdot", label='rough ground')
    plt.legend(handles=[solid_line, dash_line], fontsize=18)
    plt.title("Solution")
    plt.savefig("cutting_plane" + str(count) + ".jpg", dpi=200)
```

Define Function to Find Path at Shortest Haul Time

```
def calculate_schedule(g=nx.Graph(), ms=Model(), f={}, x={}):
    edge_length = nx.get_edge_attributes(g, "length")
    node_demand = nx.get_node_attributes(g, "d")
    edge_weight = {}
    for e in g.edges_iter():
        if x[e] == 0 and x[(e[1], e[0])] == 0:
            edge_weight[e] = edge_length[e] / 24
        if x[e] == 1 or x[(e[1], e[0])] == 1:
            edge_weight[e] = edge_length[e] / 36
    nx.set_edge_attributes(g, "weight", edge_weight)
```

```
    shortest_paths = nx.shortest_path(g, weight="weight")
    shortest_path_length = nx.shortest_path_length(g, weight="weight")

    Vs = [v for v in g.nodes_iter() if node_demand[v] < 0]
    Vt = [v for v in g.nodes_iter() if node_demand[v] >= 0]
    for s in Vs:
        for t in Vt:
            l = shortest_path_length[s][t]
            f[s][t].Obj = l
    ms.update()
```

Define Function for Optimization

```
    ms.optimize()
    nx.set_edge_attributes(g, "flag", x)
    schedule = {s: {t: [] for t in Vt} for s in Vs}
    if ms.status == CPLEX.Status.OPTIMAL:
        for s in Vs:
            for t in Vt:
                if f[s][t].x > 0:
                    schedule[s][t] = [f[s][t].x, shortest_path_length[s][t], shortest_paths[s][t]]
                else:
                    schedule[s][t] = [0]
    return schedule

def print_schedule(schedule={}, Vs=[], Vt=[], count=0):
    f = open("cutting_plane_" + str(count) + ".txt", 'w')
    for s in Vs:
        for t in Vt:
            if schedule[s][t][0] > 0:
                f.write("transportation amount:    " + str(schedule[s][t][0]) + ",   ")
                f.write("path:  ")
                p = schedule[s][t][2]
                for v in p:
                    f.write("(" + str(v[0]) + "," + str(v[1]) + ")--")
                f.write("\n")
    f.close()
```

Initialize Site Attributes

```
Demand = [[-15000, -3700, 3700, 9000, 9000, 8000,
           -1000, -11200, -2300, -22000, -6900, 11200],
          [-62600, 22500, 33800, 36000, 23000, 22200,
           8100, -24800, -9900, -2200, 14300, 7900],
          [-3700, 22500, 28100, 23000, 24300, 14200,
           -12400, -34400, -72500, -28500, -2500, 0],
```

```
        [0, -1400, 2300, 1200, 9000, -5900, -9900, -2700, 2300, -100, 0, 0]]

G = generate_grid_network(4, 12, Demand)
G.node[(1, 3)]['d'] = 6000
G.add_node((1, -1), d=30000, pos=[(-1 + 0.5) * 0.15, (-1 + 0.5) * 0.15])
G.add_edge((1, 0), (1, -1), length=distance(G.node[(1, 0)]["pos"], G.node[(1, -1)]["pos"]))

edge_length = nx.get_edge_attributes(G, "length")
C_max = np.sum(np.sum(np.abs(np.array(Demand)))) / 2
D_max = G.number_of_nodes()
```

Input Parameters

```
maintain_cost_road = 400 / 30 / 180  # /m3*km
maintain_cost_ground = 300 / 30 / 180  # /m3*km
transportation_cost_road = 5200 / (4 * 15 * 0.75 * 36)  # /m3*km
transportation_cost_ground = 5200 / (4 * 15 * 0.75 * 24)  # /m3*km
construction_cost = 17500  # /km
```

Objective Function and Constraints

```
edge_weight = {}
for e in G.edges_iter():
    edge_weight[e] = (maintain_cost_ground +
                  transportation_cost_ground) * edge_length[e]
nx.set_edge_attributes(G, "weight", edge_weight)

H = G.to_directed()

edge_length = nx.get_edge_attributes(H, "length")
node_demand = nx.get_node_attributes(H, "d")

edge_weight = {}
for e in G.edges_iter():
    edge_weight[e] = (maintain_cost_ground +
                  transportation_cost_ground) * edge_length[e]
nx.set_edge_attributes(G, "weight", edge_weight)
shortest_paths = nx.shortest_path(G, weight="weight")
shortest_path_length = nx.shortest_path_length(G, weight="weight")
Vs = [v for v in G.nodes_iter() if node_demand[v] < 0]
Vt = [v for v in G.nodes_iter() if node_demand[v] >= 0]
m_schedule = Model()
f = {s: {} for s in Vs}
for s in Vs:
    for t in Vt:
        l = shortest_path_length[s][t]
```

