Optimization of Temporary Haul Road Design and Earthmoving Job Planning based on Site Rough-grading Design

by

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ABSTRACT

Site rough-grading operations are the preliminary work of the construction projects in remote areas especially in Northern Alberta. Haulage cost typically accounts for around 30% of the total cost of mass earthmoving projects. The temporary haul road network built in the earthmoving field is one major factor influencing haulage cost and production efficiency, which remains an empirical design problem at present. In order to convert it into an analytical problem, this study firstly utilizes the Floyd-Warshall algorithm and linear programming model to formulate the earthmoving planning based on a certain layout of temporary road network, shedding light on the potential benefits of selecting routes and directions for handling earthmoving jobs. On the basis of the optimization of earthmoving job planning, the optimization of layout of temporary road network is further proposed by using multi-generation compete genetic algorithm. The optimization approaches are explained in details through a practical application. Based on analytical analysis and numerical applications, it is proved that the optimization approach can reduce the total cost of the project and shortens its duration. In addition, simulation models are used to prove the effectiveness and feasibility of optimization results. The study conducts comprehensive and in-depth analyses to tackle the temporary haul road network design problem in the context of earthworks planning, which can provide decision support in planning and executing massive earthworks.

PREFACE

This thesis is an original work by Chang Liu. No part of this thesis has been previously published.

ACKNOWLEDGEMENT

I sincerely thank Dr. Ming Lu, my supervisor and mentor. I am extremely grateful for his vision, support, encouragement, and guidance for years during my study. His sound knowledge, deep thinking, and academic rigor have led my way to the successful completion of my MSc program, as well as motivated me to bring out myself.

Special thanks to Sam Johnson, Project Manager, Commercial / Civil, Alberta North, Graham Management Services for sharing his vision and insight and providing case study support in the present research. His continuous support and assistance helped me in collecting and sharing project data, analyzing construction processes, and gaining insight into field operations, which provided me a great opportunity to obtain experience and knowledge on earthworks design and construction.

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c	capacity of one truck;
C_c	construction and removal costs;
C_e	hourly or daily costs of equipment and crew;
C_m	maintenance, risk and other costs;
C_t	total cost;
$C_{m\text{-}r}$	maintenance, risk and other costs if trucks haul on rough ground;
$C_{m\text{-}t}$	maintenance, risk and other costs if trucks haul on temporary road network;
C_{op}	operating cost;
C_{rn}	road network costs;
d_{ij}	Euclidean distance between the centroids of adjacent i^{th} and j^{th} cells;
f	the working efficiency;
n	truck number;
p	proportion of temporarily built roads;
$\mathbf{P}_{ij}$	shortest haul-time path matrix;
Q	total earthwork quantity after balancing cut and fill volume;
s_{ij}	shortest haul time between the i^{th} and j^{th} cells;
$\mathbf{S}_{ij}$	shortest haul time matrix;
t_h	average haul time per trip;
t_{limit}	limit of the average haul time per in genetic algorithm;
v_{ij}	haul speed of a fully-loaded truck between adjacent i^{th} and j^{th} cells;
V_{ij}	volume to be moved between the i^{th} and j^{th} cells;
$V_{i\text{-}cut}$	total cut volume of the i^{th} cell;
$V_{j\text{-}fill}$	total fill volume of the j^{th} cell;
w_{ij}	weight between i^{th} and j^{th} cells;
$\mathbf{W}_{ij}$	weight matrix;

1 Introduction

The temporary road network design is a major factor influencing haulage cost and production efficiency for mass earthworks in remote areas. So far the design of haul road network relies on experience and there is no analytical method to achieve optimal layout. To increase the earthmoving productivity and save cost, there is an immediate necessity to augment currently empirical design methods with analytical methods.

In order to ensure safety and productivity of earthmoving operations in the preliminary site-grading phase of developing infrastructure, mining and industrial projects, temporary haul road networks are designed, developed, and maintained, which generally contain many intersections and carry complicated traffic flows of heavy trucks. In current practice of mining engineering, guidelines are generally available to regulate on all aspects of haul road design on mining projects, including its alignment, surface, material and trucks operating on it so as to ensure efficiency and safety; for instance, the road width should be 3 to 4 times the width of the widest heavy hauler (Tannant and Regensburg 2001). Unlike the mining project, for site grading and earthmoving operations over a large area, it is not realistic to link a loading area (cut) and a dumpsite area (fill) by permanent haul roads. The common practice is to build a limited length of temporary haul roads (e.g. gravel surfaced) along the critical truck hauling paths on site. Those haul roads need to be maintained from time to time and eventually removed at the end of construction. Trucks also need to operate on rough-ground roads, which require the frequent use of graders or bulldozers to maintain serviceability.

As a critical component of planning mass earthworks projects, haul road network should be well-planned and designed based on the available information such as site grading designs (cut and fill design). As for haul road network layout design, there are two main tasks: 1) to design a cost-efficient haul road network which is conducive to delivering the project within the expected duration and budget; and 2) to achieve an execution earthmoving plan for the operators to execute at the earthmoving stage. To achieve optimized earthmoving planning, the present research connects the concepts in transportation engineering with construction engineering. To further design an effective haul road network, the present research proposes a grid-based temporary haul road network design and optimization method applicable to a site for which grading design has been completed.

In Chapter 3, adding to the existing body of knowledge, a quantitative methodology for optimizing the detailed planning of earthmoving jobs based on a particular temporary haul road network design is proposed. Each job is defined in terms of the source cell, the destination cell, the earth volume, and the shortest-hauling-time path between the source and destination. Through seamless integration of the Floyd-Warshall algorithm and linear programming model, following the existing haul road network, the shortest average unit haul time of trucks can be obtained. Based on the resulting average unit haul time, cost equations are defined to account for 1) the direct truck-hauling crew cost and 2) building, maintenance and removal costs of temporary haul roads. As such, the cost associated with executing the optimized earthmoving job plan over a particular haul road network design can be readily assessed, making it straightforward for project managers to evaluate the layout design.

Current empirical design methods cannot guarantee the generation of the most cost-effective temporary haul road network design. Based on the evaluation criteria after establishing the approach for achieving optimized earthmoving planning, different design layouts can be compared with one another on the same basis, which provides the opportunity to optimize the layout of temporary haul road network through heuristic searching algorithms. In Chapter 3, the layout optimization method is also established on the basis of the Floyd-Warshall algorithm and a linear programming model. Based on the genetic algorithm and the objective function defined for genetic algorithm, the optimal layout design of temporary haul road network can be achieved so that the decision-makers can finally benefit from an optimized layout in the planning stage. The road planning problem is no longer empirical, and it becomes analytical and solvable as part of earthworks design so to some extent the research successfully solves a subjective planning problem in an objective fashion. The proposed approach could assist both experienced decision-makers and junior engineers to identify an optimized temporary haul road network design along with earthmoving operations planning.

The proposed optimization approaches based on the defined total cost (C_t) are illustrated in the Figure 1.1. The optimizations can meet practical needs for both temporary road network planning and earthmoving execution planning.

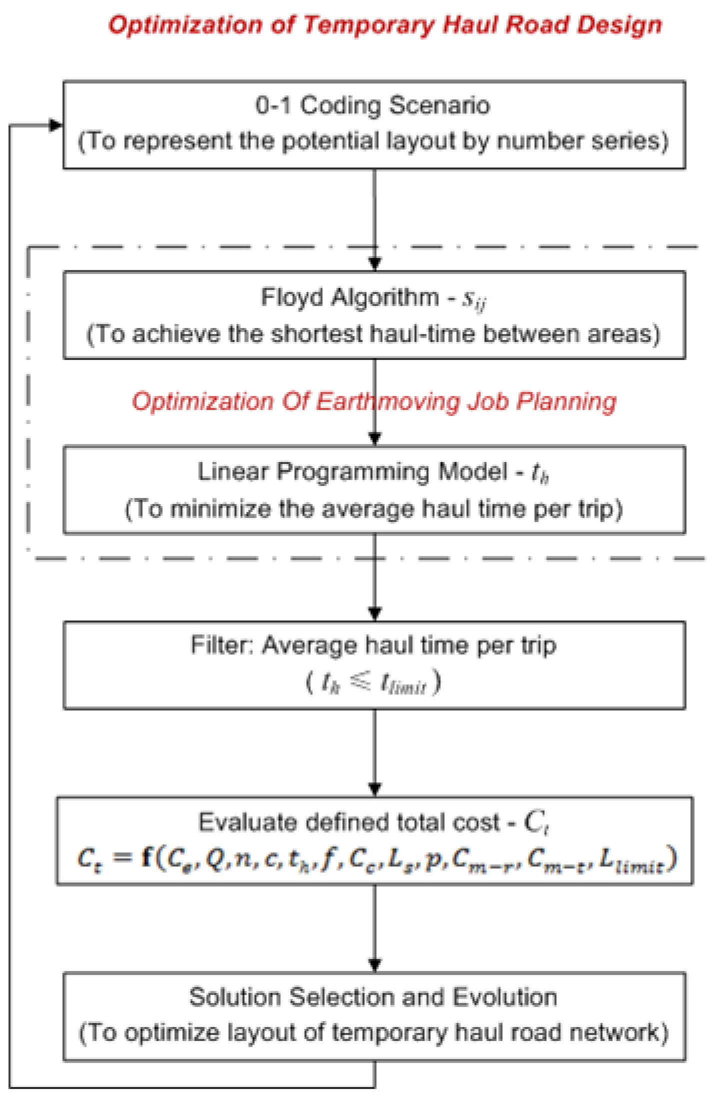


Figure 1.1 Optimization Flowchart

The relationships between optimization of earthmoving job plan and optimization of temporary haul road layout are demonstrated in the Figure 1.2. Although the optimization of earthmoving job plan is embedded into the layout optimization at the planning stage, optimization of earthmoving job plan can be performed separately based on the existing layout of haul road network at the construction stage.

In Chapter 4, the proposed approaches are demonstrated in steps using numerical examples and further applied in a case study which is a real-world massive earthmoving project in Northern Alberta. Furthermore, simulation models are used as validation tool to prove the effectiveness and feasibility of the optimization results. In addition, limitations of proposed methods and conclusions are stated in Chapter 5.

2 Literature Review

Research has built a solid foundation for earthworks optimization, especially in regard to balancing cut and fill volumes in site-grading design. Theoretically, it is widely held that project cost can be minimized through formulating an optimal plan for transportation of materials between cut sections and fill sections (Mayer and Stark 1981). Among the optimization approaches, mass diagram is the simplest and the most commonly used especially for planning linear construction projects such as road construction (Jayawardane and Harris 1990). To address more complex problems, linear programming model plays the key role to minimize haul distances and decide haul directions for earthmoving operations (Son et al. 2005). With the ever-increasing computing power, large-scale optimizations for mass earthworks can be readily achieved through using professional software such as *Civil 3D* or *AGTEK* as demonstrated in Figure 1.2. For instance, the problem for allocating earthwork materials was formulated as a linear programming model based on the mathematical program of *LINGO* (de Lima et al. 2012).

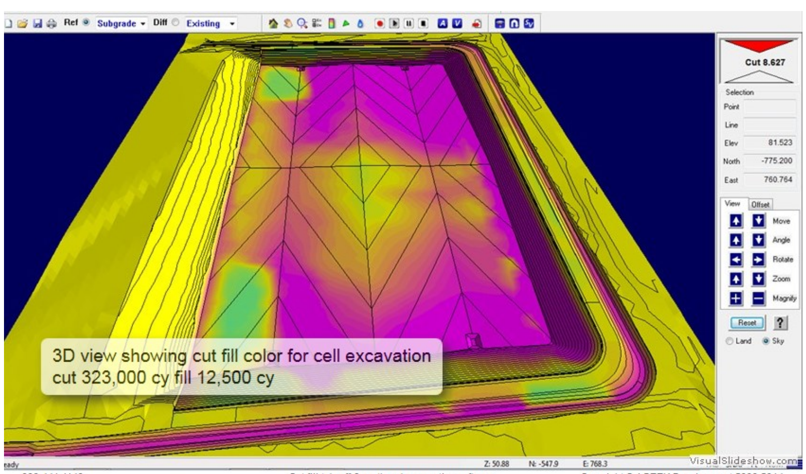


Figure 2.1 AGTEK Interface

With the rapid development of computer technology, discrete event simulation has provided the key methodology to lend effective, relevant decision support for productivity improvement on earthworks projects. Discrete event simulation is a powerful tool to simulate earthmoving operations by factoring in uncertainties. Simulation applications are mainly intended to guide fleet selection and improve productivity of earthmoving operations. Resource-based earthmoving simulation shows its great value in practical applications (Oloufa 1993; Shi and AbouRizk 1994; Hajjar and AbouRizk 1997). With the introduction of evolutionary optimization algorithms, earthwork simulation tools are further enhanced (Marzouk and Moselhi 2003). Integrating pervious research, Moselhi and Alshibani (2009) developed the simulation model for large-scale earthmoving operations. The researches provide insight for improving earthworks, but none has yet formulated a quantitative approach to enhance the cost efficiency of hauling operations by optimizing the design a haul road network. It is noteworthy that simulation research cannot help to improve the layout of haul road network and therefore cannot help to establish the fundamental theory for haul road network layout optimization.

The layout design of haul roads in earthworks can also be classified into "site layout planning problem" in research. Site-layout plan optimization generally assumes the Euclidean distance between two site locations as the travel distance by material handling resources (Zhang et al. 2008; Sanad et al. 2008; Said et al. 2013). It is noteworthy that Euclidean distances were also applied in calculation of haul distances in earthworks design and planning (Son et al. 2005) and average haul distance of trucks are essential criteria in real practice for decades, which can help to estimate cycle time of trucks and direct cost.

2.1 Limitations in Previous Research and Practice

The temporary nature and the complexity inherent in designing an efficient haul road network during the earthmoving operations planning stage have led to a lack of sophisticated guidelines and a shortage of analytic techniques in the construction engineering and management domain. Despite substantial advances, construction operations simulation and earthmoving optimization research has not formalized methodologies that generate cost-effective plans for earthmoving operations based on elaborate temporary haul road network design. This has partly accounted for the fact that optimization results do not necessarily translate into efficiency and profitability in practical applications.

Apparently, simulation models can provide practitioners with insight and lend them decision support during the planning and execution stages of a construction project. On the other hand, simulation models need to be built case by case, making a model specific to the input data describing particular project scenarios and requiring significant efforts to update a model. Additionally, in previous earthmoving simulation research, earthmoving jobs were assumed to be well defined in terms of volume, source, and destination, while the research objectives were largely to select the most efficient fleet and improve resource utilization by eliminating unwanted waiting or queuing time. In general, earthmoving job planning integrated with the temporary road network design has not yet been dealt with in an integrative fashion in previous simulation research.

With regards to optimization research, research deliverables from the mathematical formulation are generally given in the form of either a cut-and-fill-balanced earthworks design (Ji et al. 2009) or minimized haul distances with haul directions for earthmoving operations (Son et al. 2005), without factoring in the haul road network design. The conventional method is to represent the haul distance by linking the centroid of a cut cell to that of a fill cell with a straight line section. It should be pointed out, the Euclidean distance, which represents the point-to-point straight-line path in a site layout model (as in Son et al. 2005), does not in general factor in a haul road network on a construction site. This oversimplifies the haul road alignment design in practice while also ignoring the cost and time implications of laying out temporary haul roads of different grades (gravel road vs. rough ground) along different sections of the truck hauling path. As a result, the haul distance estimate used in planning analyses can be significantly shorter than the actual situation in the field; while given the same distance of a haul road section, the average haul time of the truck can differ considerably when truck hauls on gravel surface instead of rough ground.

