**Integrated system for earthmoving operations**
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# INTEGRATED SYSTEM FOR EARTHMOVING OPERATIONS

**PRASHANT VERMA**

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**In**
**The Department**
**Of**
**Building, Civil and Environmental Engineering**

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# ABSTRACT

# INTEGRATED SYSTEM FOR EARTHMOVING OPERATIONS

**Prashant Verma**

Earthwork allocations are needed in excavation work to determine the quantities of material to be moved from each cut section to each fill section. Two basic methods of earthwork allocations are available: mass diagram and linear programming. The mass diagram can be used to determine the most economic distribution of cut and fill. However, the usefulness of mass diagram diminishes for situations in which haul costs are not directly proportional to the haul distance; swell and shrinkage vary along the roadway; and additional quantities of soil are available at borrow pit or may be disposed of at disposal sites.

This study presents an integrated system for estimating earthmoving production, selecting fleet and optimizing earthmoving operations. Geographic information system (GIS) is employed to acquire and analyze spatial data. Fleet Production and Cost Analysis (FPC) is used as software tool to select the best Fleet. The methodology used in the development of optimization model is based on the Mixed-Integer Linear Programming which determines optimum quantity of materials to be moved between different cut and fill sections, borrow pits and disposal sites. The standard Microsoft Excel Solver has been used to run the presented MILP model. This study also proposes an algorithm for determining longitudinal interval for a part of road segment.

The study concludes that the presented integrated system can assist engineers, contractors and clients of earthmoving projects in quantity take-off determination work, for selecting best equipment fleet and in determining the optimum quantity of earthwork materials to be moved between different sections so as to finish the project in minimum time and within budget with optimum use of available resources.

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# CHAPTER 1

# INTRODUCTION

## 1.1 General

Earthmoving operation is common in most of the construction projects, varying from small tasks in foundation work to very big tasks in dams and highway constructions. In heavy civil engineering projects earthmoving operations generally represent a major bid item that has great effect in determining the total cost and duration of the project. Accuracy in earthwork estimation and proper optimization can even affect the success of whole project. Considerable efforts have been made in the development of efficient methods and systems for estimating earthmoving production, selecting equipment, and optimizing resources.

To determine the earthwork quantities for different cut and fill sections, Geographical Information System software is found to be very effective. 3D Analyst ®. of ArcView, GIS software, have been used for that purpose. To determine total job material handling costs using various equipments in different fleet combinations performance database of different manufacturers of equipment is needed. To determine the best Fleet, FPC (Fleet Production and Cost Analysis), professional software by Caterpillar, is used.

This research presents a methodology for optimization of earthwork allocation in excavation work. Usually earthwork optimization aims at minimizing cost, maximizing production, finishing work on time and meeting the specification requirements. The objective of the presented optimization model is to minimize the total cost of earthmoving operation. As the Objective Function and Constraints are in the form of mixed-integer linear equations, methodology used in the development of optimization model is based on the Mixed-Integer Linear Programming method which gives optimum quantity of materials need to be moved between cut sections (or borrow pits) and fill sections (or disposal sites) to have minimum total cost.

## 1.2 Research Objectives

The main objective of this research is to present a methodology for estimating earthmoving production, selecting fleet and optimizing earthmoving operation work.

The research objectives can be listed as follows:

- Understand the quantity takeoff determination process.
- Understand fleet selection method.
- Determine the optimization methodology for earthmoving operation.
- Determine a computer-based tool capable of running presented methodology and give satisfactory output.
- Develop an integrated system for earthmoving operations.

## 1.3 Scope and Limitations

The presented integrated system uses GIS, FPC and MILP as its three components which can assist engineers, contractors and clients of earthmoving projects in getting the accurate earthwork quantities, selecting the best equipment fleet and getting optimum quantity of earthwork materials to be moved between different sections so as to finish the project in minimum time and within budget with optimum use of available resources.

Physical integration of the three components of the presented system has not been done due to restriction in professional software in doing so.

In the MILP model, unit cost function of purchase and excavation of borrow pits have been considered as stepwise having two components. In this presented model, required quantities of cut and fill, the capacities of the landfills and borrow pits, plant fleet production rate and duration of project have been considered as constraints.

## 1.4 Thesis organization

### 1.4.1 Literature Review

Chapter 2 includes a summery of the literature review. An intensive review of literature for different optimization models in the area of earthmoving operations, based on different theories, is discussed, in this chapter. A review of the application of Mass Haul Method, Linear Programming, Queuing theory, Expert systems and Simulation method in construction industry, particularly for the earthmoving operations, is presented.