```
        f[s][t] = m_schedule.addVar(0.0, CPLEX.INFINITY, l, CPLEX.CONTINUOUS)
m_schedule.setParam("OutputFlag", 0)
m_schedule.update()

for s in Vs:
    m_schedule.addConstr(quicksum([f[s][t] for t in Vt]) == -node_demand[s])
for t in Vt:
    m_schedule.addConstr(quicksum([f[s][t] for s in Vs]) == node_demand[t])
m_schedule.optimize()
m = Model()
x = {}
f1 = {}
f2 = {}
fs = {}
for a in H.edges_iter():
    x[a] = m.addVar(obj=construction_cost * edge_length[a], vtype=CPLEX.BINARY)
    f1[a] = m.addVar(lb=0.0, ub=C_max, obj=(maintain_cost_ground +
                                transportation_cost_ground) * edge_length[a],
vtype=CPLEX.CONTINUOUS)
    f2[a] = m.addVar(lb=0.0, ub=C_max, obj=(maintain_cost_road +
                                transportation_cost_road) * edge_length[a],
vtype=CPLEX.CONTINUOUS)
m.update()
```

Flow Balance Constraints

```
for v in H.nodes_iter():
    m.addConstr(lhs=quicksum([f1[a] + f2[a] for a in H.out_edges_iter(v)])
                - quicksum([f1[a] + f2[a] for a in H.in_edges_iter(v)]),
            sense=CPLEX.EQUAL, rhs=node_demand[v])
```

Cutting Plane Method based MILP

```
m.optimize()
schedule = calculate_schedule(G, m_schedule, f, x)
solution_num = 0
draw_solution(H, x, solution_num)
print_schedule(schedule, Vs, Vt, solution_num)

G_t = nx.Graph()
for a in H.edges_iter():
    if x[a].x > 0.9:
        G_t.add_edge(a[0], a[1])
while not nx.is_connected(G_t):
    for l in nx.connected_components(G_t):
```

```
    m.addConstr(lhs=quicksum([x[a] for a in H.edges_iter() if a[0] in l and a[1] in l]) / len(l),
            sense=CPLEX.LESS_EQUAL,
            rhs=quicksum([x[a] for a in H.edges_iter(l) if a[0] not in l or a[1] not in l]))
  m.optimize()
  schedule = calculate_schedule(G, m_schedule, f, x)
  solution_num += 1
  draw_solution(H, x, solution_num)
  print_schedule(schedule, Vs, Vt, solution_num)
  G_t.clear()
  G_t = nx.Graph()
  for a in H.edges_iter():
    if x[a].x > 0.9:
      G_t.add_edge(a[0], a[1])
  c = nx.connected_components(G_t)
```

Print Out Solution

```
fig = plt.figure(figsize=(20, 8))
ax = fig.add_subplot(111, aspect='equal')
nx.draw_networkx_nodes(G, pos=nx.get_node_attributes(
  G, "pos"), node_size=50, with_labels=False)
nx.draw_networkx_edges(G, pos=nx.get_node_attributes(
  G, "pos"), with_labels=False, style="dashdot", alpha=0.2, arrows=False)
nx.draw_networkx_edges(G, pos=nx.get_node_attributes(G, "pos"),
                edgelist=edge_list, width=3, edge_color="b",
                arrows=False)
plt.xlim(-0.15, 1.8)
plt.subplots_adjust(top=0.95, bottom=0.005, left=0.005, right=1.0)
plt.legend(handles=[solid_line, dash_line], fontsize=18)
plt.title("Solution")

plt.show()
```

Appendix G. Codes of Parameter Stability Region Identification for MILP

This appendix provides the codes for identifying MILP model input parameter stability regions, including two major parts: C-MILP optimization and one-dimensional line search algorithms. Note C-MILP optimization part uses the same codes in Appendix E. The codes were written in Python language in Python Spyder platform.

Import Functional Boxes

```
import math
import matplotlib.pyplot as plt
import networkx as nx
import numpy as np
from sympy import *
init_printing(use_unicode=True)
import pandas as pd
from cplex import *
```

Initialize Input Parameter

```
alpha,beta,n,c,v1,v2,sigma1,sigma2,TH1,TH2=symbols('alpha beta n c v1 v2 sigma1 sigma2
TH1 TH2')
x={alpha:5200,beta:9000,c:15,n:4,v1:24,sigma1:1200,TH1:5000, TH2:15000}
```

One Dimensional Line Search Algorithm