Consequently, the research has not yet addressed the immediate needs of field personnel by accounting for sufficient details on earthmoving job planning. As such, the cost efficiency gained from optimization analysis cannot be clearly communicated and readily materialized in the field. In order to overcome the identified limitations in previous simulation and optimization research, the present research is intended to take an integrative approach to problem definition and optimization formulation in such a way that the resulting haul road network layout design can be passed to the superintendent in the field, along with the associated detailed earthmoving job plan.

2.2 Overview of Present Research

To address the "earthmoving job planning over haul road network" problem and assist in making critical decisions in practice, this research is intended to add to the state of the art in construction optimization and simulation by proposing a new methodology. The methodology optimizes the planning of detailed earthmoving jobs based on a particular haul road network design, by seamlessly integrating a linear programming model formulation and a shortest-path-finding algorithm commonly applied in transportation engineering. As such, the objective of generating earthmoving job plans and haul road network designs can be simultaneously fulfilled, achieving both time-efficiency and cost-effectiveness.

In order for a contractor to justify the building and maintenance costs of temporary haul road networks, project duration needs to be accelerated without significantly increasing the project cost. In the present research, a cost function is defined to serve as an effective performance measurement of the temporary haul road network design, which is based on 1) the average hauling time per hauling trip resulting from the optimization analysis; and 2) the total length of temporary haul road in the site. The cost function also accounts for direct truck-hauling crew costs and indirect costs for constructing and maintaining temporary haul roads and rough-ground roads. As such, the cost associated with executing the optimized earthmoving job plan over a particular layout design of temporary haul road network can be readily estimated, making it straightforward for project managers to compare alternatives and select the best one manual or through heuristic searching algorithm.

In regards to earthmoving job planning optimization based on a detailed haul road network design, the use of the haul time for a truck to move earth from the source location to the destination location is a more appropriate performance measure than the haul distance due mainly to two facts: 1) the turn-by-turn travel path on the haul road network needs to be specified for each earthmoving job, while multiple path choices may exist between the same origin and destination; 2) truck hauling speeds differ considerably on different types of roads in the haul road network (temporary gravel-surfaced haul road vs. rough-ground road), while costs to build and maintain various types of haul roads and rough-ground roads also markedly differ.

The remainder of this study starts with differentiating the long-haul vs. the short-haul problems and two network optimization algorithms commonly applied in the transportation engineering domain. Then, a grid-based temporary road network design method is introduced, applicable to a typical site for which grading design and existing ground survey are completed. Further, illustrated by a numerical case, mathematical formulations are provided for optimizing detailed planning of earthmoving jobs based on a particular temporary haul road network design. Each job is defined in terms of the source cell, the destination cell, the earth volume, and the shortest-hauling-time path between source and destination cells. Next, a cost function is established to ensure cost-effectiveness of the optimization results. To demonstrate the application of the proposed methodology in a real-world setting, a case study is presented, in which earthmoving plans based on alternative designs of temporary haul road networks are generated and evaluated. Additionally, using the case study, the research also 1) validates the haul road network design obtained from an independent optimization analysis by cross-checking against the empirical design extracted based on the site layout of the actual case study; and 2) sheds light on the effect of grid size selection upon sufficiency and accuracy of the proposed grid-based methodology for haul road network design and earthmoving job plan. Conclusions are drawn in the end in terms of academic and practical contributions of the present research along with follow-up enhancements.

2.3 Differences from Previous Research

Short-Haul Problem vs. Long-haul Problem

Research has also addressed earthmoving operations in connection with planning long-distance haul roads to export or import earth materials. A novel approach was developed for geography information system (GIS)-based optimization of earthmoving site layout on a dam construction project (Kang et al. 2013). The proposed approach was based on the Dijkstra's algorithm, which is essentially a shortest-path search algorithm in transportation engineering, mainly used for route selection in tackling transportation and logistics problems. The same algorithm was also used to optimize real-time operations of trucks in mining sites based on GPS, improving the selection of routes (Choi and Nieto 2011).

It is noteworthy that for such long-haul problems, the cut and fill balance in the local site is generally not an applicable constraint. A local site is commonly represented as one point on the map associated with a particular quantity of earth to export or import. The site is connected to nearby highways via access roads. As such, addressing long-haul problems is mainly concerned with optimizing truck routing over a network of permanent roads and highways. In such cases, the temporary haul road network design on a local site area is generally irrelevant. In contrast, the problem of designing temporary haul road networks on an earthworks site can be treated as a short-haul problem, which entails detailed analysis of earthmoving operations patterns between multiple loading spots and multiple dumping spots.

The Floyd-Warshall algorithm is another classic algorithm for travel path optimization in the transportation engineering domain. The Floyd-Warshall algorithm, originally developed by Floyd

(1962), has been used to solve a wide range of transport network planning and logistics planning problems in transportation engineering (e.g. Pradhan and Mahinthakumar 2013; Dou et al. 2014). Different from the Dijkstra's Algorithm, the Floyd-Warshall algorithm is designed to handle a large number of sources and thus provides an effective methodology to address the "earthmoving job planning over haul road network" problem from the unique perspective of a multi-source-multi-destination network planning problem in transportation engineering.

Rough-ground Road vs. Temporary Haul Road vs. Permanent Haul Road

In current practice of mining engineering, haul road design guidelines are already available to regulate on all aspects of the haul road for mining projects, including its alignment, surface, material and trucks operating on it so as to ensure efficiency and safety; for instance, the width of haul road should be three to four times the width of the widest heavy hauler (Tannant and Regensburg 2001). Unlike the mining project, for site grading and earthmoving operations over a large area, it is not realistic to link a loading area (cut) and a dumpsite area (fill) by permanent or semi-permanent haul roads since the project generally lasts several months. The common practice is to build a limited length of temporary haul roads (e.g. gravel surfaced) along the critical truck hauling paths on site. Those haul roads need to be maintained (e.g. watering) from time to time and eventually removed at the end of construction. Haulers or trucks also need to operate on original rough-ground of earthmoving field, which require the frequent use of graders or bulldozers to maintain serviceability.

In the *Guidelines for Mine Haul Road Design* (Tannant and Regensburg 2001), haul roads are categorized into temporary, semi-permanent and permanent haul road. The temporary road is stated to be built with lower construction standards, which leads to higher rolling resistance. Due to different needs in earthworks, transportation path with low traffic flow can be built with low-standard temporary haul road or remain rough ground. Therefore, in a large-scale earthmoving field, several different haul road sections comprise the temporary haul road network. To quantitatively evaluate the cost-efficiency of certain layout of temporary haul road network, it is meaningful to propose the analytical method and perform optimization. The decision makers and project managers can benefit much through this study in earthworks.

3 Optimizations Based on Temporary Haul Road Networks Design

3.1 Proposed Methodology

An overview of proposed methodology to address the earthmoving plan optimization and layout optimization of a temporary haul road network is shown in Figure 3.1.

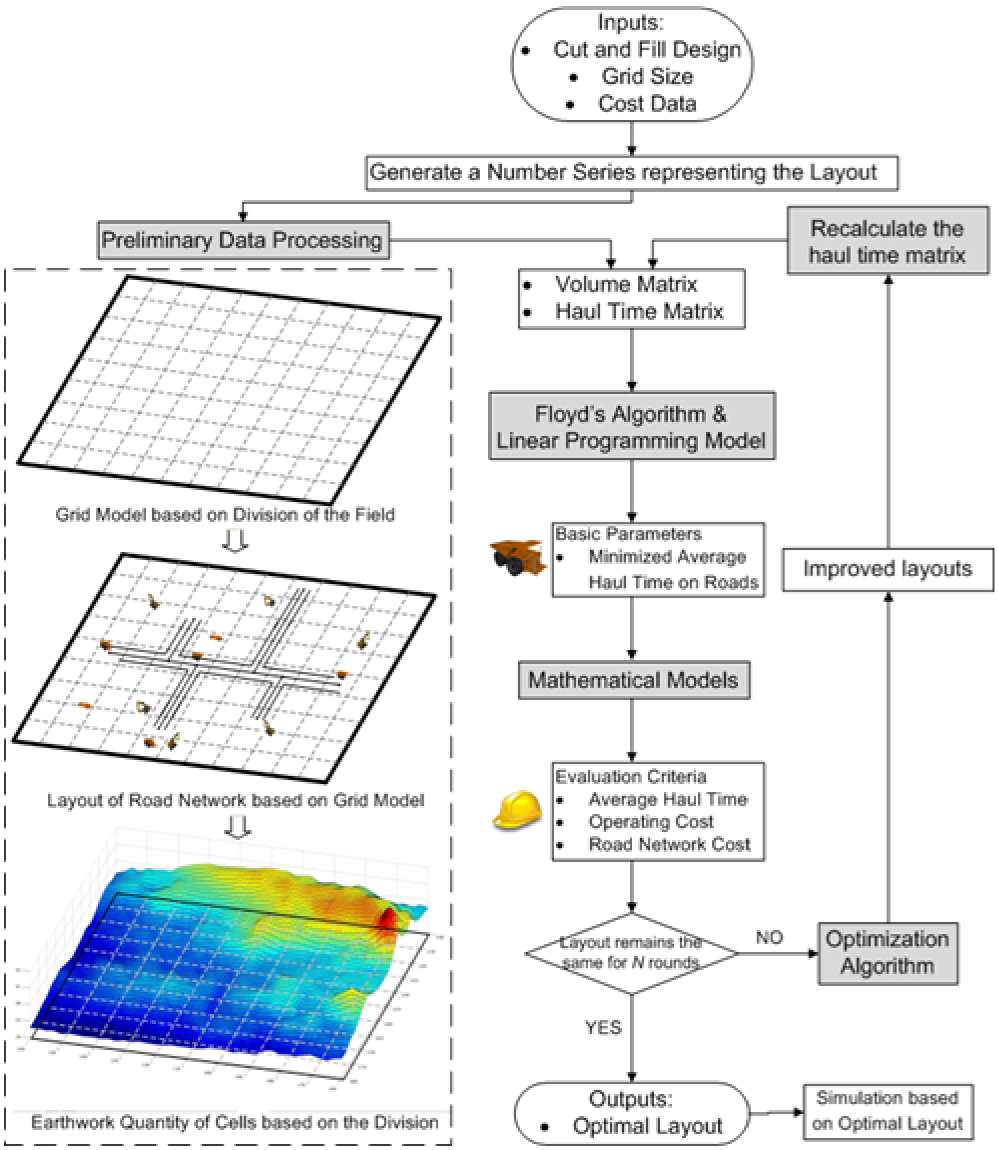


Figure 3.1 Flowchart of the Methodology

The site grading design provides the main input and the site is divided into grids, with cell width being 150 meters or 200 meters. Each line section linking the centroids of two adjacent cells in the grid system horizontally, vertically, or diagonally is encoded as either 1 or 0, with “1” and “0” denoting “gravel-surfaced haul road” and “rough-ground road”, respectively. Note allowing for diagonally linking the centroids of two adjacent cells can effectively simplify any curved alignment in haul road design. As such, a number series can be used to sufficiently represent a potential layout design. Given the site grading design and the layout of the haul road network, the earthwork volume matrix and the truck haul time matrix can be established. Then the Floyd-Warshall algorithm and linear programming model are used to generate detailed earthmoving job plans and identify particular truck-hauling paths for each earthmoving job. At the end, the resulting earthmoving job plan is associated with the minimized average haul time per trip based on a particular design. On the same basis, different alternatives of haul road network designs for the same site can be analyzed and compared based on evaluation criteria including average haul time, operating cost and road network cost. Thus the layout of temporary road network can be improved gradually through heuristic searching algorithm and the optimal layout can be finally achieved. In the following sections, important steps of the proposed methodology are explained in details and illustrated by a numerical example.

3.2 Optimization of Earthmoving Job Planning

3.2.1 Gird Model

The grid model is applied to represent the potential layout of a temporary haul road network. It is obvious that the grid size of a grid model is crucial to design the expected layout of road network. Ideally, in order to increase the accuracy of earthworks quantity takeoff and haul time estimate, the grid size should be as small as possible. Nonetheless, 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. In practice, one main constraint in setting grid size for haul road network design is the distance between two access roads to the main haul road, which is exactly equal to the grid size as demonstrated in Figure 3.2. Generally, the highway geometric design guide regulates the distance exceeds a minimum threshold in order to ensure traffic safety. For instance, the Alberta Ministry of Transportation regulates this distance to be no shorter than 150 m (Alberta Infrastructure and Transportation 1999). By referencing this minimum value and considering other field constraints, the grid size used to model the potential layout of the haul road network should be constrained within certain practical limits. Herein, the grid size of the proposed approach is suggested to be in the range from 150 m to 200 m and the sensitivity analysis of the grid size upon analytical results will be addressed in a later section.

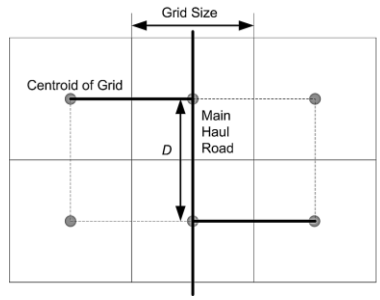


Figure 3.2 Distance between Two Accesses to Main Haul Road (D)

On the other hand, if the grid size is too big, the proposed method may no longer be valid for the following reasons: the division of field by using large grid size cannot model a potential layout accurately. In addition, the detailed earthmoving operations within a cell would be ignored due to the large grid size. Practically, it is common practice for a dozer and a grader to self-balance a small earthmoving area (100 m by 100 m or 150 m by 150 m). Thus, the intra-cell haul distance and effort of trucks, given the cell width is within 100 m or 150 m, can be neglected in the approach being proposed. As such, it is reasonably assumed the net volume (cut or fill) in each cell is concentrated at the center of each cell for site grading operations. However, when dividing the field into 300 m cells, the haul distances of trucks within 300 m cells would be ignored based on our model, which is not realistic in the real world.

In the numerical example, the earthmoving site (600 m by 600 m) is divided into 9 cells (200 m by 200 m each) and connecting adjacent cell centroids generates 20 potential road sections as demonstrated in Figure 3.3. The dotted line indicates rough-ground road as “0” and solid line indicates the gravel-surfaced haul road as “1”. Based on the grid model, the layout in Figure 3.3 can also be represented in a number series with 20 variables, [0, 0, 1, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0], each number denoting the state of a particular road section as listed in Table 3.1.

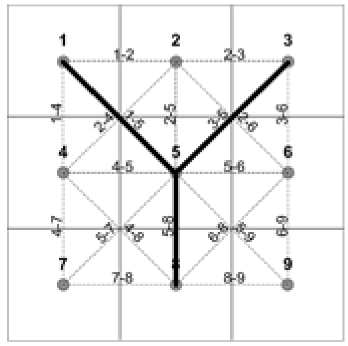


Figure 3.3 Grid Model for Layout Design

Table 3.1 Variables for Road Sections

Road Section	Variable
1-2	0
1-4	0
1-5	1
2-3	0
2-4	0
2-5	0
2-6	0
3-5	1
3-6	0
4-5	0
4-7	0
4-8	0
5-6	0
5-7	0
5-8	1
5-9	0
6-8	0
6-9	0
7-8	0
8-9	0

3.2.2 Floyd-Warshall Algorithm

In the present research, the Floyd-Warshall algorithm is applied to identify the shortest-haul-time path between a cut cell and a fill cell in the field, providing the crucial input in order to formulate the optimal plan of earthmoving operations based on a haul road network design.

The optimization objective is to minimize the average haul time per trip while also identifying the shortest origin-to-destination paths to move earth in the site. To identify the shortest path between each pair of areas, all the combinations are enumerated and the solution is incrementally improved until the solution reaches the minimum. The weight - which is assigned for each road section connecting two adjacent cell centroids in the field grid - represents the haul time on the corresponding road section. The weight matrix is calculated simply following the Eq. (1),

$$w_{ij} = d_{ij}/v_{ij} \quad (1)$$

where w_{ij} is the weight between i^{th} and j^{th} cells, d_{ij} is the distance between centroids of adjacent cells i and j and v_{ij} is the haul speed of a fully-loaded truck between adjacent cells i and j, which is a variable depending on types of roads (gravel-surfaced haul road vs. rough-ground road).