### 1.4.2 Presented Methodology

In this research work, ArcView's 3D Analyst ® has been used to determine cut and fill quantities. Fleet Production and Cost Analysis (FPC) is used as software tool to select the desirable Fleet, which can move the materials for the lowest cost. This research also proposed an algorithm for determining longitudinal interval for a part of road segment. Mixed-Integer Linear Programming has been used for optimizing earthmoving operation between different cut sections or borrows pits and fill sections or disposal sites using a particular fleet within the project duration. These are illustrated in chapter 3.

### 1.4.3 Implementation and Verification of the Model

MILP optimization problems have been solved using Microsoft Excel Solver which gives optimum value of decision variables, i.e., optimum quantity of materials to be moved between different cut sections (or borrow pits) to fill sections (or disposal sites) to get minimum cost of completing the project within project duration using a specific type of fleet. Presented methodology has been verified with the different types of data needed for each individual component and satisfactory results have been found.

### 1.4.4 Conclusion

The presented integrated system can assist engineers, contractors and clients of earthmoving projects in getting the accurate earthwork quantities, selecting best equipment fleet and getting optimum quantity of earthwork materials to be moved between different sections so as to finish the project in minimum time and budget with optimum use of available resources.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Earthwork volumes represent the basis on which contractors are being paid for highway construction. The earthwork volumes between successive roadway stations are also used in determining the economic distribution of earthwork. It is essential that the volumes are accurately computed because disagreements related to earthwork volumes often cause the owner and the contractor to look to the courts for settlement (Easa, 2001).

It is generally necessary to consider the quantities of material to be excavated or generally used in the highway excavation process. This information can be useful in the development of a preliminary cost estimate for the work to be undertaken. It can also be used as part of the design process in the selection of the final cross-section and alignment characteristics of the roadway. Quantity estimates are often part of the information given to the contractors bidding to complete the work. In past years quantity estimation was a slow and tedious task, which involved extensive and repetitive calculation. In more recent years, computer software has been developed whereby these calculations can be done automatically. This has improved the ability of the designers to consider various design alternatives (Innes, 1995).

Earthwork estimators currently use graphical software programs to determine the quantity of cut and fill on a project. However, they can only make educated and sensitive guess as to the actual haul distance and direction that they need to haul the excavated soil. The estimator has to look at the plan's design elevations and then scale the distances from the major cut areas to the major fill areas. This gives the estimator a general idea as to the haul direction and how far the excavation needs to be hauled. Alternatively, the estimator may determine the centre of mass to identify haul distances. In either case, the result is an approximate haul distances and directions (Son, Mattila and Myers 2005).

## 2.2 Quantity of material estimation

According to Siyam (1987), for all spacing combinations, the spacing between cross sections has the largest influence on accuracy of volume determination in road construction work. Accuracy decreases with the increasing distance between cross sections. To keep volume accuracy within certain limit, there should be limit for longitudinal distance between different cross sections for a road segment.

Accurate estimating of earthmoving quantities is crucial to developing realistic plans. Traditionally, cut and fill quantities between two successive sections along an embankment are calculated using the average-end-area method or the prismoidal model. (Meyer and Gibson, 1980). For unequal end sections, the latter tends to yield more accurate estimates than the former, but require additional field data gathering, limiting its use (Epps and Corey, 1990).