```
l={}
u={}
A1=alpha/(n*c*v1)+sigma1/TH1
A2=alpha/(n*c*v2)+sigma2/TH2
B=beta
y=A1.evalf(subs=x)
variables=[alpha,n,c,v1,sigma1,TH1]
for var in variables:
    f=A1.subs({i:x[i] for i in variables if i!=var})
    a= m.optimize (f-y-0.038,var)[0]                    # C-MILP solving
    b= m.optimize (f-y+0.209,var)[0]
    l[var.name]=round(min(a,b),3)
    u[var.name]=round(max(a,b),3)
```

```
data1=pd.DataFrame()
data1['Min']=pd.Series(l)
data1['Max']=pd.Series(u)
data1

l={}
u={}
y=A2.evalf(subs=x)
variables=[alpha,n,c,v2,sigma2,TH2]
for var in variables:
    f=A2.subs({i:x[i] for i in variables if i!=var})
    a= m.optimize (f-y-0.038,var)[0]
    b= m.optimize (f-y+0.209,var)[0]
    l[var.name]=round(min(a,b),3)
    u[var.name]=round(max(a,b),3)
data2=pd.DataFrame()
data2['Min']=pd.Series(l)
data2['Max']=pd.Series(u)
data2
```

Print Out Solution

```
vars=[alpha,n,c,v1,v2,sigma1,sigma2,TH1,TH2]
l={}
u={}
for var in vars:
    if var.name in data1.index and var in data2.index:
        l[var]=max(data1.loc[var.name,'Min'],data2.loc[var.name,'Min'])
        u[var]=min(data1.loc[var.name,'Max'],data2.loc[var.name,'Max'])
    elif var.name in data1.index:
        l[var]=data1.loc[var.name,'Min']
        u[var]=data1.loc[var.name,'Max']
    else:
        l[var]=data2.loc[var.name,'Min']
        u[var]=data2.loc[var.name,'Max']
data=pd.DataFrame()
data['Min']=pd.Series(l)
data['Max']=pd.Series(u)
data.loc['beta']={'Min':9000-340,'Max':9000-3128}
data
```

Appendix H. Codes of Earthmoving Operation Analysis Platform (*EOAP)* Tool

This appendix provides the codes for EOAP tool, including EOAP tool UI development, truck number optimizer and equipment type optimizer. The codes were written in Python language in Python Spyder platform.

Import Functional Boxes

```
import tkinter as tk
from tkinter import *
from tkinter import ttk
from simulation import *
from enum import Enum
from ast import literal_eval as make_tuple
```

Initialize Class for Parameter

```
class ParamName(Enum):
    TRUCK_CAPACITY = 0
    EXCAVATOR_COST = 1
    TRUCK_COST = 2
    OTHER_COST = 3
    LOAD_VOLUME = 4
    SIM_NUM = 5
    FULL_SPEED_BAD = 6
    FULL_SPEED_GOOD = 7
    EMPTY_SPEED_BAD = 8
    EMPTY_SPEED_GOOD = 9
    LOAD_TIME = 10
    DUMP_TIME = 11
```

Initialize Class for EOAP Tool User Interface

```
class simulationUI(Tk):
    def_init_(self):
        super().__init__()
        self.title(u'Earthmoving Operation Analysis Platform (EOAP)')
        self.param = Param(True)
        self.excavatorType = set()
        self.truckType = set()

        mainframe = ttk.Frame(self)
        mainframe.grid(column=0, row=0)
```

```
        self.taskLabelFrame = simulationUI.TaskLabelFrame(mainframe, self.param)

        row = 0
        self.taskLabelFrame.frame.grid_configure(pady=5)
        self.taskLabelFrame.frame.grid(column=0, columnspan=6, row=row)

        row += 1
        btn = tk.Button(mainframe, text='Optimize Truck Number', command=self.ShowSubWin1,
height=2)
        btn.grid(column = 2, row=row, pady=30)
        btn = tk.Button(mainframe, text='Optimize Truck/Excavator Type',
command=self.ShowSubWin2, height=2)
        btn.grid(column = 3, row=row, pady=30)
```

Truck Number Identification

```
    def ShowSubWin1(self):
        w = tk.Toplevel()
        w.title='Optimize Truck Number'
        mainframe = ttk.Frame(w)
        mainframe.grid(column=0, row=0)

        param_names = [ParamName.TRUCK_CAPACITY, ParamName.EXCAVATOR_COST,
ParamName.TRUCK_COST,
                    ParamName.OTHER_COST, ParamName.LOAD_VOLUME,
ParamName.SIM_NUM]
        self.ParamEntries = [simulationUI.ParamEntry(mainframe, id, self.param) for id in
param_names]
        tri_param_names = [ParamName.FULL_SPEED_BAD,
ParamName.FULL_SPEED_GOOD, ParamName.EMPTY_SPEED_BAD,
                      ParamName.EMPTY_SPEED_GOOD, ParamName.LOAD_TIME,
ParamName.DUMP_TIME]
        self.TriLabelFrames = [simulationUI.TriLabelFrame(mainframe, id, self.param) for id in
tri_param_names]

        row = 0
        col = 0
        for i in range(len(param_names)):
            if col == 6:
                col = 0
                row += 1
            self.ParamEntries[i].Label.grid(column=col, row=row, sticky=E)
            self.ParamEntries[i].Label.grid_configure(padx=3, pady=3)
            self.ParamEntries[i].Entry.grid(column=col+1, row=row, sticky=W)
            self.ParamEntries[i].Entry.grid_configure(padx=3, pady=3)
```