In the numerical example, the haul speed of fully-loaded trucks on temporarily built gravel-surfaced road and rough-ground road is assumed to be 27 km/h and 18 km/h, respectively. Given haul speeds and distances between cell centroids, the weight matrix **W** in terms of truck hauling times can be determined by Eq. (2), where "∞" means no direct connection. For example, the weight of road section 1-2 is 40 second (d_{12} = 200 m; v_{12} = 18 km/h; $w_{12} = d_{12}/v_{12}$ = 40 s) and the weight of road section 1-5 is 38 second (d_{15} = 283 m; v_{15} = 27 km/h; $w_{15} = d_{15}/v_{15}$ = 38 s).

$$\mathbf{W} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \end{array} \begin{array}{c} \begin{array}{ccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \end{array} \\ \begin{bmatrix} - & 40 & \infty & 40 & 38 & \infty & \infty & \infty & \infty \\ 40 & - & 40 & 57 & 40 & 57 & \infty & \infty & \infty \\ \infty & 40 & - & \infty & 38 & 40 & \infty & \infty & \infty \\ 40 & 57 & \infty & - & 40 & \infty & 40 & 57 & \infty \\ 38 & 40 & 38 & 40 & - & 40 & 57 & 27 & 57 \\ \infty & 57 & 40 & \infty & 40 & - & \infty & 57 & 40 \\ \infty & \infty & \infty & 40 & 57 & \infty & - & 40 & \infty \\ \infty & \infty & \infty & 57 & 27 & 57 & 40 & - & 40 \\ \infty & \infty & \infty & \infty & 57 & 40 & \infty & 40 & - \end{bmatrix} \end{array} \tag{2}$$

As for the weight matrix **S**, each element s_{ij} denotes the shortest haul time between cells i and j. By applying the Floyd-Warshall algorithm, the shortest haul time path between cells i and j is represented by a combination of intermediate vertices ($e_1, e_2 \ldots, e_k$) –which are the centroids of cells in the present application case. Let $s_{ij}^{(k)}$ be the weight of the shortest path from i to j such that all intermediate vertices on the path (if any) are in set {1, 2,…,k}. And $s_{ij}^{(0)}$ is set to be w_{ij} without any intermediate vertices. The shortest haul time between i^{th} and j^{th} cells (s_{ij}) is determined based on Eq. (3) (Gross and Yellen 2003).

$$s_{ij}^{(k)} = \min\left(s_{ij}^{(k-1)}, s_{ik}^{(k-1)} + s_{kj}^{(k-1)}\right) \tag{3}$$

for k = 1,…, n. where n is the total number of cells. The algorithm is further elaborated in Appendix A and application is illustrated with a numerical example.

Based on the haul time matrix defined for adjacent cells, the shortest haul time and the corresponding haul path between two non-adjacent cells can be established through applying the Floyd-Warshall algorithm. Theoretically taking the shortest-haul-time path for each earthmoving job leads to the most time-efficient earthmoving operations on the road network.

The outputs resulting from the Floyd-Warshall algorithm include the shortest haul time matrix **S** in Eq. (4) and the shortest haul-time path matrix **P** in Eq. (5). s_{ij}, the shortest haul time between two cells, is shown in Table 3.2. Note, s_{ij} is equal to s_{ji} because the present research assumes one single type of trucks is employed and the average truck speed is only dependent on the haul road type, regardless of truck being fully-loaded or empty. It should be pointed out one-way haul time per unit (truck fully loaded) is defined as the objective function in the present research. Thus, the two-way speeds on different types of haul roads are not distinguished and those weights denoting the travel time along "truck haul" and "truck return" directions between two cells are symmetrical along the diagonal division line of the matrix in Eq. (4).

$$\mathbf{S} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \end{array} \begin{array}{c} \begin{array}{ccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \end{array} \\ \begin{bmatrix} - & 40 & 77 & 40 & 38 & 77 & 88 & 64 & 94 \\ 40 & - & 40 & 57 & 40 & 57 & 97 & 67 & 97 \\ 77 & 40 & - & 78 & 38 & 40 & 94 & 64 & 80 \\ 40 & 57 & 78 & - & 40 & 80 & 40 & 57 & 97 \\ 38 & 40 & 38 & 40 & - & 40 & 57 & 27 & 57 \\ 77 & 57 & 40 & 80 & 40 & - & 97 & 57 & 40 \\ 80 & 97 & 94 & 40 & 57 & 97 & - & 40 & 80 \\ 64 & 67 & 64 & 57 & 27 & 57 & 40 & - & 40 \\ 94 & 97 & 80 & 97 & 57 & 40 & 50 & 40 & - \end{bmatrix} \end{array} \tag{4}$$

$$\mathbf{P} = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \end{array} \begin{array}{c} \begin{array}{ccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \end{array} \\ \begin{bmatrix} - & 1\text{-}2 & 1\text{-}5\text{-}3 & 1\text{-}4 & 1\text{-}5 & 1\text{-}5\text{-}6 & 1\text{-}4\text{-}7 & 1\text{-}5\text{-}8 & 1\text{-}5\text{-}9 \\ 2\text{-}1 & - & 2\text{-}3 & 2\text{-}4 & 2\text{-}5 & 2\text{-}6 & 2\text{-}4\text{-}7 & 2\text{-}5\text{-}8 & 2\text{-}5\text{-}9 \\ 3\text{-}5\text{-}1 & 3\text{-}2 & - & 3\text{-}5\text{-}4 & 3\text{-}5 & 3\text{-}6 & 3\text{-}5\text{-}7 & 3\text{-}5\text{-}8 & 3\text{-}6\text{-}9 \\ 4\text{-}1 & 4\text{-}2 & 4\text{-}5\text{-}3 & - & 4\text{-}5 & 4\text{-}5\text{-}6 & 4\text{-}7 & 4\text{-}8 & 4\text{-}5\text{-}9 \\ 5\text{-}1 & 5\text{-}2 & 5\text{-}3 & 5\text{-}4 & - & 5\text{-}6 & 5\text{-}7 & 5\text{-}8 & 5\text{-}9 \\ 6\text{-}5\text{-}1 & 6\text{-}2 & 6\text{-}3 & 6\text{-}5\text{-}4 & 6\text{-}5 & - & 6\text{-}5\text{-}7 & 6\text{-}8 & 6\text{-}9 \\ 7\text{-}4\text{-}1 & 7\text{-}4\text{-}2 & 7\text{-}5\text{-}3 & 7\text{-}4 & 7\text{-}5 & 7\text{-}5\text{-}6 & - & 7\text{-}8 & 7\text{-}8\text{-}9 \\ 8\text{-}5\text{-}1 & 8\text{-}5\text{-}2 & 8\text{-}5\text{-}3 & 8\text{-}4 & 8\text{-}5 & 8\text{-}6 & 8\text{-}7 & - & 8\text{-}9 \\ 9\text{-}5\text{-}1 & 9\text{-}5\text{-}2 & 9\text{-}6\text{-}3 & 9\text{-}5\text{-}4 & 9\text{-}5 & 9\text{-}6 & 9\text{-}8\text{-}7 & 9\text{-}8 & - \end{bmatrix} \end{array} \tag{5}$$

Table 3.2 Shortest Haul Time between Cells

i	j	s_{ij} (s)
1	2	40
1	3	77
1	4	40
1	5	38
1	6	77
1	7	80
1	8	64
1	9	94
2	3	40
2	4	57
2	5	40
2	6	57
2	7	97
2	8	67
2	9	97
3	4	78
3	5	38
3	6	40
3	7	94
3	8	64
3	9	80
4	5	40
4	6	80
4	7	40
4	8	57
4	9	97
5	6	40
5	7	57
5	8	27
5	9	57
6	7	97
6	8	57
6	9	40
7	8	40
7	9	80
8	9	40

3.2.3 Linear Programming Model

In addition to the shortest-haul-time path in the temporary haul road network, the optimal earthmoving plan in terms of the volume, the source, and the destination of each job can be generated at an upper level optimization formulation. As input data, the linear programming model formulation requires the total cell volume matrix based on site grading design and the haul time matrix resulting from the Floyd-Warshall algorithm. The total cut or fill volume of each cell in the site grid system can be easily determined through gird-based quantity takeoff functions available in current professional grading design and quantity takeoff software such as *Civil 3D*. The resulting volume matrix serves as the boundary constraints in linear programming in terms of the total cut or fill volume for each cell. Because the shortest haul time matrix is already determined through Floyd-Warshall algorithm, the linear programming model demonstrated in Eq. (6) can be used to generate detailed earthmoving jobs, achieving the minimized average truck haul time per trip, given a certain temporary haul road network.

$$\begin{aligned} &\text{Min } t_h = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} s_{ij}V_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} V_{ij}} \\ s.t. \quad &\sum_{j=1}^{m} V_{ij} = V_{i-cut}, 1 \le i \le n \\ &\sum_{i=1}^{n} V_{ij} = V_{j-fill}, 1 \le j \le m \\ &V_{ij} \ge 0, s_{ij} \ge 0 \end{aligned} \tag{6}$$

where t_h is the average haul time per trip, V_{ij} is the volume to be moved between the i^{th} and j^{th} cells, $V_{i\text{-}cut}$ is the total cut volume of the i^{th} cell, $V_{j\text{-}fill}$ is the total fill volume of the j^{th} cell, and s_{ij} is the shortest haul time between the i^{th} and j^{th} cells determined through applying the Floyd-Warshall algorithm based on truck haul time between adjacent areas in the site.

In the numerical example, the inputs of linear programming model include (1) the coefficients s_{ij} in the shortest haul time matrix $\mathbf{S}_{ij}$ and (2) the cell volumes, as shown in Figure 3.4. Note, the number given in each cell represents its total volume of earthworks, with the minus sign "-" denoting cut volume and the plus sign "+" denoting fill volume. Outputs of linear programming model define specific earthmoving jobs, each being described by a specific source (cut cell), a specific destination (fill cell), and a specific volume, along with a specific path. They can be grouped together as the optimized earthmoving plan leading to the minimized average haul time per trip.

Cell 1 **-1000**	Cell 2 **-4000**	Cell 3 **-5000**
Cell 4 **+550**	Cell 5 **-500**	Cell 6 **+800**
Cell 7 **+ 450**	Cell 8 **+6700**	Cell 9 **+2000**

Figure 3.4 Earthmoving Volume of Cells (m^3)

The proposed methodology, which is based on the integration of the Floyd-Warshall algorithm and linear programming model, was coded into computer programs in *Matlab* in order to arrive at the solutions. For the current case, the minimized average haul time is 52 s/m^3 and the earthmoving plan consisting of 7 jobs is demonstrated in Figure 3.5 and Table 3.3 ready for execution at the construction stage.

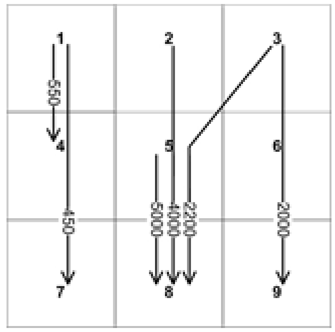


Figure 3.5 Optimized Earthmoving Plan (m^3)

Table 3.3 Optimized Earthmoving Plan

Job No.	i	j	Path	V_{ij} (m^3)
1	1	4	1-4	550
2	1	7	1-7	450
3	2	8	2-5-8	4000
4	3	6	3-6	800
5	3	8	3-5-8	2200
6	3	9	3-6-9	2000
7	5	8	5-8	5000

3.2.4 Cost Evaluation

It is anticipated that average unit haul time can be further reduced if the haul road network becomes more complicated and the total length of temporarily built gravel-surfaced road becomes longer. Thus, the optimization objective of shortening average unit haul time can potentially lead to higher costs of building and maintaining the haul road network. In reality, the practical goal of building the temporary haul road network is to accelerate project progress without significantly increasing project cost. Due to the tradeoff between the average haul time and the cost associated with the haul road network, it is necessary to establish a cost function in order to adequately evaluate the identified time-cost tradeoff relationship.

The cost function should account for 1) direct truck hauling costs depending on the average unit haul time and 2) costs relevant to building and maintaining temporary road networks, as in Eq. (7). The direct truck-hauling cost (C_{th}) is given in Eq. (8) as the product of the hourly fleet cost and total haul duration. The haul road network cost defined as Eq. (9) includes costs to build gravel-surfaced haul roads and maintain both gravel surfaced and rough-ground haul roads.

$$C_t = C_{th} + C_{rn} \quad (7)$$

$$C_{th} = C_e \cdot T \quad (8)$$

$$C_{rn} = C_c + C_m \quad (9)$$

where C_t is the total cost, C_{th} is the direct truck-hauling cost, C_{rn} is the road network related cost, C_e is the hourly or daily cost of fleet equipment and crew, T is the total haul duration, C_c is the construction and removal costs of the temporary haul road network related to lengths of roads of various types, C_m is the maintenance, risk and other costs.

The total haul duration is estimated by Eq. (10),

$$T = Q/(n \cdot c) \cdot t_h/f \quad (10)$$

where Q is the total earthwork quantity in cubic meters (i.e. the total cut volume, which is equal to the total fill volume for a cut-fill balanced grading site), n is the truck number (assuming the use of a fleet of the same type of trucks), c is the volume capacity of one truck in cubic meters, t_h is the average haul time which is actually the result of the above optimization analysis, and f is the operations efficiency factor (45-min hour is generally applied in construction planning).

Due to the temporary nature of developing haul road networks on a mass earthworks project, the maintenance cost of haul road can be simplified to be a function of the proportion of the length of temporarily built gravel-surfaced haul roads over the total length of haul roads (including rough-ground roads and gravel-surfaced haul roads). It is noteworthy that road maintenance costs and vehicle operation/maintenance costs on rough ground roads and gravel-surfaced haul roads differ substantially. Despite lower building cost, rough ground road is much more costly considering such factors as frequent road maintenance, safety-related risks and more wear and tear on tires and trucks.

Thus, the maintenance, risks and other cost as given in Eq. (11) is defined to account for the effect of the proportion of temporarily built gravel-surfaced haul roads within the overall haul road network on site.

$$C_m = p \cdot C_{m-t} + (1 - p) \cdot C_{m-r} \tag{11}$$

Where C_{m-r} is the maintenance, risk and other costs if trucks haul on rough-ground roads, C_{m-t} is the maintenance, risk and other costs if trucks haul on gravel-surfaced haul roads, and p is the proportion of temporarily built haul roads within the overall haul road network, which is the ratio of the gravel-surfaced road length over the maximum road length in the current haul road network design.

If there is no temporary gravel-surfaced haul road to be build, then p is 0%, and C_m will be identical to the maintenance cost in connection with rough-ground roads C_{m-r} ($C_m = C_{m-r} + 0\% \cdot C_{m-t} - 0\% \cdot C_{m-r} = C_{m-r}$). If trucks haul on gravel-surfaced haul roads across the entire site, then p is 100%, and C_m will be equal to the maintenance cost in connection with temporarily built haul roads C_{m-t} ($C_m = C_{m-r} + 100\% \cdot C_{m-t} - 100\% \cdot C_{m-r} = C_{m-t}$). Note comparing unit rates ($/km), C_{m-r} is generally much higher than C_{m-t}.

In order to ensure the cost-effectiveness of the road network design and the time-efficiency of the derived earthmoving job plan, the cost of executing the optimized earthmoving job plan over a particular road network design can be readily estimated by the established cost Eq. (7) to (9), which will be demonstrated in the ensuing practical case study. This makes it straightforward for project managers to compare multiple alternative designs and select the best one.