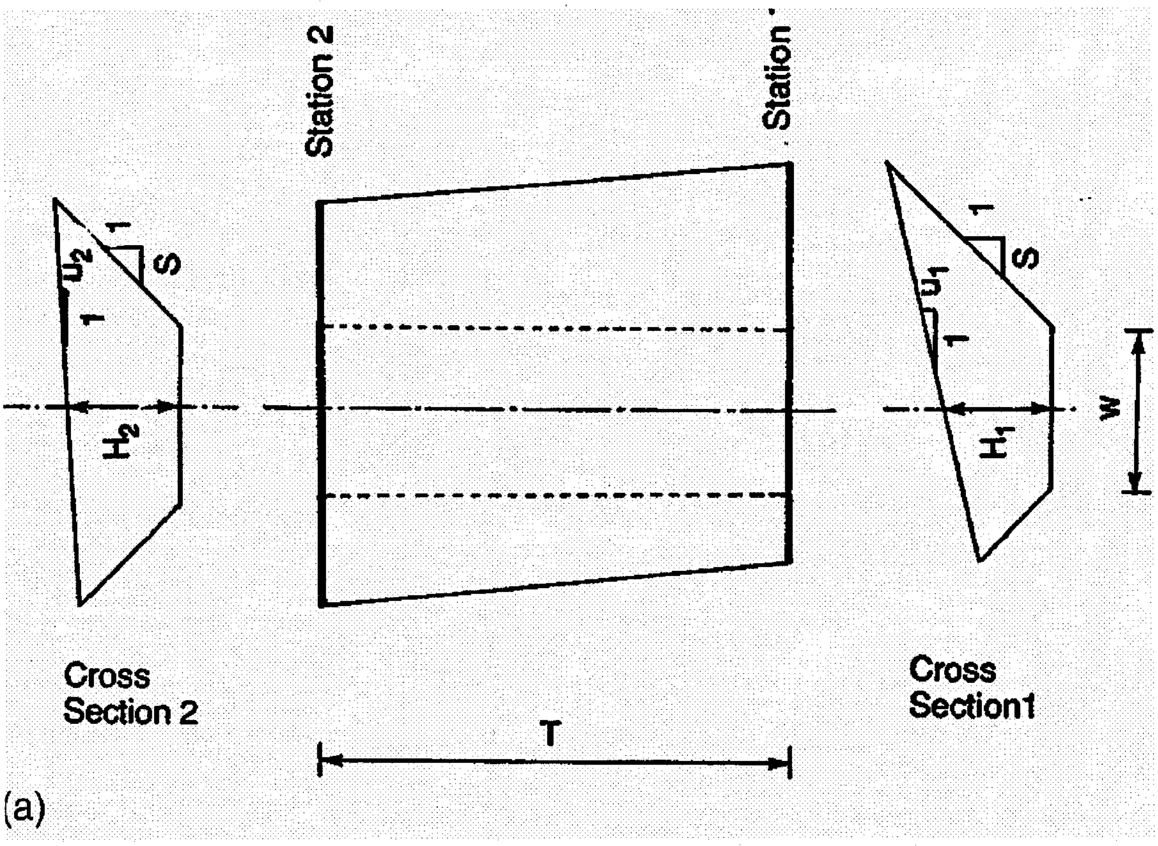


**Fig 2.1: Geometry of roadway section between two stations-straight roadways**
Source: Easa, 1992

### 2.2.1 Models for straight roadways-

**Average end-area model-** In the average end-area model, the volume is computed by multiplying the distance between two stations by the average of their end cross-sectional areas

$V \text{ (average end area)} = T\,(A1+A2)/2$

Where V= volume of earth between Stations 1 and 2;

T=distance between stations;

and A1 and A2 areas of the cross sections at Stations 1 and 2, respectively.

**Prismoidal model-** In the prismoidal model, the volume is computed assuming that the ground profile between each station pair is linear

V (Prismoidal) = T (A1+4Am+A2)/6

Where Am=area of the middle cross section

and A1 and A2 areas of the cross sections at end Stations, respectively.

For linear profiles, the prismoidal model gives the exact volume, while the average end-area model generally overestimates the volume (Easa, 1992).

**Pyramid frustum formula-** Easa (1991) noted that both method, average-end-area method or the prismoidal methods, yield inaccurate estimates if two successive sections are not of same type (cut or fill), and proposed employing the pyramid frustum formula to compute quantities of cut and fill at such sections.

Because the volumes formed in the transition areas are frustum-like solids, the PF formula is more accurate than the AEA formula. The proposed formula, which is a function of only the end areas and the distance between them, is as simple as the AEA formula (Easa, 1991).

For terrain with large ground cross slopes, the transition from cut to fill produces transition and sidehill cross-sections. A transition cross section is a cut or fill section where the ground intersects the grade at the roadway edge. A side hill cross section is the intermediate section with both cut and fill areas. The transition and sidehill cross sections are normally established during the construction stage.

The volume of the pyramid frustum between two sections 1 and 2 can be derived by applying the known prismoidal formula, which is given by

$V = d\,(A_1 + 4A_m + A_2)/\,6$

In which $A_m$ = area of the middle cross section and d = distance between the end cross sections.