```
            col += 2

        row += 1
        col = 0
        for i in range(len(self.TriLabelFrames)):
            if col == 6:
                col = 0
                row += 1
            self.TriLabelFrames[i].frame.grid(column=col, columnspan=2, row=row)
            self.TriLabelFrames[i].frame.grid_configure(padx=3, pady=5)
            col += 2

        row += 1
        col = 2
        self.ParamEntries[-1].Label.grid(column=col, row=row, sticky=E)
        self.ParamEntries[-1].Label.grid_configure(padx=3, pady=3)
        self.ParamEntries[-1].Entry.grid(column=col+1, row=row, sticky=W)
        self.ParamEntries[-1].Entry.grid_configure(padx=3, pady=3)
        self.SimButton = ttk.Button(mainframe, command=self.Simulation, text=u'Run')
        self.SimButton.grid(column=col+2, columnspan = 2, row=row)
```

Equipment Type Identification

```
    def ShowSubWin2(self):
        w = tk.Toplevel()
        w.title('Optimize Truck/Excavator Type')
        mainframe = ttk.Frame(w)
        mainframe.grid(column=0, row=0)
        excavatorTypeFrame = simulationUI.DeviceTypeFrame(mainframe,0,self.excavatorType)
        truckTypeFrame = simulationUI.DeviceTypeFrame(mainframe,1,self.truckType)

        row = 0
        deviceTypeFrame = excavatorTypeFrame
        deviceTypeFrame.Label.grid(column=0, row=row, padx=10, sticky=E)
        deviceTypeFrame.typeComb.grid(column=1, row=row, padx=10, sticky=W)
        deviceTypeFrame.lstBox.grid(column=3, row=row, rowspan=2, padx=15, pady=15)
        row += 1
        deviceTypeFrame.addBtn.grid(column=0, row=row, padx=10)
        deviceTypeFrame.delBtn.grid(column=1, row=row, padx=10)
        row+=1
        deviceTypeFrame = truckTypeFrame
        deviceTypeFrame.Label.grid(column=0, row=row, padx=10, sticky=E)
        deviceTypeFrame.typeComb.grid(column=1, row=row,padx=10, sticky=W)
        deviceTypeFrame.lstBox.grid(column=3, row=row, rowspan=2, pady=15)
        row += 1
        deviceTypeFrame.addBtn.grid(column=0, row=row)
```

```
        deviceTypeFrame.delBtn.grid(column=1, row=row)
        row += 1
        self.batchSimBtn = ttk.Button(mainframe, text='Optimize',
command=self.BatchSimulation)
        self.batchSimBtn.grid(column=3, row=row, pady=15)
```

Built-in Equipment Performance Variables

```
    def BatchSimulation(self):
        def SetParam(e, t):
            if e in ['307', '308D']:
                self.param.load_volume = 0.23
                self.param.excavator_cost = 150
                self.param.useMC = True
                self.param.tri_load_time = Triangular(0.21, 0.28, 0.38)
            elif e in ['311D']:
                self.param.load_volume = 0.45
                self.param.excavator_cost = 160
                self.param.useMC = True
                self.param.tri_load_time = Triangular(0.22, 0.28, 0.39)
            elif e in ['M314F', 'M315D2', '312D']:
                self.param.load_volume = 0.61
                self.param.excavator_cost = 175
                self.param.useMC = True
                self.param.tri_load_time = Triangular(0.22, 0.30, 0.40)
            elif e in ['M316F','M317D2','M318F','315DL']:
                self.param.load_volume = 0.75
                self.param.excavator_cost = 180
                self.param.useMC = True
                self.param.tri_load_time = Triangular(0.22, 0.30, 0.40)
            elif e in ['M320F','M320D2','319D']:
                self.param.load_volume = 0.90
                self.param.excavator_cost = 185
                self.param.useMC = True
                self.param.tri_load_time = Triangular(0.25, 0.33, 0.42)
            elif e in ['322F','M322D2','320D','323D']:
                self.param.load_volume = 0.80
                self.param.excavator_cost = 190
                self.param.useMC = True
                self.param.tri_load_time = Triangular(0.26, 0.33, 0.42)
            elif e in ['324D']:
                self.param.load_volume = 1.0
                self.param.excavator_cost = 210
                self.param.useMC = True
                self.param.tri_load_time = Triangular(0.27, 0.35, 0.43)
```