3.3 Layout Optimization of Temporary Haul Road Network

Based on Figure 3.1, Figure 3.6 further illustrates the details of proposed optimization approach to achieve the optimized layout of temporary haul road network.

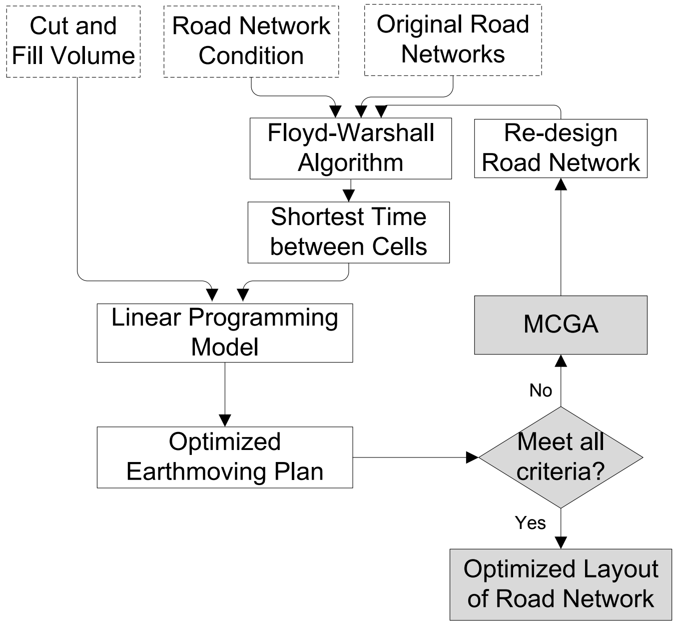


Figure 3.6 Flowchart of Layout Optimization

In mass earthmoving projects, the field is generally divided into cells, and the cut and fill volume of each cell can be easily obtained. Meanwhile, several number series will be generated, representing different layout designs of original road networks. For each layout design of temporary road network, shortest average haul time along with the optimized earthmoving plan can be obtained by applying the Floyd-Warshall algorithm and the linear programming model as proposed in the Eq. (5).

Then different layouts can be compared based on the criteria achieved from the proposed algorithm. The optimization of temporary road network design can be developed through gradual improvement by using "multi-generation competing" genetic algorithms (MCGA) among all the potential layouts. The optimization approach is applied to an example and the optimized layout of temporary haul road network is eventually achieved. Simulation models encoded with earthmoving plans are established in order to validate the optimization approach.

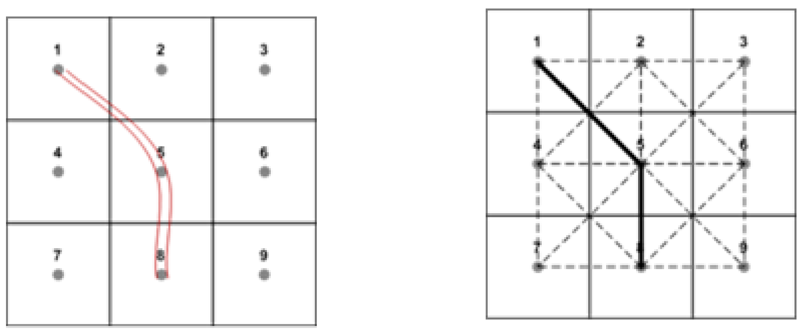
3.3.1 Input Data

According to the outline of earthmoving site, the field will be divided into cells, the cut and fill volumes of cells is essential. Also, empirical or historical speed data of trucks is fundamental to achieve optimized earthmoving plan. Therefore, to further achieve the optimized layout, the inputs of proposed methodology include cut and fill data of the area (designed surface and raw survey data preferred), different haul speeds of trucks on different surfaces, parameters of the optimization algorithm and empirical or historical cost data as following:

- Construction and removal costs of the gravel-surfaced temporary haul road;
- Maintenance and other costs for the gravel-surfaced temporary haul roads and for rough ground road respectively;
- The maximum potential road length within the entire site area;
- Mean truck-haul speed on temporary haul road;
- Mean haul speed on rough ground;
- Truck volume capacity;
- Truck number;
- Hourly cost of equipment and crew;
- Working efficiency factor;

3.3.2 0-1 Problem

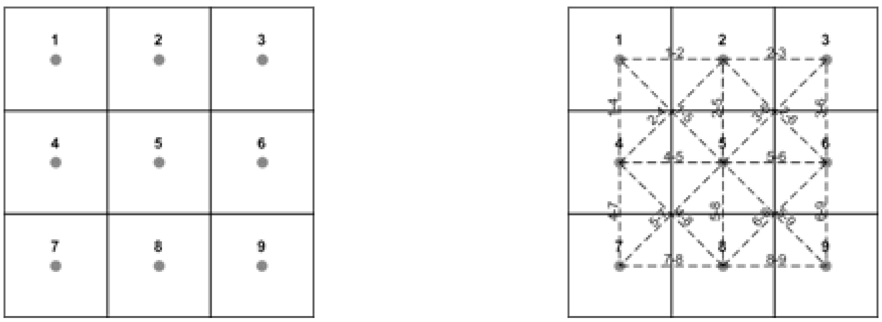
In this study, the haul road network layout design is based on a rectangular grid system with a larger width that is applied to profile the site geometrically. The haul road alignment design is constrained by the granularity of the grid system. Also, the curved alignment can be approximated with by linking the centroids of two adjacent cells diagonally as demonstrated in the Figure 3.7.



(a) Curved alignment (b) Road Network Model

Figure 3.7 Curved Alignment Represented by Diagonal Link

As the foundation for optimization, temporary road network design is conceptualized to be a set of 0-1 knapsack problems. The layout can be divided into road sections, and each road section can be represented in either 0 or 1. So the layout can be encoded into number series. For the numerical example, the conceptual model of potential road network is demonstrated in Figure 3.8 and, for each cell, the centroid is simplified to be the geometric center of cell and the potential road network can be observed. Each dash line between centroids of cells means a decision whether to build the temporary haul road or not. Therefore, the layout of temporary road network can be represented as the number series such as [0, 1, 0, …, 0, 0, 1]. "0" means remaining rough-ground road between i-th centroid and j-th centroid. "1" means the temporary road is available between i-th centroid and j-th centroid. The number series can be later encoded into genetic algorithm for optimization purpose.



(a) Cells overlaid on the field (b) Network model overlaid on cells

Figure 3.8 0-1 Model for Potential Temporary Road Networks

3.3.3 Optimization Algorithm (Genetic Algorithm)

Among all the possible layouts, to evaluate each individual layout, each optimized earthmoving plan and minimized average haul time are calculated based on the linear programming and Floyd-Warshall which describes the most optimistic operating condition that road network are fully utilized. On the basis of fully utilizations of haul road network, the possible layouts can be compared with each other. Since the scale of optimization is quite large especially for a large number of cells after dividing the field, for such a large-scale optimization problem, the genetic algorithm is suitable and chosen for optimization.

The optimization is accomplished through applying genetic algorithms to search the optimum temporary road network design. Genetic algorithms have the limitation that it converges towards a local optimum instead of the global optimum of the problem. MCGA, can address this limitation to some extent and it confers the advantages including faster searching speed and easier to achieve the global optimum (MCGA, Deng et al. 2007). Due to the significant difference of computing time, multi-generation compete genetic algorithm is chosen and programmed in *MATLAB*. The parameters of MCGA are given in the Table 3.4. The Floyd-Warshall algorithm and linear programming model are embedded as the first two consecutive analytical steps, which provide input to the GA optimization (referring to Fig. 3.9.).

Table 3.4 Parameters of Multi-generation Compete Genetic Algorithm

Variable	Description
N	Size of chromosomes depending on the temporary road network size;
MP	Size of multi-generation;
NIND	Number of individuals;
GGAP	Generation gap;
MAXGEN	Termination criteria which means the length of time during which minimum value remains the same;

The flowchart of MCGA algorithm which is illustrated in Figure 3.9 indicates details in the proposed optimization. After inputting the data including the earthwork design, the parameters of genetic algorithm and empirical parameters of the objective function, the algorithm starts to search for the optimized temporary road network. All the possible layout of temporary road network is considered. When the termination criteria are reached, the optimal layout is obtained. The purpose to achieve the optimized temporary haul road network is 1) to accelerate the earthmoving operations and total project duration 2) to reduce the total cost including the construction and removal cost of road network.

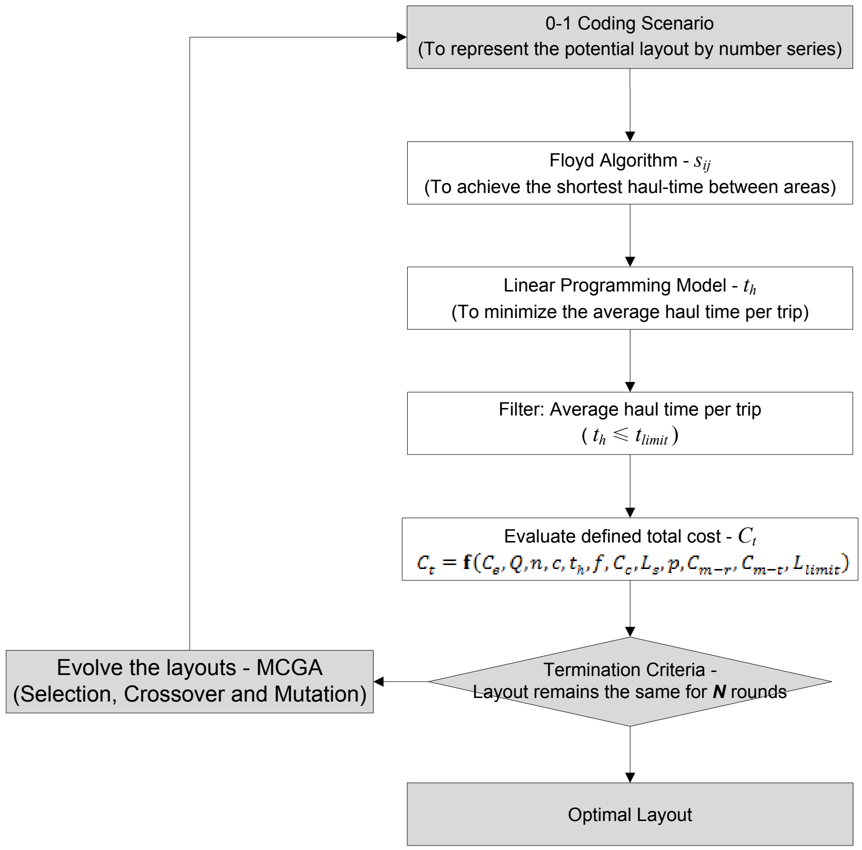


Figure 3.9 Flowchart of Optimization Approach

To achieve the optimal layout, the evolvement will be determined based on the fitness value. If the fitness value of certain layout is high, it is more likely to remain it in the next generation of MCGA. Otherwise, the layout with low fitness value will be replaced by other possible layout. In this study, the fitness is determined by two evaluation criteria which are the total cost ($C_{t\text{-}op}$, as defined in the Eq. (6)) and the average haul time achieved through Floyd-Warshall algorithm and Linear Programming model. If defined total cost based on certain layout is low, the fitness of layout will be high and it is more likely to be the optimal layout. If the average haul time based on certain layout is beyond expected limit of average haul time, although defined total cost is low, the fitness of the layout will be defined as zero and it will not become the optimal layout. Thus, the objective function of MCGA algorithm can be demonstrated in Eq. (12). According to the objective function of MCGA algorithm, it is expected that the average haul time if building the optimal layout (t_{op}) should be under the required average haul time (t_{limit}) while the project based on the optimal layout can achieve the lowest total costs.

$$Min\ C_{t-op} \tag{12}$$

$$t_{op} \leq t_{limit} = 1/2 \cdot (f \cdot n \cdot c \cdot 60/P - t_o)$$

where Q is the total earthwork quantity in cubic meters (i.e. the total cut volume, which is equal to the total fill volume for a cut-fill balanced grading site), n is the truck number (assuming the use of a fleet of the same type of trucks), c is the volume capacity of one truck in cubic meters, P is the expected productivity, t_o is the loading, dumping and waiting time of trucks and f is the operations efficiency factor (45-min hour is generally applied in construction planning).

The productivity data can be easily retrieved through commercial databased like *RSMeans* which has become one of the most sophisticated and most reliable sources of data in North America[1]. The latest version of *RSMeans* makes estimating tools alongside with over the

[1] Jackson, T. (2011). *Yahoo News*.

network storage and the archival of cost data on an Internet-based platform. Also, *RSMeans* classifies methods by MasterFormat 2010 and publishes data including material cost, labor crew rates, equipment rates, productivity information and market variations. Thus, to be aligned with the productivity data definition for typical earthmoving methods as found in databases like *RSMeans*, the proposed equation can be easily applied in real practice. (Refer to P52 for an example in the case study).

Through the proposed approaches, from random starting points, the optimized layout of temporary road network can be finally derived from alternatives. It is noteworthy that the variable in the MCGA algorithm is a number series representing the layout of road network. In short, in connection with each solution of the objective function, the Floyd-Warshall algorithm along with the linear programming model is applied to any possible layout to determine its average haul time and optimized earthmoving plan. The computing time of proposed optimization approaches mainly depends on the problem size. For the small-scale optimization where the field is divided into dozen cells, the computing time can be within minutes. However, for the large-scale optimization where complicated earthmoving field is divided into more than 50 cells, the computing time can be in the order of hours.

<http://www.reedconstructiondata.com/Market-Intelligence/Articles/2011/11/RSMeans-Longest-running-Publication-Building-Construction-Cost-Data-Celebrates-70-Years-RCD010936W/>

4 Case Study

4.1 Practical Application to Achieve Optimized Earthmoving Plan

To illustrate the application of the proposed methodology, a practical case is used to evaluate the performance of the optimized earthmoving job plan based on a particular layout of the temporary haul road network. The rough grading project is the preliminary work of a campsite construction in northern Alberta, the site area of which is around 120 hectares. The survey data for the original terrain and the elevation data of designed surface after grading are available. The field is divided into 48 cells whose grid size is 150 m by 150 m as shown in Figure 4.1 and the cut or fill quantity of each cell is calculated, which is based on checking the difference between site ground survey data and design surface data.