For a frustum of a pyramid, the ratio of the corresponding dimensions of the end areas is constant. The ratio is given by $C_2 / C_1 = B_2 / B_1$

Also, the areas of the end cross sections are given by

$A_1 = \frac{1}{2}\, b_1 c_1$

$A_2 = \frac{1}{2}\, b_2\, c_2$

The area of the middle cross section is computed as

$A_m = \frac{1}{2}\, b_m c_m$

Where $b_m$ and $c_m$ are given by

$b_m = (b_1 + b_2)/2$

$c_m = (c_1 + c_2)/2$

Thus $A_m = \frac{1}{4}\,(A_1 + A_2 + \sqrt{A_1 A_2})$

Finally substituting for Am in first equation gives

$V = d\,(A_1 + \sqrt{A_1 A_2} + A_2)/\,6$

which is the required PF formula. It is interesting to note that this formula requires only the areas of the end cross sections.

By comparing results from applying AEA formula and PF formula to the pyramid frustum-like solids of roadway transition areas, Easa (1991) proved that AEA produces large errors, especially when end areas differ substantially.

The PF formula requires only end areas and therefore it is as simple as the AEA formula. Because the PF formula is more accurate, it should be used in volume computations for roadway transition areas (Easa, 1991).

### 2.2.2 Models for Curved Roadways-

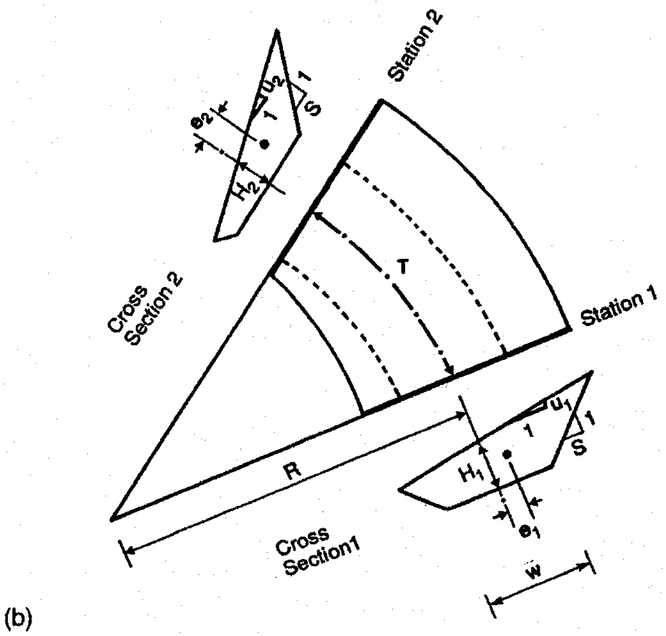


**Fig 2.2: Geometry of roadway section between two stations curve roadway**
**Source – Easa, 1992**

Earthwork volumes for roadway horizontal curves can be computed using a model based on Pappus' theorem or a mathematical model.

**Pappus' model** –The Pappus-based model is analogous to the average end-area model for straight roadways. In this model, the volume is approximately computed as the average of the volumes resulting from rotating the areas of the two cross sections about an axis in their planes (Anderson *et al.*, 1985). For example, the volume of the solid formed by rotating Cross section 1 equals $A_1$ multiplied by the length of the path traced out by the centroid of the cross section. The Pappus-based model is exact only if the two cross sections are identical.

**Mathematical model** –The accuracy of estimate provided by Pappus' theorem deteriorates as the difference between the two end areas increases (Easa, 1992). (Easa, 1992) proposed a mathematical model that accounts for transition section (sections containing area of both cut and fill) and moderates changes in ground cross slope in curved portions of the highway. Uses of that model require simplifying the end section, assuming a linear ground profile. Siyam (1987) had recommended employing the theory of least squares to determine the equation of line of best fit to represent the approximation of the ground elevation. However, this can result in a simplified section with the different cross section area than the original section (Easa 1987). An alternate method to determine the equation of the line of best use without reducing the volume accuracy was presented by Easa and can be employed for curved section of the embankment. In order to increase the estimating accuracy, the longitudinal interval "L" between the end sections is made dependent on the horizontal curvature of the highway at that location, and can be determined from

$L = x\,(1-1/R)$

X is the specific interval

R is the radius of horizontal curvature.

The mathematical model calculates earthwork volumes based on triple integration (Easa 1992). The model is applicable when the longitudinal ground profile linearly varies between the stations and the ground cross slope between the stations is linear and constant. The model is applicable to cut (or fill) and transition sections. The mathematical model is not accurate when the ground cross slope is not constant or when the longitudinal ground profile between stations is highly nonlinear. It is also not applicable for transition sections when one of the end cross sections is not one sided (triangle). For these conditions, the mathematical solution of earthwork volumes is too complex to be derived.