```
elif e in ['329D']:
    self.param.load_volume = 1.10
    self.param.excavator_cost = 225
    self.param.useMC = True
    self.param.tri_load_time = Triangular(0.27, 0.35, 0.44)
elif e in ['336D']:
    self.param.load_volume = 0.53
    self.param.excavator_cost = 245
    self.param.useMC = True
    self.param.tri_load_time = Triangular(0.28, 0.36, 0.45)
elif e in ['349D2','349E','349F']:
    self.param.load_volume = 2.30
    self.param.excavator_cost = 270
    self.param.useMC = True
    self.param.tri_load_time = Triangular(0.27, 0.35, 0.49)
elif e in ['365CL']:
    self.param.load_volume = 1.90
    self.param.excavator_cost = 300
    self.param.useMC = True
    self.param.tri_load_time = Triangular(0.27, 0.43, 0.60)
elif e in ['385C']:
    self.param.load_volume = 3.80
    self.param.excavator_cost = 325
    self.param.useMC = True
    self.param.tri_load_time = Triangular(0.28, 0.45, 0.67)

if t in ['725C']:
    self.param.truck_capacity = 11
    self.param.truck_cost = 75
    self.param.tri_full_speed_bad = Triangular(13, 22, 33)
    self.param.tri_full_speed_good = Triangular(28, 45, 56)
    self.param.tri_empty_speed_bad = Triangular(29, 34, 49)
    self.param.tri_empty_speed_good = Triangular(41, 51, 56)
elif t in ['730C']:
    self.param.truck_capacity = 13.3
    self.param.truck_cost = 80
    self.param.tri_full_speed_bad = Triangular(17, 24, 38)
    self.param.tri_full_speed_good = Triangular(35, 50, 60)
    self.param.tri_empty_speed_bad = Triangular(31, 37, 50)
    self.param.tri_empty_speed_good = Triangular(46, 52, 60)
elif t in ['735C']:
    self.param.truck_capacity = 15
    self.param.truck_cost = 85
    self.param.tri_full_speed_bad = Triangular(12, 20, 51)
    self.param.tri_full_speed_good = Triangular(34, 50, 60)
    self.param.tri_empty_speed_bad = Triangular(27, 33, 46)
```

```
            self.param.tri_empty_speed_good = Triangular(36, 51, 60)
        elif t in ['740C']:
            self.param.truck_capacity = 18
            self.param.truck_cost = 90
            self.param.tri_full_speed_bad = Triangular(16, 24, 34)
            self.param.tri_full_speed_good = Triangular(29, 45, 55)
            self.param.tri_empty_speed_bad = Triangular(30, 36, 45)
            self.param.tri_empty_speed_good = Triangular(38, 50, 55)
        elif t in ['745C']:
            self.param.truck_capacity = 18.5
            self.param.truck_cost = 100
            self.param.tri_full_speed_bad = Triangular(15, 22, 30)
            self.param.tri_full_speed_good = Triangular(28, 45, 55)
            self.param.tri_empty_speed_bad = Triangular(31, 36, 48)
            self.param.tri_empty_speed_good = Triangular(40, 51, 55)
```

Simulation Output Print Out

```
    self.batchSimBtn.state(['disabled'])
    sim_result = dict()
    for excavator in self.excavatorType:
        for truck in self.truckType:
            SetParam(excavator, truck)
            self.param.sim_num = 10
            print('\nExcavator: {}, Truck: {}'.format(excavator, truck))
            print('================================')
            best_trucknum, best_cost = JobSim(self.param)
            sim_result[(excavator, truck)] = (sum(best_cost), best_trucknum)
    if len(sim_result.keys()) > 0:
        v, k = min(zip(sim_result.values(), sim_result.keys()))
        print('\nSimulation Result:\n\tBest excavator:\t{}\n\tBest truck:\t{}\n\tTotal
cost:\t${:.2f}'.format(k[0], k[1], v[0]))
    self.batchSimBtn.state(['!disabled'])

  def Simulation(self):
    self.SimButton.state(['disabled'])
    self.param.useMC = False
    for t in self.ParamEntries:
        t.SetParam(self.param)
    for t in self.TriLabelFrames:
        t.SetParam(self.param)
    if not self.param.useMC:
        self.param.sim_num = 1
    best_trucknum, best_cost = JobSim(self.param)
    print(u'Total cost: {}'.format(sum(best_cost)))
    self.SimButton.state(['!disabled'])
```

EOAP Tool User Interface Development