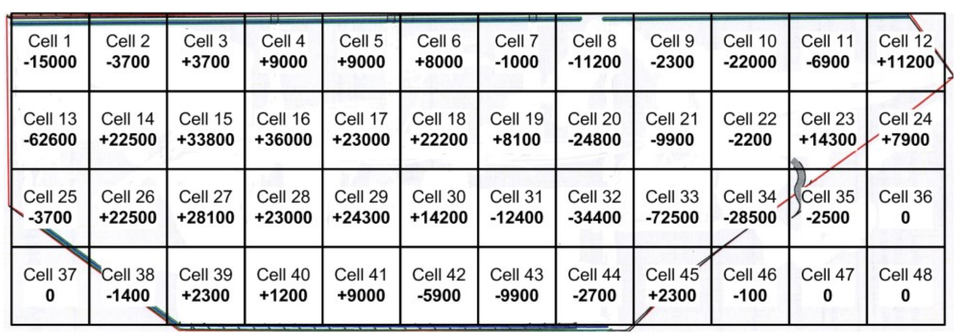


Figure 4.1 Volume of Cells based on Division of the Field (m^3)

The cost data were provided by the field manager who had over five years of working experience on similar projects. Construction and removal costs of the temporary haul road (gravel-surfaced) is \$17500/km; Maintenance and other costs for the temporary haul road (gravel-surfaced) is \$500/d and for rough ground road is \$1500/d, respectively; The maximum potential road length within the entire site area is 5000 m; Mean truck-haul speed on temporary haul road is 36 km/h; Mean haul speed on rough ground is 24 km/h; Truck volume capacity is 40 m^3; Hourly cost of equipment and crew is $5000/h; Working efficiency factor is 0.75; 8 trucks of the same type make up the fleet. Based on the cost data, Eq. (13) to (16) can be evaluated for the purpose of cost-benefit analysis. The total cost (C_t) is essentially a function depending on two variables, namely: t_h (the average unit haul time in hour) and L (the total length of temporary gravel-surfaced haul road in meter).

$$T = 335600\ m^3/(8 \cdot 40\ m^3) \cdot t_h/0.75 \tag{13}$$

$$C_{th} = \$5000/h \cdot T \tag{14}$$

$$C_{rn} = \$17500/1000m \cdot L + L/5000m \cdot \$500/d \cdot T + (1 - L/5000m) \cdot \$1500/d \cdot T \tag{15}$$

$$C_t = \$5187.5/h \cdot 1398.33 \cdot t_h + \$17.5/m \cdot L - L/5000m \cdot \$125/h \cdot 1398.33 \cdot t_h \tag{16}$$

4.1.1 Comparison between Layout Options

Based on input and empirical data from the site manager, comparison was made for four layout options of the temporary haul road network with varied total length and configuration of gravel-surfaced haul roads, as demonstrated with solid line sections in Figure 4.2 to Figure 4.5. Among the four options, option 1 has the shortest total length of gravel-surfaced haul roads (450 m) with the simplest layout design; while option 4 features the longest gravel-surfaced haul road (4024 m) and the most complicated configuration. The decision maker intends to identify the layout option associated with the lowest total cost, by implementing the proposed earthmoving job planning optimization methodology and cost evaluation equations. For each layout option, total duration, truck-hauling cost, road network cost and total cost are calculated according to Eq. (13) to (16), as listed in Table 4.1.

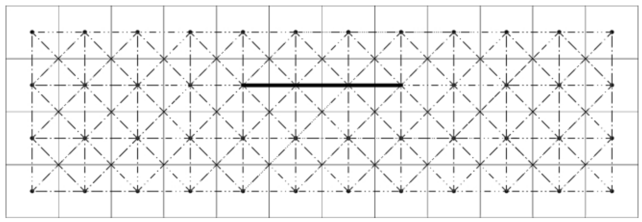


Figure 4.2 Layout Option 1

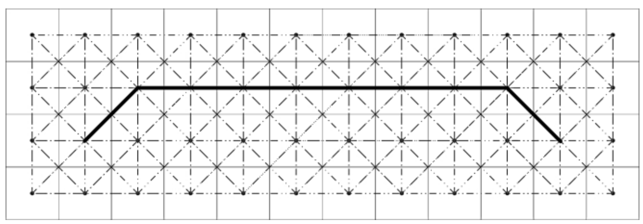


Figure 4.3 Layout Option 2

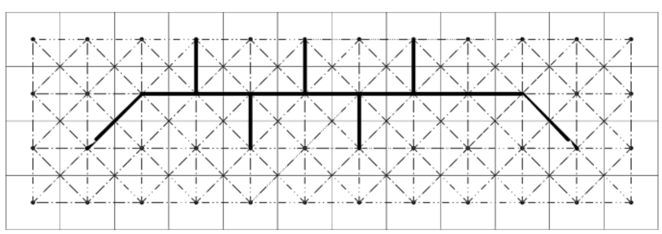


Figure 4.4 Layout Option 3

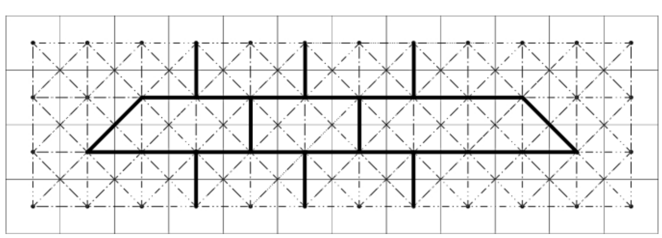


Figure 4.5 Layout Option 4

Table 4.1 Comparison between Haul Road Layout Options

Layout Option ID.	Average Unit Haul Time (min/m^3)	Estimated Total Haul Duration (h) (13)	Truck-Hauling Cost ($) (14)	Road Length (m)	Road Network Cost ($) (15)	Total Cost ($) (16)
"No Gravel Road"	1.715	39.969	200,000	0	7,494	207,494
1	1.574	36.683	185,000	450	14,340	199,340
2	1.504	35.052	175,000	1474	31,076	206,076
3	1.347	31.393	155,000	2224	43,061	198,061
4	1.280	29.831	150,000	4024	73,012	223,012

According to Table 4.1, building the temporary haul road network as per any of the four options can reduce the average unit haul time and the total haul duration, compared with the "No Gravel Road" option; but it does not always reduce the total cost. For instance, the total cost of Option 4 ($223,012) is 10% higher than the "No Gravel Road" option which only maintains rough ground roads ($207,494). Among all the layout options, in terms of the total cost based on the established cost equations, Option 3 is the best layout as it can considerably shorten the total haul duration (31.393 h) while incurring the lowest total cost ($198,061). Note the cost of Layout Option 3 turns out to be even lower than building no gravel haul road at all ($207,494). This can be attributed to the fact that efficiency gain from building haul roads outstrips the cost of building and maintaining haul roads themselves. In short, this case study has validated the proposed methodology and proven that building a well-designed temporary haul road network in support of site grading operations can be time-efficient, cost-effective, and practically feasible.

Table 4.2 Optimized Earthmoving Job Plans based on Layout Option 1

Job No.	i	j	V_{ij} (m^3)
1	3	1	3700
2	4	8	7600
3	4	32	1400
4	5	8	3600
5	5	10	2700
6	5	44	2700
7	6	10	5800
8	6	22	2200
9	12	10	11200
10	14	1	5900
11	14	13	16600
12	15	1	5400
13	15	2	3700
14	15	7	169
15	15	13	16672
16	15	33	7659
17	15	38	200
18	16	7	180
19	16	20	9314
20	16	33	26505
21	17	7	160
22	17	20	3871
23	17	33	5469
24	17	34	13500
25	18	7	165
26	18	20	7737
27	18	33	13398
28	18	43	900
29	19	33	8100
30	23	11	1158
31	23	34	12800
32	23	35	342
33	24	11	5742
34	24	35	2158
35	26	13	18800

36	26	25	3700
37	27	7	162
38	27	13	10528
39	27	32	11329
40	27	33	6080
41	28	7	165
42	28	20	3877
43	28	31	4475
44	28	32	9196
45	28	33	5287
46	29	21	9900
47	29	31	5443
48	29	32	8957
49	30	9	2300
50	30	31	2482
51	30	32	3518
52	30	42	5900
53	39	10	2300
54	40	38	1200
55	41	43	9000
56	45	34	2200
57	45	46	100

Table 4.3 Optimized Earthmoving Job Plans based on Layout Option 3

Job No.	i	j	V_{ij} (m^3)
1	3	2	3700
2	4	33	9000
3	5	8	6300
4	5	44	2700
5	6	8	4900
6	6	10	900
7	6	22	2200
8	12	10	11200
9	14	1	6897
10	14	13	14203
11	14	25	1400
12	15	10	3040
13	15	13	5900
14	15	20	3920

15	15	21	9900
16	15	33	6866
17	15	34	3974
18	15	38	200
19	16	20	9917
20	16	33	26083
21	17	10	3548
22	17	20	5593
23	17	33	8934
24	17	34	4925
25	18	10	3312
26	18	20	5369
27	18	33	8450
28	18	34	4601
29	18	43	467
30	19	7	738
31	19	33	6929
32	19	43	433
33	23	11	1500
34	23	34	12800
35	24	11	5400
36	24	35	2500
37	26	13	22500
38	27	1	8103
39	27	13	19997
40	28	31	5290
41	28	32	11471
42	28	33	6238
43	29	7	262
44	29	9	2300
45	29	31	5337
46	29	32	16401
47	30	31	1773
48	30	32	6527
49	30	42	5900
50	39	25	2300
51	40	38	1200
52	41	43	9000
53	45	34	2200
54	45	46	100

Further scrutiny of the optimized earthmoving plans resulting from option 3 and option 4 leads to one additional observation critical to earthmoving job planning: option 3 (54 jobs) reduces both the minimized average haul time and the total job number when compared with layout option 1 (57 jobs). With three fewer jobs, option 3 can significantly reduce site mobilization efforts and facilitate earthmoving operations, thus is preferred over option 1 from the perspective of field execution. As a result, layout option 3 is deemed the best layout among the four options. In reality, the total costs for option 1 and option 3 are close, so the optimized earthmoving plans associated with the two options, listed in Table 4.2 and Table 4.3, can be both presented to the field personnel, who would make the final choice by further evaluating the feasibility of field implementation. In short, the proposed approach lends effective, transparent decision support to guide practitioners in earthmoving job planning, temporary haul road network design and job plan execution.

4.1.2 Effect of Grid Size Selection

As mentioned in the previous section, the distance between two access roads mainly decides the grid size and 150 m is recommended as a proper choice. In order to shed light on the selection of the grid size suitable for practical application, results from analyzing three cases with different grid sizes (150 m, 200 m, 300 m) based on layout option 1 and layout option 3 are presented and compared. The proposed methodology was repeated on two additional grid-size scenarios and the final results are compared against the base-case scenario (150 m grid size), shown in Table 4.2 and Table 4.3 for layout option 1 and layout option 3, respectively.

For more complicated haul road layout models, the larger grid size tends to oversimplify the road network design, leading to insufficiency in the obtained haul road network design and inaccuracy in calculating the average unit haul time and the associated cost. Considerable differences are observed to generally indicate that the larger grid size leads to a greater value of the average unit haul time from optimization, thus resulting in a less accurate overestimate of the cost for building road networks. For instance, in Table 4.4, applying the same option (layout option 1) to design the road network, 5.78% longer haul duration and 6.45% higher total cost occur to the scenario of applying 200 m grid size than the scenario of using 150 m grid size. When the grid size is set as 300 m, the changes on the final results would become even more significant, namely: 22.55% and 22.03% on average unit haul time and total cost, respectively. Similar observations can be made on the effect of changing grid size upon the analytical results as for Layout Option 3, as shown in Table 4.5. To sum it up, 150 m or 200 m grid size can be effective in order to achieve a more sufficient design of temporary haul road network and more accurate time & cost estimate.

Table 4.4 Comparison between Grid Sizes - Layout Option 1

Grid Size (m)	Average Unit Haul Time (min/m^3)	Estimated Haul Duration (h)	Total Cost ($)	Haul Duration Difference (%)	Total Cost Difference (%)
150	1.574	36.683	199,340	-	-
200	1.665	38.804	212,194	+5.78	+6.45
300	1.929	44.956	243,255	+22.55	+22.03

Table 4.5 Comparison between Grid Sizes - Layout Option 3

Grid Size (m)	Average Unit Haul Time (min/m^3)	Estimated Haul Duration (h)	Total Cost ($)	Haul Duration Difference (%)	Total Cost Difference (%)
150	1.347	31.393	198,061	-	-
200	1.471	34.282	212,477	+9.20	+7.28
300	1.652	38.501	236,948	+22.64	+19.63

4.1.3 Summary

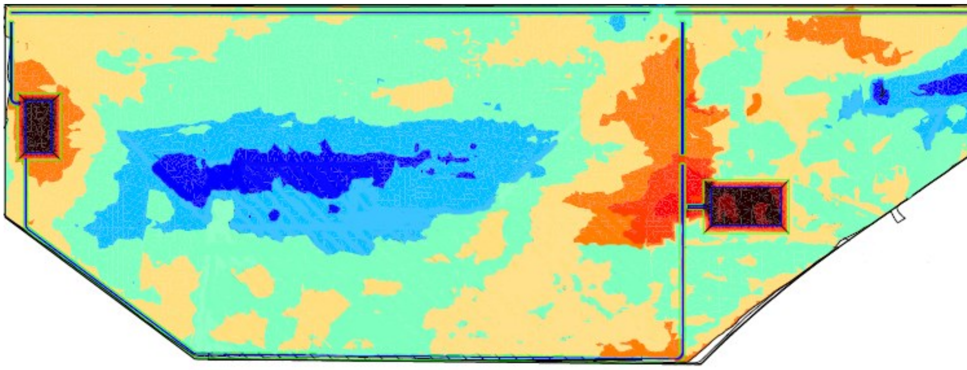
In this section, the proposed method has successfully applied to a practical earthmoving case in northern Alberta. Previous research has not yet deliberately addressed how to optimize earthmoving operations planning in connection with the layout design of temporary haul road networks for mass earthworks projects. The research has introduced concepts in transportation engineering into the construction domain (such as formulating the design of temporary haul road networks into grid model, the Floyd-Warshall algorithm for network planning optimization.) The present research has proposed a quantitative methodology for optimizing earthmoving job planning based on evaluation of the road network design during the detailed construction planning stage. Through seamless integration of Floyd-Warshall algorithm and Linear Programming model, the shortest average unit haul time along with earthmoving plan can be obtained while automatically fulfilling site grading design specifications. Each job is defined in terms of the source cell, the destination cell, the earth volume, and the shortest-hauling-time path between source and destination. To some extent, the proposed methodology converts an empirical planning issue in construction engineering into an analytical problem, amenable to formulating quantitative solutions.

4.2 Practical Application to Optimize Layout of Temporary Haul Road Network

4.2.1 Overview of Earthmoving Project

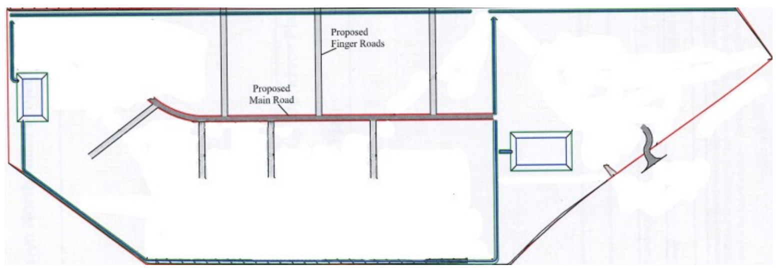
To illustrate and verify the proposed approach for layout optimization, the case study about a site-grading project was chosen, which is used as the practical application for earthmoving job plan optimization. The site-grading project is the preliminary work package of a camp site construction in Fort McMurray, AB. The field which is around 120 hectares is divided into 48 cells whose spacing is 150 m by 150 m. The project has around 335,600 m^3 of earth required to be balanced through cut and fill.

Input data of the proposed method are cut and fill volumes, speed conditions of trucks, empirical cost data and as-built empirical temporary road network model. Designed cut and fill areas are illustrated in Figure 4.6 whose volumes are measured in cubic meters of undisturbed soil along with the cell numbers given in Figure 4.1 (Volume of Cells based on Division of the Field). The temporary road illustrated is designed based on past experience which is converted into the model of temporary road network illustrated in Figure 4.7. Figure 4.7 also demonstrates the conceptualization of a practical layout into a layout model which can be later represented into a variable for optimization as a number series.