```
    class DeviceTypeFrame():
        def __init__(self, parent, id, deviceType):
            labels = {0: 'Excavator Type',
                      1: 'Truck Type'}
            self.Label = ttk.Label(parent, text=labels[id])
            self.typeComb = ttk.Combobox(parent, width=8)
            self.addBtn = ttk.Button(parent, text='Add', command=self.AddDeviceType)
            self.delBtn = ttk.Button(parent, text='Delete', command=self.DelDeviceType)
            self.lstBoxStr = StringVar()
            self.lstBox = tk.Listbox(parent, height=5, listvariable=self.lstBoxStr,
selectmod=tk.MULTIPLE)
            if id == 1:
                self.allTypes = ['725C', '730C', '735C', '740C', '745C']
            else:
                self.allTypes = ['307C', '308D', '311D', '312D', '315DL', '319D ', '320D', '322F', '323D',
'324D', '329D', '336D',
                                 '349D2', '349E', '349F', '365CL', '385C', 'M314F', 'M315D2', 'M316F',
'M317D2', 'M318F', 'M320D2', 'M320F', 'M322D2']
            self.typeComb['values'] = tuple(self.allTypes)
            self.typeComb.current(0)
            self.selectedTypes = deviceType

        def AddDeviceType(self):
            self.selectedTypes.add(self.allTypes[self.typeComb.current()])
            self.lstBoxStr.set(' '.join(self.selectedTypes))

        def DelDeviceType(self):
            lstStr = make_tuple(self.lstBoxStr.get())
            for i in self.lstBox.curselection():
                self.selectedTypes.discard(lstStr[i])
            self.lstBoxStr.set(' '.join(self.selectedTypes))

    class ParamEntry():
        def __init__(self, parent, id, param):
            labels = {ParamName.TRUCK_CAPACITY: u'Truck Capacity (m3)',
                      ParamName.EXCAVATOR_COST: u'Excavator Unit Rate ($/hr)',
                      ParamName.TRUCK_COST: u'Truck Unit Rate ($/hr)',
                      ParamName.OTHER_COST: u'Field Overhead Unit Rate ($/hr)',
                      ParamName.LOAD_VOLUME: u'Bucket Size (m3)',
                      ParamName.SIM_NUM: u'Run Count'}
            params = {ParamName.TRUCK_CAPACITY: param.truck_capacity,
                      ParamName.EXCAVATOR_COST: param.excavator_cost,
                      ParamName.TRUCK_COST: param.truck_cost,
```

```
            ParamName.OTHER_COST: param.other_cost,
            ParamName.LOAD_VOLUME: param.load_volume,
            ParamName.SIM_NUM: param.sim_num}
        self.Label = ttk.Label(parent, text=labels[id])
        self.strVar = StringVar()
        self.Entry = ttk.Entry(parent, width=8, textvariable=self.strVar)
        self.id = id
        self.strVar.set(str(params[id]))

    def SetParam(self, param):
        if self.id == ParamName.TRUCK_CAPACITY:
            param.truck_capacity = float(self.strVar.get())
        elif self.id == ParamName.EXCAVATOR_COST:
            param.excavator_cost = float(self.strVar.get())
        elif self.id == ParamName.TRUCK_COST:
            param.truck_cost = float(self.strVar.get())
        elif self.id == ParamName.OTHER_COST:
            param.other_cost = float(self.strVar.get())
        elif self.id == ParamName.LOAD_VOLUME:
            param.load_volume = float(self.strVar.get())
        elif self.id == ParamName.SIM_NUM:
            param.sim_num = int(self.strVar.get())
        else:
            pass

class TaskLabelFrame():
    def __init__(self, parent, param):
        self.param = param
        self.frame = ttk.Labelframe(parent, text=u'Haul Job(s)')
        self.taskNumLabel = ttk.Label(self.frame, text=u'Haul Job Count')
        self.taskNumLabel.grid_configure(padx=5, pady=5)
        self.taskNumStrVar = StringVar()
        self.taskNumEntry = ttk.Entry(self.frame, textvariable=self.taskNumStrVar, width=8)
        self.taskNumStrVar.set(str(len(param.total_volumes)))
        self.taskNumEntry.grid_configure(padx=5, pady=5)

        self.curTaskLabel = ttk.Label(self.frame, text=u'Current Haul Job')
        self.curTaskLabel.grid_configure(padx=5, pady=5)
        self.curTaskComb = ttk.Combobox(self.frame, width=8)
        self.curTaskComb.state(['readonly'])
        taskNo = []
        for i in range(len(param.total_volumes)):
            taskNo.append(str(i))
        self.curTaskComb['values'] = tuple(taskNo)
        self.curTaskComb.current(0)
        self.curTaskComb.bind('<<ComboboxSelected>>', self.CombCallback)
```