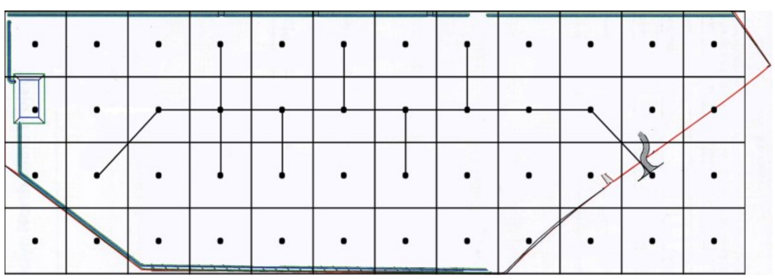


	Cut–Fill Table Stripped Surface vs. Rough Grade Design			
	Range		Area	Color
Cut	−8.92	−5.00	13233.74	
	−5.00	−4.00	5975.32	
	−4.00	−3.00	7812.19	
	−3.00	−2.00	16948.30	
	−2.00	−1.00	72276.38	
	−1.00	0.00	338997.11	
Fill	0.00	1.00	433393.98	
	1.00	2.00	151016.33	
	2.00	3.00	37729.62	
	3.00	3.77	131.40	

Figure 4.6 Designed Cut and Fill Areas of Rough Grading Design



(a) Empirical Layout

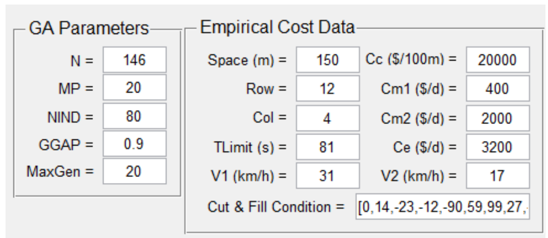


(b) Layout Model based on the Division of Field

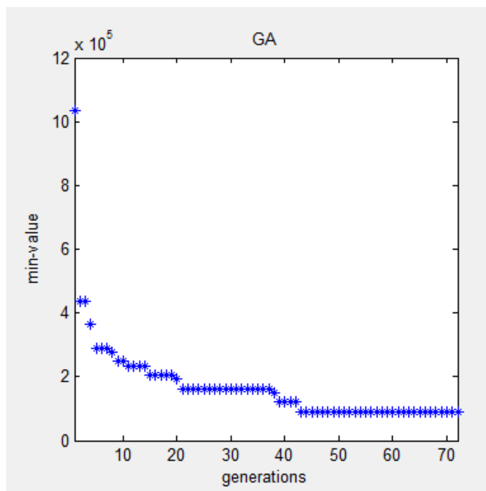
Figure 4.7 Empirical Temporary Road Network

4.2.2 Optimization of Temporary Road Network

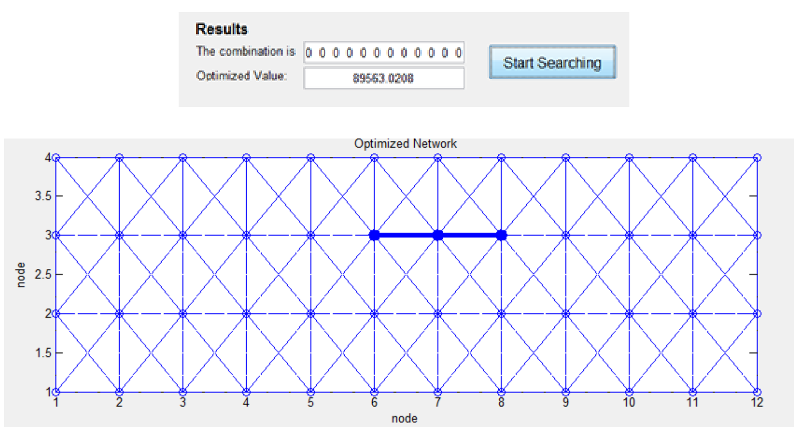
The optimized temporary road network can be obtained as demonstrated in Figure 4.8. In this case, cut and fill volumes are given and the input parameters set for genetic algorithms are determined after trials (NIND=80; N=146; MP=20; GGAP=0.9; MAXGEN=20). The empirical input data can be later determined by engineers or decision-makers. For the MCGA, the termination criteria is that a certain layout is considered to be the optimized if the layout cannot evolve any more (or find a better alternative) in continuous 20 times (MAXGEN=20). Following the proposed optimization procedures, MCGA provides evolution to the optimized layout.



(a) Input data



(b) MCGA evolution



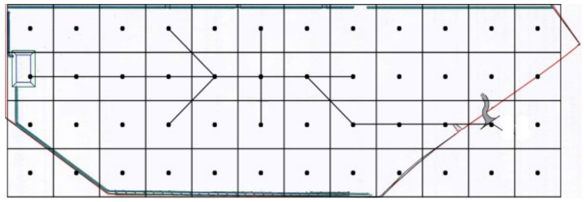
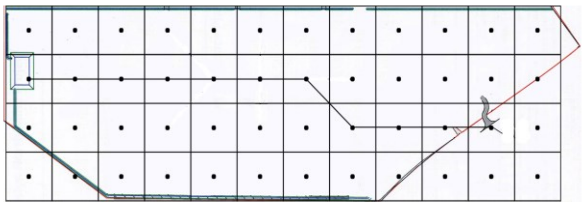
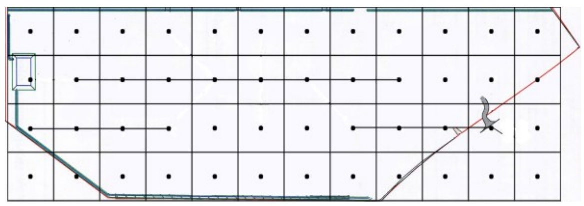
(c) Optimized layout of temporary road network

Figure 4.8 Optimization of Temporary Road Network

In the case study, the parameters of the objective function are determined by empirical and historical data. (Construction and removal costs of the gravel-surfaced temporary haul road is \$17500/km; Maintenance and other costs for the gravel-surfaced temporary haul roads \$500/d and for rough ground road is \$1500/d, respectively; The maximum potential road length within the entire site area is 5000 m; Mean truck-haul speed on temporary haul road is 36 km/h; Mean haul speed on rough ground is 24 km/h; Truck volume capacity is 30 m^3; Hourly cost of equipment and crew is \$5000/h; Working efficiency factor is 0.75; 8 trucks of the same type make up the fleet.)

Following proposed objective function for MCGA given in Chapter 3, the limit of average haul time (expected productivity is 1450m^3/hr; average loading, dumping and waiting time is 5 mins; t_{limit} = [(30m^3/truck·8truck·0.75·60min/hr)/ (1450 m^3/hr) – 5min]/2 = 1.2 min) is set in the model in order to realize the required project duration after building the temporary road network. It is noted that the limit of average haul time is coded into fitness calculation in order to restrain the computing time of the MCGA. After multiple runs, several optimal solutions can be obtained as listed in Table 4.6.

Table 4.6 Comparison between Different Layouts

No.	Optimized Layout Through MCGA	Average Haul Time	Total Cost
1		1.096 min	$ 195,085
2		1.138 min	$ 194,576
3		1.085 min	$ 196,150

Among three options, option 3 can achieve lowest average haul time while option 2 can achieve the lowest total cost. Option 2 can also achieve similar average haul time and total cost, while the road network is continuous, which is easiest and most efficient to be built particularly compared to option 3. With closest similarity to the empirical design actually developed by experienced field engineers, the option 1 can be chosen as the optimized temporary road network model, demonstrated in Figure 4.9.

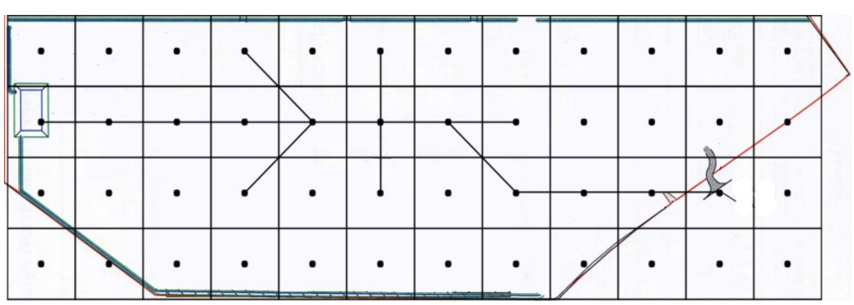


Figure 4.9 Temporary Road Network Model based on Optimized Solutions

The optimized temporary road network model, which is the output of proposed method, seems to be more complicated than the empirical model. The similarity is that the massive cut areas are also connected with the massive fill area in the optimal solution. The temporary road network design can be further fine turned in detail based on this optimized model. Given the optimized temporary road network in the project, average haul time reduces to 1.096 min if following the earthmoving plan in Table 4.7 and total cost reduces to $195,085.

Table 4.7 Optimized Earthmoving Plan based on the Optimal Layout

(Cell ID given in Fig 4.1)

Job No.	i	j	Path	V_{ij} (m^3)
1	2	3	2-3	1400
2	6	3	6-5-4-3	450
3	6	4	6-5-4	611
4	6	5	6-5	637
5	6	17	6-17	1201
6	6	18	6-18	3002
7	7	3	7-6-5-4-3	450
8	7	4	7-6-5-4	589
9	7	5	7-6-5	8363
10	7	17	7-18-17	283
11	7	18	7-18	214
12	8	9	8-9	2200
13	8	15	8-19-18-17-16-15	56
14	8	16	8-19-18-17-16	56
15	8	17	8-19-18-17	56
16	8	28	8-19-18-17-28	65
17	8	30	8-19-30	55
18	8	31	8-19-31	45
19	8	40	8-19-18-17-28-40	46
20	8	41	8-19-30-41	32

21	8	42	8-19-30-42	32
22	10	9	10-9	100
23	13	14	13-14	3700
24	19	17	19-18-17	1417
25	19	18	19-18	10983
26	20	15	20-19-18-17-16-15	5126
27	20	16	20-19-18-17-16	4961
28	20	17	20-19-18-17	4417
29	20	28	20-19-18-17-28	5775
30	20	29	20-19-18-29	4950
31	20	30	20-19-30	4826
32	20	31	20-31	1845
33	20	40	20-31-42-41-40	2053
34	20	41	20-31-42-41	214
35	20	42	20-31-42	233
36	21	15	21-20-19-18-17-16-15	11815
37	21	16	21-20-19-18-17-16	9199
38	21	17	21-20-19-18-17	8917
39	21	28	21-20-19-18-17-28	19061
40	21	29	21-20-19-18-29	9266
41	21	30	21-20-19-30	8753
42	21	31	21-20-31	2315
43	21	40	21-20-31-42-41-40	2641
44	21	41	21-20-31-42-41	258
45	21	42	21-20-31-42	275
46	22	15	22-21-20-19-18-17-16-15	4001
47	22	16	22-21-20-19-18-17-16	4021
48	22	17	22-21-20-19-18-17	3628
49	22	28	22-21-20-19-18-17-28	5093
50	22	29	22-21-20-19-18-29	3976
51	22	30	22-21-20-19-30	3870
52	22	31	22-21-20-31	1648
53	22	40	22-21-20-31-42-41-40	1815
54	22	41	22-21-20-31-42-41	216
55	22	42	22-21-20-31-42	231
56	23	36	23-36	2500
57	25	14	25-14	18800
58	25	15	25-14-15	1378
59	25	26	25-26	13640
60	25	27	25-26-27	28782

61	32	15	32-19-18-17-16-15	3320
62	32	16	32-19-18-17-16	3452
63	32	17	32-19-18-17	3106
64	32	28	32-19-18-17-28	4492
65	32	29	32-31-30-29	3448
66	32	30	32-31-30	3405
67	32	31	32-31	1504
68	32	40	32-43-42-41-40	1650
69	32	41	32-43-42-41	204
70	32	42	32-43-42	218
71	33	15	33-32-19-18-17-16-15	1282
72	33	16	32-19-18-17-16	1311
73	33	17	32-19-18-17	1277
74	33	28	33-32-19-18-17-28	1513
75	33	29	33-32-31-30-29	1304
76	33	30	33-32-31-30	1291
77	33	31	33-32-31	742
78	33	40	33-32-43-42-41-40	794
79	33	41	33-32-43-42-41	193
80	33	42	33-32-43-42	195
81	34	35	34-35	1308
82	34	36	34-35-36	892
83	37	15	37-26-15	1122
84	37	26	37-26	8860
85	37	27	37-26-27	5018
86	38	39	38-39	3700
87	43	41	43-42-41	369
88	43	42	43-42	631
89	44	41	44-43-42-41	6330
90	44	42	44-43-42	4870
91	45	41	45-44-43-42-41	1146
92	45	42	45-44-43-42	1154
93	46	35	46-35	12992
94	46	36	46-35-36	2300
95	46	41	46-45-44-43-42-41	39
96	46	42	46-45-44-43-42	161
97	46	48	46-47-48	6508
98	47	36	47-36	2208
99	47	48	47-48	4692

4.2.3 Simulation with Earthmoving Plans

The evaluation and optimization of layout design at the planning stage are accomplished, but the execution of optimal layout inherits the risks from the perspective of contractors. Essentially, the empirical layout and optimal layout cannot be built in the same earthmoving field. Therefore, the simulation models play the role to validate the proposed optimization approaches in earthwork planning. In the simulation models, the earthmoving plan can be coded such that trucks can operate on the optimal routes achieved based on certain haul road design.

In most recent research, earthmoving simulations models implemented with the optimal earthmoving plans for the haul road layouts pass the verification and validation (Liu et al. 2013). It is proved that the optimal layout of temporary road network can perform better than the empirical network through the comparison on the key performance indexes including mean simulation duration and mean haul productivity. As a result, the optimization approaches to achieve the optimized temporary haul road network are considered to be useful and effective.

The simulation models are established to encode optimized earthmoving plans. The general purpose template of *Simphony*, a discrete-event modeling environment, is used to establish the simulation models as shown in Figure 4.11. The main element in *Simphony* is "Task" which represents the activity with the duration distribution. The "Capture" and "Preempt" represent the resource requirements for "Task". In this case, haul time and return time are coded into "Execute" elements in red color based on the earthmoving plans.

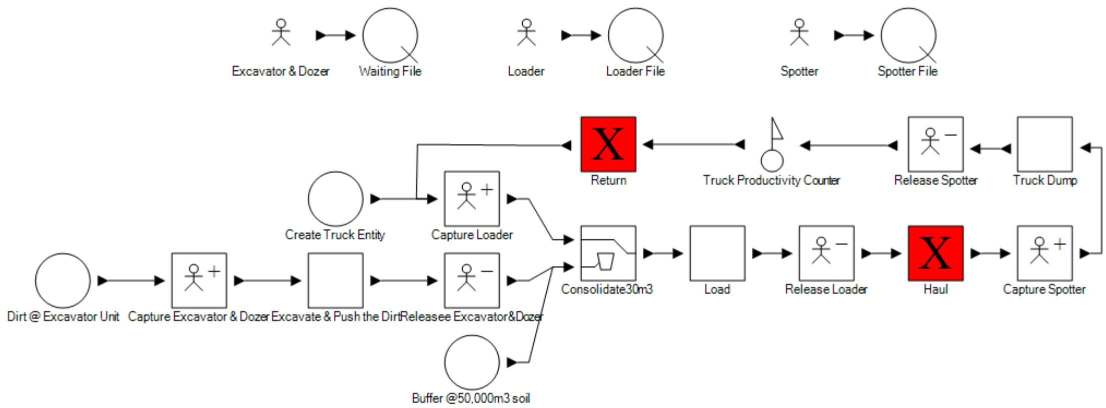


Figure 4.10 Simulation Model in *Simphony* Encoded with Earthmoving Plan

In order to demonstrate the hauling improvement on the optimized layout, the trucks govern the earthmoving productivity in our case. The following information and assumptions are related to the earthmoving operations:

- The excavators and dozers excavate and push the earth to the loading location.
- Empty trucks load the earth with the help of loaders
- Trucks haul soil to the fill area according to the optimized earthmoving plan as demonstrated in Table 4.7 following the order of job numbers.
- Transition of equipment from one cell to another is not considered.
- Trucks dump the soil under the inspection of a spotter and returns to the loading location to continue the earth moving cycle.

The simulation is assumed to be executed by 8 trucks, 4 excavators, 4 dozers, 4 loaders and 4 spotters. It is noted that earthmoving plan is coded into simulation as demonstrated in the Figure

4.12. For example, if the trucks finish the job 1, they will start the job 2 and so on so forth.

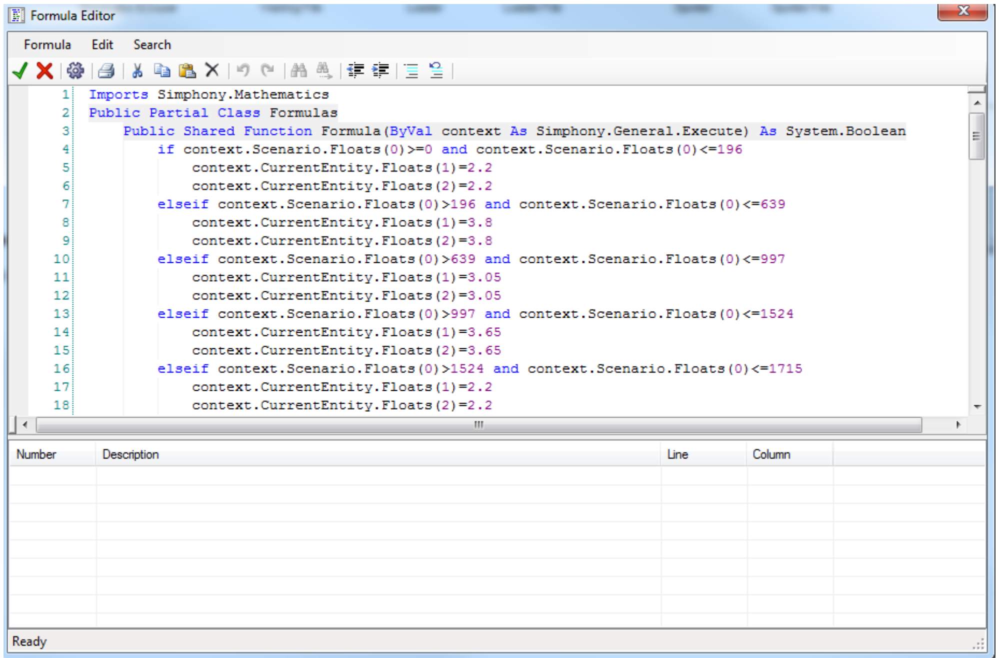


Figure 4.11 Code in the "Execution" Activity

The duration distribution, capacity and resource involved in the tasks are listed in the Table 4.8 whereas duration distributions are retrieved from the empirical and historical data.

Table 4.8 The Duration, Capacity and Resource of Tasks

No.	Task name	Resource	Duration (min)	Capacity (m^3)
1	Excavate & Push the dirt	Excavator(1), Dozer(1)	Constant (3)	10
2	Truck Load	Loader(1), Truck(1)	Constant (1.8)	30
3	Haul	Truck(1)	Obtained from proposed approach	30
4	Truck Dump	Truck(1), Spotter(1)	Constant (2)	30
5	Return	Truck(1)	Obtained from proposed approach	30

Triangular distribution of earthmoving operations is close to the historical data given in the Caterpillar Performance Handbook as demonstrated in the Figure 4.13. For example, the cycle time of 4-passes loading is simulated to be constant (1.8) while 3 to 7 passes is most common for truck loading.

Example — assume load tool spots hauler with full bucket

		988F	5130B
cycle times		.60	.45
First pass	(dump time)	.10 min.	.05 min.
2 passes	(full cycle)	.70	.50
3 passes	"	1.30	.95
4 passes	"	1.90	1.40
5 passes	"	2.50	1.85
6 passes	"	3.10	2.30
7 passes	"	3.70	2.75
8 passes	"	4.30	3.20
9 passes	"	4.90	3.65
10 passes	"	5.40	4.10

NOTE: Other sizes of loading tools will have different cycle times. See Wheel Loader section for **average** cycle times for truck loading.

Figure 4.12 Cycle Time of Truck Loading[2]

4.2.4 Summary

The proposed approach was successfully applied to a site-grading project for achieving the earthmoving plan and optimizing the temporary road network. Simulation models in *Simphony* validate the necessity of consideration of temporary road network in earthmoving simulations and the effectiveness to obtain the optimized temporary road network. The decision-makers can take advantage of the earthmoving plan to lower the earthwork costs through the proposed approach. The engineers with limited experience on temporary road network design can achieve a convincing solution by simply utilizing empirical costs. In addition, the approach is also suitable for quantitatively comparing several layouts of the temporary road network.

2 Caterpillar (1998), *Caterpillar Performance Handbook*, <http://nees.ucsd.edu/facilities/docs/Performance_Handbook_416C.pdf>

As the optimization approach cannot be detached from the empirical cost data and the conceptual model of temporary road network, it is foreseen that there is a need to improve the reliability of empirical cost data to achieve better optimized solutions. The space of cells varies depending on conditions of test cases which should be further studied. In addition, the efficiency of the optimization algorithm can be improved, which depends on complexity of the problem definition. The further improvement of the proposed approach would be worthy of research to help construction managers rely on a controllable and analytical method rather than experience for critical decision making in earthmoving planning.

4.3 Validation of Layout Optimization Approach

If earthmoving simulations encoded with earthmoving plans pass verification and validation, the entire optimization approach can be deemed useful. By comparing the minimized average haul time, total duration and total cost, the optimized temporary road network performs better than the empirical network. In order to validate the optimization approach, three simulation models encoded with corresponding earthmoving plan are developed as follows:

1. Model encoded with earthmoving plan considering rough ground (no temporary road).
2. Model encoded with earthmoving plan considering empirical temporary road network.
3. Model encoded with earthmoving plan considering optimized temporary road network 1.
4. Model encoded with earthmoving plan considering optimized temporary road network 2.

5. Model encoded with earthmoving plan considering optimized temporary road network 3.

The outputs of simulation including mean duration and productivity are listed in Table 4.9.

Table 4.9 Comparison between Models

Model No.	Simulated Total Project Duration (hrs)	Mean Haul Productivity (m^3/h)
1	309.33	814.21
2	294.60	854.92
3	**275.33**	**914.76**
4	**285.88**	**881.00**
5	**272.57**	**924.02**

The mean simulation duration to finish earthwork is about 10% shorter when comparing Model 2 (294.60 hrs) against Model 1 (309.33 hrs). Therefore the temporary road network should not be negligible in earthmoving simulation models. The mean duration to finish earthwork is about 7% shorter when comparing Model 3 (275.33 hrs) against Model 2 (294.60 hrs); The mean project duration to finish earthwork is about 3% shorter when comparing Model 4 (285.88 hrs) against Model 2 (294.60 hrs); The mean duration to finish earthwork is about 8% shorter when comparing Model 5 (272.57 hrs) against Model 2 (294.60 hrs). The optimized layouts show advantages in accelerating the project with a lower cost based on simulation. Among the optimized layouts, layout option 2 in the Model 4 is the best according to the KPIs in the simulation model. In conclusion, in this case, the optimized layouts have the potential to significantly improve the haul productivity and shorten the project duration by 3% to 8% taking advantage of simulation. The improvement of project duration and productivity can further benefit the contractor to reduce the fleet size if handling several earthworks at the same time.

4.4 Cost Saving of Optimization Method

Based on the simulation models, the analytical layout optimization method can increase the total productivity by 3% to 8%, when compared against the empirical layout design method. The increase of productivity will directly result in savings on total project duration and cost.

However, the total cost saving based on proposed optimization approaches can be far beyond the magnitude of 3% to 8%, which is very conservative estimate and only accounts for the saving in terms of truck hauling time and cost resulting from haul road network design optimization. For inexperienced personnel, the improvement based on the optimization approach can be very significant. Although experienced personnel can get close to the optimal design, they can be further helped with earthmoving job plan optimization to save on operation time and cost. The total saving resulting from the proposed framework implementing both layout design optimization and earthmoving job planning optimization will be assessed through formal field based or simulation based studies in the future.

5 Conclusions and Further Research

5.1 Conclusions

In reality, the goal of building the temporary haul road network is to accelerate project progress without significantly increasing project cost. The research adds to the existing body of knowledge by defining a cost function as an effective performance measurement of the temporary haul road network design, based on the average unit haul time, direct truck-hauling crew cost, and indirect costs for constructing and maintaining haul roads of various types. As such, the associated cost of executing the optimized earthmoving plan over a particular temporary haul road networks design can be readily estimated, making it straightforward for project managers to compare feasible alternatives. The research deliverables will potentially be of immediate use in practice and cater to the needs of earthworks contractors in terms of enhancing current practices of planning earthmoving operations and designing temporary haul road networks.

Analogous to the site grading design, the haul road network design is also based on a rectangular grid system with a larger width that is applied to geometrically profile the site. Thus, the haul road alignment design is constrained by the granularity of the grid system; curved alignment can only be approximated by linking the centroids of two adjacent cells diagonally. In addition, traffic control measures at intersections in the haul road network, such as yield/stop signs or traffic lights are ignored in the present research due to the relatively light traffic volume in comparison with the permanent road network design.

With application examples, the proposed methodology has justified that a well-designed temporary road network can be time-efficient, cost-effective, thus worthy to be built. It is emphasized that the proposed methodology for earthmoving job planning, haul road design, and time-cost evaluation of operations only adds to knowhow and experience of practitioners, providing decision support to enable them to improve performances in day-by-day practice.

The main contributions of this study include 1) adapting established concepts in transportation engineering domain for practical applications in the construction engineering domain; 2) improving earthmoving operations by factoring in the temporary haul road network which is not taken seriously in previous research efforts; 3) converting an empirical temporary road planning problem into an analytical optimization problem as part of earthworks design and earthmoving operations planning.

In conclusion, the proposed approaches have been successfully applied to the site grading project for optimizing the earthmoving operations plan and optimizing the temporary road network design simultaneously. The simulation models established in *Simphony* are used to show the necessity of consideration of temporary road networks in earthmoving simulations and validate the effectiveness of the optimized temporary road network obtained from the proposed research.

The planners or decision-makers can take advantage of the optimized results (optimized earthmoving plan and optimized temporary haul road network) in order to shorten the earthmoving duration and lower the costs. Junior engineers with limited experience on temporary road network design can deliver an impressive, practical solution by simply utilizing empirical cost data. Also, for mass earthworks, the resulting time and cost savings through proposed methods can obviously improve productivity and profitability for construction companies.

5.2 Limitations

To support critical decision-making in construction engineering, and to convert a purely empirical planning problem into a quantitative, automated methodology, further improvements on this research will be worthwhile and discussed as follows:

Earthmoving Field & Rectangular Gird

In the present research, the division of the field is straightforward and is based on the grid model, making it reasonable to assume the center of each cell to be the centroid of each cell. However, for the earthmoving fields with irregular shape or boundaries, the grid model to divide the field requires further study and assumptions.

Cut-and-fill Balanced Design

The earthwork design is one essential input of proposed optimization approach. In the present research, the earthwork design is required to be cut-and-fill balancing design especially for the linear programming model. For unbalanced designs, preliminary data processing should be made in order to achieve an "artificial balance." For example, extra volume can be counted into the volume of a specific cell on site. It is reasonable to assume that the extra cut volume to be moved out of the field is treated as the "fill" volume of the entrance cell. Based on reasonable assumptions, unbalanced designs can be artificially balanced prior to implementing the proposed methodologies.

Temporary Haul Road Network

In earthmoving projects, due to different purposes to build the haul road, haul road networks can be categorized into temporary, semi-permanent or permanent. Massive earthwork operations serve as the preliminary work of construction and usually last several months which only require a temporary road network. Therefore, if the haul road network is planned to become a permanent road after completing the earthworks, the optimization approaches require further improvements.

Layout Optimization

The layout optimization in terms of temporary haul road network design is successfully applied into the case study based on evaluation criteria including total cost and total duration. However, the constructability of a temporary road network is not considered in the numerical criteria and the objective function depends on a set of empirical cost data. The objective functions and criteria for layout optimization require refinement in future study.

Earthmoving Fleet Design

The present research assumes a fixed truck fleet (quantity and type of trucks) to be available and employed in the field and one single type of trucks is employed with the average truck speed being only determined by the haul road type, regardless of truck being fully-loaded or empty. Nonetheless, more sophisticated fleet design can be further added to the proposed optimization problem scope in the future research as such needs arise from practice.

5.3 Future Research

Serving as the decision support tool, the optimization approaches cannot be detached from the empirical cost data and the conceptual model of temporary road networks, which reside in the mental model of experienced field personnel. It is foreseen that there is a need to improve the reliability of empirical cost data in order to achieve better optimized solutions. The space of cells varies depending on conditions of test cases, which should be further studied. In addition, the efficiency of the optimization algorithm can be improved, which depends on the complexity of the problem definition. The constructability is crucial in real practice but it cannot be easily modelled into objective functions which require deeper thoughts and more sophisticated modeling. However, the optimization studies make contributions to connecting the transportation engineering with construction engineering and management. In short, the further improvement of the proposed approach would be well warranted to help construction managers take advantage of practical yet analytical methods, instead of relying on experiences alone, for critical decision making in earthmoving planning.

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APPENDIX A. Program for Optimized Earthmoving Plan

Elaboration of Floyd-Warshall Algorithm

Relevant variables and matrices are defined for the algorithm as follows:

wij: The weight of an edge between vertex *i* and *j* in a network

W: *n x n* matrix representing the edge weights of an n-vertex network, where **W** = *wij*.

$sij^{(k)}$: The weight of the shortest path from vertex *i* to *j* for which all intermediate vertices are in the set (*1, 2,…,k*).

$\mathbf{S^{(k)}}$: *n*×*n* matrix representing the path distances between vertices in a n-vertex network, where $\mathbf{S^{(k)}} = sij^{(k)}$

Note a shortest path does not contain the same vertex more than once; for the shortest path from *i* to *j* such that any intermediate vertices on the path are chosen from the set (*1, 2,…, k*), there are two possibilities:

1. *k* is not a vertex on the path, so the shortest such path has length $sij^{(k-1)}$
2. *k* is a vertex on the path, so the shortest such path has length $sik^{(k-1)} + skj^{(k-1)}$

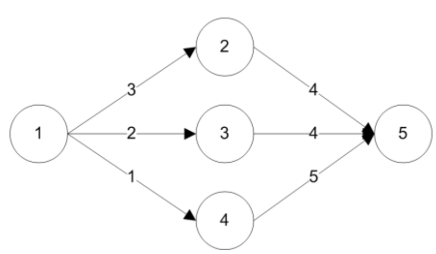
So we see that we can recursively define $sij^{(k)}$ as:

$$s_{ij}^{(0)} = w_{ij}$$

$$s_{ij}^{(k)} = \min\left(s_{ij}^{(k-1)}, s_{ik}^{(k-1)} + s_{kj}^{(k-1)}\right)$$

for *k* = 1,…, *n*. where *n* is the total number of cells.