```
        self.curTaskComb.grid_configure(padx=5, pady=5)

        self.addTaskBtn = ttk.Button(self.frame, text=u'Add', width=8, command=self.AddTask)
        self.addTaskBtn.grid_configure(padx=5, pady=5)
        self.removeTaskBtn = ttk.Button(self.frame, text=u'Delete', width=8,
command=self.DelTask)
        self.removeTaskBtn.grid_configure(padx=5, pady=5)

        self.totalVolLabel = ttk.Label(self.frame, text=u'Earthwork Quantity (m3)')
        self.totalVolLabel.grid_configure(padx=5, pady=5)
        self.totalVolStrVar = StringVar()
        self.totalVolEntry = ttk.Entry(self.frame, textvariable=self.totalVolStrVar, width=8)
        self.totalVolStrVar.set(str(param.total_volumes[0]))
        self.totalVolEntry.grid_configure(padx=5, pady=5)
        self.totalVolEntry.bind('<FocusOut>', self.TotalVolCallback)

        self.goodDisLabel = ttk.Label(self.frame, text=u'Length of High-grade Road (m)')
        self.goodDisLabel.grid_configure(padx=5, pady=5)
        self.goodDisStrVar = StringVar()
        self.goodDisEntry = ttk.Entry(self.frame, textvariable=self.goodDisStrVar, width=8)
        self.goodDisStrVar.set(str(param.good_distances[0]))
        self.goodDisEntry.grid_configure(padx=5, pady=5)
        self.goodDisEntry.bind('<FocusOut>', self.GoodDisCallback)

        self.badDisLabel = ttk.Label(self.frame, text=u'Length of Low-grade Road (m)')
        self.badDisLabel.grid_configure(padx=5, pady=5)
        self.badDisStrVar = StringVar()
        self.badDisEntry = ttk.Entry(self.frame, textvariable=self.badDisStrVar, width=8)
        self.badDisStrVar.set(str(param.bad_distances[0]))
        self.badDisEntry.grid_configure(padx=5, pady=5)
        self.badDisEntry.bind('<FocusOut>', self.BadDisCallback)

        self.Layout()

    def TotalVolCallback(self, event):
        t = self.curTaskComb.current()
        self.param.total_volumes[t] = float(self.totalVolStrVar.get())

    def GoodDisCallback(self, event):
        t = self.curTaskComb.current()
        self.param.good_distances[t] = float(self.goodDisStrVar.get())

    def BadDisCallback(self, event):
        t = self.curTaskComb.current()
        self.param.bad_distances[t] = float(self.badDisStrVar.get())
```

```
def CombCallback(self, event):
    t = self.curTaskComb.current()
    self.totalVolStrVar.set(self.param.total_volumes[t])
    self.goodDisStrVar.set(self.param.good_distances[t])
    self.badDisStrVar.set(self.param.bad_distances[t])

def AddTask(self):
    self.param.total_volumes.append(24000)
    self.param.good_distances.append(900)
    self.param.bad_distances.append(424)
    self.taskNumStrVar.set(len(self.param.total_volumes))
    taskNo = []
    for i in range(len(self.param.total_volumes)):
        taskNo.append(str(i))
    self.curTaskComb['values'] = tuple(taskNo)
    self.curTaskComb.current(len(self.param.total_volumes) - 1)
    if (len(self.param.total_volumes) == 1):
        self.removeTaskBtn.state(['disabled'])
    else:
        self.removeTaskBtn.state(['!disabled'])

def DelTask(self):
    t = self.curTaskComb.current()
    self.param.total_volumes.pop(t)
    self.param.good_distances.pop(t)
    self.param.bad_distances.pop(t)
    taskNo = []
    for i in range(len(self.param.total_volumes)):
        taskNo.append(str(i))
    self.curTaskComb['values'] = tuple(taskNo)
    self.curTaskComb.current(0)
    if (len(self.param.total_volumes) == 1):
        self.removeTaskBtn.state(['disabled'])
    self.taskNumStrVar.set(len(self.param.total_volumes))
    self.totalVolStrVar.set(self.param.total_volumes[0])
    self.goodDisStrVar.set(self.param.good_distances[0])
    self.badDisStrVar.set(self.param.bad_distances[0])

def Layout(self):
    row = 0
    self.taskNumLabel.grid(column=0, row=row, sticky=E)
    self.taskNumEntry.grid(column=1, row=row, sticky=W)
    self.taskNumEntry.state(['disabled'])
    self.curTaskLabel.grid(column=2, row=row, sticky=E)
    self.curTaskComb.grid(column=3, row=row, sticky=W)
    self.addTaskBtn.grid(column=4, row=row)
```