For example, in a 5-vertex network, s_{15} can be finally derived as follows:



$$S^{(0)} = W = \begin{pmatrix} \infty & 3 & 2 & 1 & \infty \\ \infty & \infty & \infty & \infty & 4 \\ \infty & \infty & \infty & \infty & 4 \\ \infty & \infty & \infty & \infty & 4 \\ \infty & \infty & \infty & \infty & \infty \end{pmatrix};\ s_{15}^{(0)} = \infty$$

For $S^{(1)}$ matrix, $s_{ij}^{(1)} = s_{ij}^{(0)}$ except for $s_{15}^{(1)} = \min\left(s_{15}^{(0)}, s_{11}^{(0)} + s_{15}^{(0)}\right) = \min(\infty, \infty) = \infty$

For $S^{(2)}$ matrix, $s_{ij}^{(2)} = s_{ij}^{(1)}$ except for $s_{15}^{(2)} = \min\left(s_{15}^{(1)}, s_{12}^{(1)} + s_{25}^{(1)}\right) = \min(\infty, 7) = 7$

For $S^{(3)}$ matrix, $s_{ij}^{(3)} = s_{ij}^{(2)}$ except for $s_{15}^{(3)} = \min\left(s_{15}^{(2)}, s_{13}^{(2)} + s_{35}^{(2)}\right) = \min(7,6) = 6$

For $S^{(4)}$ matrix, $s_{ij}^{(4)} = s_{ij}^{(3)}$ except for $s_{15}^{(4)} = \min\left(s_{15}^{(3)}, s_{13}^{(3)} + s_{35}^{(3)}\right) = \min(6,5) = 5$

For $S^{(5)}$ matrix, $s_{ij}^{(5)} = s_{ij}^{(4)}$ and $s_{15}^{(5)} = \min\left(s_{15}^{(4)}, s_{15}^{(4)} + s_{55}^{(4)}\right) = \min(5, \infty) = 5$

Therefore, the weight of shortest path between vertex *1* and *5* is determined to be 5 by applying the Floyd-Warshall algorithm.

The detailed programming is given as following:

```
function [D,R] = floyd(a)
%Floyd method to find the shortest path
% D is the min-distance matrix; R is the min-path matrix
n=size(a,1);
D=a;
R=zeros(n,n);
for i=1:n
    for j=1:n
        R(i,j)=j;
    end
end
for k=1:n
    for i=1:n
        for j=1:n
            if D(i,k)+D(k,j)<D(i,j);
                R(i,j)=R(i,k);
                D(i,j)=D(i,k)+D(k,j);
            end
        end
    end
end
end
```

Achievement of Earthmoving Plan (Layout Option 3)

```
a=inf*ones(48,48); %a is a 48*48 matrix, which is the road time network
        for i=1:48;
        a(i,i)=inf;
        if i+1>0 && i+1<=48
        a(i,i+1)=22.5;a(i+1,i)=22.5;
        end
        if i-1>0
        a(i,i-1)=22.5;a(i-1,i)=22.5;
        end
        if i+12>0 && i+12<=48
        a(i,i+12)=22.5;a(i+12,i)=22.5;
        end
        if i+11>0 && i+11<=48
        a(i,i+11)=31.82;a(i+11,i)=31.82;
        end
        if i+13>0 && i+13<=48
        a(i,i+13)=31.82;a(i+13,i)=31.82;
        end
        end


%Layout Option 3
a(12,13)=inf;a(13,12)=inf; a(24,25)=inf;a(25,24)=inf; (36,37)=inf;a(37,36)=inf;
a(1,12)=inf;a(12,1)=inf; a(13,24)=inf;a(24,13)=inf;
a(25,36)=inf;a(36,25)=inf;a(37,48)=inf;a(48,37)=inf;a(12,25)=inf;a(25,12)=inf;
a(24,37)=inf;a(37,24)=inf; a(46,34)=inf;a(34,46)=inf;
a(26,15)=21.6;a(15,26)=21.6;a(22,35)=21.6;a(35,22)=21.6;
a(16,15)=15;a(15,16)=15;a(17,16)=15;a(16,17)=15;a(17,18)=15;a(18,17)=15;a(19,18)=15;a(18,1
9)=15;a(20,19)=15;a(19,20)=15; a(20,21)=15;a(21,20)=15;a(21,22)=15;a(22,21)=15;
a(4,16)=15;a(16,4)=15;a(17,29)=15;a(29,17)=15;a(6,18)=15;a(18,6)=15;a(19,31)=15;a(31,19)=1
5;a(8,20)=15;a(20,8)=15;


[D,R]=floyd(a);
T=reshape(D,2304,1);


vl=zeros(96,2304);    %vl is the constraint matrix A
```

```
for j=1:48
for i=1:48
vl(j,(j-1)*48+i)=1;
end
end
for j=1:48
for i=1:48
vl(48+j,(i-1)*48+j)=1;
end
end


ob=[15000,3700,0,0,0,0,1000,11200,2300,22000,6900,0,62600,0,0,0,0,0,0,24800,9900,2200,0,0,
3700,0,0,0,0,0,12400,34400,72500,28500,2500,0,0,1400,0,0,0,5900,9900,2700,0,0,0,0,0,0,3700,
9000,9000,8000,0,0,0,0,0,11200,0,22500,33800,36000,23000,22200,8100,0,0,0,14300,7900,0,22
500,28100,23000,24300,14200,0,0,0,0,0,0,0,0,2300,1200,9000,0,0,0,2200,0,0,0];
ob1=reshape(ob,96,1); %ob is the constaint matrix B
ob1=ob


T1=T;
lb=zeros(2304,1);ub=[];A=[];b=[];Aeq=vl;beq=ob1;
[x,fval]=linprog(T1,A,b,Aeq,beq,lb);
x=reshape(x,48,48)
f=fval/(sum(ob)/2)
```

APPENDIX B. Program for Optimization of Temporary Haul Road Network

MCGA Functions

GA Initialize the Populations

```
function Chrom = GAInitPop( NIND,N )
%NIND is the size of each generation
%N is the length of each gene
Chrom=zeros(NIND,N);
for i =1:NIND
	a=zeros(1,N);
	for i1=1:N
		if rand()<=0.5
			a(i1)=0;
		else
			a(i1)=1;
		end
	end
	Chrom(i,:)=a;
end
a1=zeros(1,N);
	for i1=1:N
		a1(i1)=0;
	end
	a2=zeros(1,N);
	for i1=1:N
		a2(i1)=1;
	end
	Chrom(1,:)=a1;
	Chrom(NIND,:)=a2;
end
```

GA EliteIndi

```
function [MinObjV,MinChrom] = GAEliteIndi( Chrom,ObjV,MinObjV,MinChrom )
%manual select
MP=length(Chrom);
for i=1:MP
	[Min0,minI]=min(ObjV{i});
	if Min0<= MinObjV(i) && Min0~=0
```

```
            MinObjV(i)=Min0;
            MinChrom(i,:)=Chrom{i}(minI,:);
        end
end
end
```

GA Fitness

```
function FitnV = GAFitness( ct,c)
%ob1 is the objective function
%fitness is 1./ob1
[a,b]=size(ct);
FitnV=1./(1-48+ct);
for i=1:a
        if ct(i)>c
            FitnV(i,1)=0;
        end
end
end
```

GA Immigrant

```
function [Chrom,ObjV] = GAimmigrant(Chrom,ObjV)
%immigrant factor
MP=length(Chrom);
for i=1:MP
        if min(ObjV{i})~=0
        [Min0,minI]=min(ObjV{i});
        end
        next_i=i+1;
        if next_i>MP;next_i=mod(next_i,MP);end
        [Max0,maxI]=max(ObjV{next_i});
        Chrom{next_i}(maxI,:)=Chrom{i}(minI,:);
        ObjV{next_i}(maxI)=ObjV{i}(minI);
End
```

GA Intercross

```
function [ a,b ] = GAintercross( a,b )
%a&b are two individuls for intercross
```

```
L=length(a);
r1=randsrc(1,1,[1:L]);
r2=randsrc(1,1,[1:L]);
if r1~=r2
    a0=a;b0=b;
    s=min([r1,r2]);
    e=max([r1,r2]);
    for i=s:e
        a(i)=b0(i);
        b(i)=a0(i);
    end
end
end
```

GA Mutation

```
function SelCh = GAMutate( SelCh,Pm)
%Pm is the possibility
[NSel,L]=size(SelCh);
for i=1:NSel
    if Pm>=rand
        R=randperm(L);
        SelCh(i,R(1:2))=SelCh(i,R(2:-1:1));
    end
end
end
```

GA Recombine

```
function SelCh = GARecombin( SelCh,Pc )
%Pc is the intercross possibility
NSel=size(SelCh,1);
for i=1:2:NSel-mod(NSel,2)
    if Pc>=rand
        [SelCh(i,:),SelCh(i+1,:)]=GAintercross(SelCh(i,:),SelCh(i+1,:));
    end
end
end
```

GA Reins

```
function Chrom = GAReins( Chrom,SelCh,ObjV )
%UNTITLED12 Summary of this function goes here
%      Detailed explanation goes here
NIND=size(Chrom,1);
NSel=size(SelCh,1);
[TobjV,index]=sort(ObjV);
Chrom=[Chrom(index(1:NIND-NSel),:);SelCh];
end
```

GA Reverse

```
function SelCh = GAReverse( SelCh,ObjV,row1,col1,ob,t1,t2 )
[row,col]=size(SelCh);
SelCh1=SelCh;
for i=1:row
        r1=randsrc(1,1,[1:col]);
        r2=randsrc(1,1,[1:col]);
        mininverse=min([r1 r2]);
        maxinverse=max([r1 r2]);
        SelCh1(i,mininverse:maxinverse)=SelCh1(i,maxinverse:-1:mininverse);
end
ct = GAcost(SelCh1,row1,col1,ob,t1,t2);
ObjV1=ct;
index=mean(ObjV1)<mean(ObjV);
SelCh(index,:)=SelCh1(index,:);
end
```

GA Selection

```
function SelCh = GASelect(Chrom,FitnV,GGAP)
%Chrom/FitnV/
%GGAP is the possibility
NIND=size(Chrom,1);
NSel=max(floor(NIND*GGAP+.5),2);
ChrIx=GASus(FitnV,NSel);
SelCh=Chrom(ChrIx,:);
end
```

GA Sus

```
function NewChrIx= GASus( FitnV,Nsel )
%Nsel the number select for next generation
[Nind,ans]=size(FitnV);
cumfit=cumsum(FitnV);
trials=cumfit(Nind)/Nsel*(rand+(0:Nsel-1)');
Mf=cumfit(:,ones(1,Nsel));
Mt=trials(:,ones(1,Nind))';
[NewChrIx,ans]=find(Mt<Mf&[zeros(1,Nsel);Mf(1:Nind-1,:)]<=Mt);
[ans,shuf]=sort(rand(Nsel,1));
NewChrIx=NewChrIx(shuf);
end
```

Optimization based on MCGA

```
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)


NIND=str2double(get(handles.NIND,'string'));
N=str2double(get(handles.N,'string'));
MP=str2double(get(handles.MP,'string'));
GGAP=str2double(get(handles.GGAP,'string'));
Row=str2double(get(handles.Row,'string'));
Col=str2double(get(handles.Col,'string'));
D=str2double(get(handles.D,'string'));
TLimit=str2double(get(handles.TLimit,'string'));
CLimit=str2double(get(handles.CLimit,'string'));
V1=str2double(get(handles.V1,'string'));
V2=str2double(get(handles.V2,'string'));
MaxGen=str2double(get(handles.MaxGen,'string'));
CF=str2num(get(handles.CF,'string'));
b=Row*Col;
ob=zeros(1,2*b);
for i=1:b
    i1=b+i;
    if CF(1,i) >=0
        ob(1,i)=CF(1,i);
```

```
        elseif CF(1,i)<0;
                ob(1,i1)=abs(CF(1,i));
        end
end


h=waitbar(0,'Calculating... Please Wait...')
set(h,'name','Start Searching the Best Route')%Waiting Bar


%%Initial
for i=1:MP
        Chrom{i}=GAInitPop(NIND,N);
        pc{i}=0.7+(0.9-0.7)*rand(MP,1);
        pm{i}=0.001+(0.05-0.001)*rand(MP,1);
end


t1=D/V1*3.6;%paved road speed m/s
t2=D/V2*3.6;%unpaved road speed m/s
%%Optimize
gen=0;
gen0=0;
minY=9.999e10;
c=470000;
row=Row;
col=Col;


for i=1:MP
        [ct{i},tcost{i},roadcost{i}] = GAcost(Chrom{i},row,col,ob,t1,t2);
        ObjV{i}=tcost{i};
end
MinObjV=minY*ones(MP,1);
MinChrom=ones(MP,N);


while gen0<=MaxGen
        gen=gen+1;
        progress=['Current Gene',num2str((gen0+1)/MaxGen*100),'%...'];
```

```
    waitbar(gen/100,h,progress);
    for i=1:MP
        FitnV{i}=GAFitness(tcost{i},ct{i},TLimit,CLimit,c);
        %%Select
        SelCh{i}=GASelect(Chrom{i},FitnV{i},GGAP);
        %%Intercross
        SelCh{i}=GARecombin(SelCh{i},pc{i});
        %%Mutate
        SelCh{i}=GAMutate(SelCh{i},pm{i});
        %%Insert
        [ct1,tcost1,roadcost1] = GAcost(Chrom{i},row,col,ob,t1,t2);
        ObjVSel{i}=tcost1;
        %%Reverse
        SelCh{i}=GAReverse(SelCh{i},ObjVSel{i},row,col,ob,t1,t2);
        %%Reins
        Chrom{i}=GAReins(Chrom{i},SelCh{i},tcost1);
        [ct{i},tcost{i},roadcost{i}] = GAcost(Chrom{i},row,col,ob,t1,t2);
        ObjV{i}=tcost{i};
    end
    [Chrom,ObjV]=GAimmigrant(Chrom,ObjV);
    [MinObjV,MinChrom]=GAEliteIndi(Chrom,ObjV,MinObjV,MinChrom);
    %%Outputs
    YY(gen)=min(MinObjV);
    if YY(gen)<minY && YY(gen)~=0
        minY=YY(gen);
        gen0=0;
    else
        gen0=gen0+1;
    end
end


%%Plot
axes(handles.fig1)
plot(1:gen,YY,'*')
title('GA')
xlabel('generations')
ylabel('min-value')
xlim([1,gen])
[Y,I]=min(MinObjV);
```

```
X=(MinChrom(I,:));
set(handles.opt,'string',num2str(Y))
set(handles.cb,'string',num2str(X))


%Try to plot the figure;
    a1=X;
    nod=row*col;
    a=inf*ones(nod,nod); %a is a 16*16 matrix, which is the road time network
    i1=1;
    for i=1:nod;
        a(i,i)=0;
        if i+1>0 && i+1<=nod && mod(i,row)~=0
        a(i,i+1)=t2+a1(i1)*(t1-t2);
        a(i+1,i)=t2+a1(i1)*(t1-t2);
        i1=i1+1;
        end
        if i+row>0 && i+row<=nod
        a(i,i+row)=t2+a1(i1)*(t1-t2);
        a(i+row,i)=t2+a1(i1)*(t1-t2);
        i1=i1+1;
        end
        if i+row+1>0 && i+row+1<=nod && mod(i,row)~=0
        a(i,i+row+1)=t2+a1(i1)*(1.414*t1-t2);
        a(i+row+1,i)=t2+a1(i1)*(1.414*t1-t2);
        i1=i1+1;
        end
        if i+row-1>0 && i+row-1<=nod && mod(i,row)~=0 && mod(i,row)~=1
        a(i,i+row-1)=t2+a1(i1)*(1.414*t1-t2);
        a(i+row-1,i)=t2+a1(i1)*(1.414*t1-t2);
        i1=i1+1;
        end
    end


axes(handles.fig2)
hold on
box on
for i=1:nod
    for j=1:nod
```

```
        if a(i,j)~=0 && a(i,j)~=Inf && a(i,j)~=t2
        y2=[(fix((i-1)/row))+1,(fix((j-1)/row))+1];
        x2=[(mod(i-1,row))+1,(mod(j-1,row))+1];
        plot(x2,y2,'-o','LineWidth',4)
        elseif a(i,j)~=0 && a(i,j)~=Inf && a(i,j)==t2
        y2=[(fix((i-1)/row))+1,(fix((j-1)/row))+1];
        x2=[(mod(i-1,row))+1,(mod(j-1,row))+1];
        plot(x2,y2,'--o','LineWidth',1)
        end
    end
end
    title('Optimized Network')
    xlabel('node')
    ylabel('node')
    xlim([1,row])
    ylim([1,col])
close(h)
msgbox('Finish Searching')
```