```
        self.removeTaskBtn.grid(column=5, row=row)
        row += 1
        self.totalVolLabel.grid(column=0, row=row, sticky=E)
        self.totalVolEntry.grid(column=1, row=row, sticky=W)
        self.goodDisLabel.grid(column=2, row=row, sticky=E)
        self.goodDisEntry.grid(column=3, row=row, sticky=W)
        self.badDisLabel.grid(column=4, row=row, sticky=E)
        self.badDisEntry.grid(column=5, row=row, sticky=W)
        if (len(self.param.total_volumes) == 1):
            self.removeTaskBtn.state(['disabled'])

class TriLabelFrame():
    def __init__(self, parent, id, param):
        labels = {ParamName.EMPTY_SPEED_GOOD: u'Unloaded Speed on High-grade
(km/h)',
                  ParamName.FULL_SPEED_GOOD: u'Loaded Speed on High-grade (km/h)',
                  ParamName.EMPTY_SPEED_BAD: u'Unloaded Speed on Low-grade (km/h)',
                  ParamName.FULL_SPEED_BAD: u'Loaded Speed on Low-grade (km/h)',
                  ParamName.LOAD_TIME: u'Load One Bucket (min)',
                  ParamName.DUMP_TIME: u'Truck Dumping (min)'}
        params = {ParamName.EMPTY_SPEED_GOOD: param.tri_empty_speed_good,
                  ParamName.FULL_SPEED_GOOD: param.tri_full_speed_good,
                  ParamName.EMPTY_SPEED_BAD: param.tri_empty_speed_bad,
                  ParamName.FULL_SPEED_BAD: param.tri_full_speed_bad,
                  ParamName.LOAD_TIME: param.tri_load_time,
                  ParamName.DUMP_TIME: param.tri_dump_time}

        self.frame = ttk.LabelFrame(parent, text=labels[id])
        self.Type = ttk.Label(self.frame, text=u'Type')
        self.TypeComb = ttk.Combobox(self.frame, width = 8)
        self.TypeComb['values'] = (u'Constant', u'Triangle')
        self.TypeComb.state(['readonly'])
        self.id = id
        self.tri = params[id]

        if self.tri.Min == self.tri.Max:
            self.TypeComb.current(0)
        else:
            self.TypeComb.current(1)
        self.TypeComb.bind('<<ComboboxSelected>>', self.CombCallback)

        entryWidth = 8
        self.Min = ttk.Label(self.frame, text='Min')
        self.MinVar = StringVar()
        self.MinEntry = ttk.Entry(self.frame, width=entryWidth, textvariable=self.MinVar)
        self.MinVar.set(str(self.tri.Min))
```

```
        self.Mode= ttk.Label(self.frame, text='Mode')
        self.ModeVar = StringVar()
        self.ModeEntry = ttk.Entry(self.frame, width=entryWidth, textvariable=self.ModeVar)
        self.ModeVar.set(str(self.tri.Mode))

        self.Max = ttk.Label(self.frame, text='Max')
        self.MaxVar = StringVar()
        self.MaxEntry = ttk.Entry(self.frame, width=entryWidth, textvariable=self.MaxVar)
        self.MaxVar.set(str(self.tri.Max))

        self.Layout()
        self.SetSpeedType()

    def Layout(self):
        row = 0
        self.Type.grid(column=0, row=row, sticky=E)
        self.TypeComb.grid(column=1, row=row, sticky=W)
        row += 1
        self.Mode.grid(column=0, row=row, sticky=E)
        self.ModeEntry.grid(column=1, row=row, sticky=W)
        row += 1
        self.Min.grid(column=0, row=row, sticky=E)
        self.MinEntry.grid(column=1, row=row, sticky=W)
        row += 1
        self.Max.grid(column=0, row=row,sticky=E)
        self.MaxEntry.grid(column=1, row=row, sticky=W)
        for child in self.frame.winfo_children():
            child.grid_configure(padx=3, pady=3)

    def CombCallback(self, event):
        self.SetSpeedType()

    def SetSpeedType(self):
        t = self.TypeComb.current()
        if t == 0:
            self.MinEntry.state(['disabled'])
            self.MaxEntry.state(['disabled'])
            self.MinVar.set(self.ModeVar.get())
            self.MaxVar.set(self.ModeVar.get())
        else:
            self.MinEntry.state(['!disabled'])
            self.MaxEntry.state(['!disabled'])

    def SetParam(self, param):
        t = self.TypeComb.current()
```

```
        if t == 0:
            self.tri.Mode = float(self.ModeVar.get())
            self.tri.Min = self.tri.Mode
            self.tri.Max = self.tri.Mode
        else:
            param.useMC = True
            self.tri.Mode = float(self.ModeVar.get())
            self.tri.Min = float(self.MinVar.get())
            self.tri.Max = float(self.MaxVar.get())

if __name__ == '__main__':
    sui = simulationUI()
    sui.mainloop()
```