**Simulation-** Monte Carlo simulation technique is used to compute earthwork volumes of curved roadways with complex ground profiles and cross sections i.e. even for variable ground cross slope and highly nonlinear longitudinal ground profile between stations. The model, based on the hit-or-miss concept, is an extension of the method of computing an area using simulation.

Monte Carlo simulation involves the generation of random numbers that are then used to generate random variables based on specific probability distributions of the respective random variables. This simulation technique is very powerful for analyzing complex engineering systems, and has been used for several general applications.

Easa (2003) stated that mathematical model is not accurate for greatly fluctuating profiles, such as those in hilly and mountainous terrains and so he developed a model for estimating earthwork volumes for such profiles using Monte Carlo simulation. In his paper he illustrates how a completely deterministic problem can be solved using a probabilistic simulation. The results show that the simulation model improves the estimates of earthwork volumes compared to traditional and mathematical models.

## 2.3 GEOGRAPHIC INFORMATION SYSTEMS (GIS)

### 2.3.1 Introduction

GIS can be defined as system of spatially referenced information, including computer programs that acquire, store, manipulate, analyze, and display spatial data. GIS can also be defined as "an organized collection of computer hardware, software, and geographic data designed to capture, store, update, manipulate, analyze, and display geographically referenced data"(Holdstock 1998).

A full GIS, or geographic information system, requires:

Hardware (computers and peripherals)

Software

Data

People

Training

and sound analysis methods for interpreting the results generated by the GIS.

Simply put, a GIS combines layers of information about a place to give you a better understanding of that place. What layers of information you combine depends on your purpose—finding the best location for a new store, analyzing environmental damage, viewing similar crimes in a city to detect a pattern, and so on.

### 2.3.2 GIS Applications

**General**

GIS is a powerful tool that has been successfully applied in various fields. Spatial queries, such as topological queries, as well as non-spatial queries, are rapidly retrieved by a GIS. Question regarding location and condition of specific elements can readily be answered. GIS also enhances modeling, enabling various scenarios to be examined and assessed at reasonable speed. Graphic functions such as edge matching, aggregation, classification, measurements and overlay are readily carried out by most GIS packages. The full potential of GIS is still being realized and with the advances in computer technology, further applications are expected (Hassanein 2002).

Avenue, programming language of ArcView, offers a rich set of spatial data types among the available classes, in combination of a quiet broad implementation of datastructrures and the storage of the spatial data within easily accessible shapefiles. ArcView's 3D-Analsyt extension gives full access to TINs (Triangulated Irregular Networks). 3D-Scene of ArcView is very basic functionality in the sense of manipulation of the points of the view and the scene itself, but it's one big advantage in querying the displayed TIN shapefiles. One can easily select nodes, edges and faces within the 3D-Scenes.

### In Construction Industry

GIS has been successfully utilized in the field of construction management. Although environmental engineering has been the prime field that benefited from GIS (Gomez *et al.,* 1996, Gooding *et al.,* 1993), GIS is increasingly being used in transportation engineering, highway management, evaluation of alternatives for highway route alignment, groundwater modeling as well as construction industry. GIS has also been employed to select the optimum routes for highway and location of bridges, monitor pavement compaction, select the optimum location for landfills and sequence snow removal operations.

Jeljeli et al (1993) explored potential construction applications that could benefit from implementing GIS, and addresses issues such as utilizing GIS to select equipment based on soil type and work conditions. The possibility of employing GIS in both the bidding and design phases was also explored, as well as its use in pre-qualification of contractors. The use of Arc View's 3D Analyst ® was investigated by Price (1999). The study showed that 3D Analyst ® can be readily utilized to determine cut and fill quantities. Hassanein (2002) used GIS to acquire and analyze spatial data, and automatic computation of cut and fill quantities and the development of mass haul diagram. Jha, McCall and Schonfeld (2001) proposed an integrated GIS-Genetic Algorithm (GA) - Computer Visualization (CV) model for highway development, which can improve decision-making capabilities in selecting the preferred highway alternative. It can also enhance public and political acceptability due to effective visualization of future transportation enhancements. GIS serves as the prime source for necessary data and maps, and GAs are used to optimize highway alignments.

### 2.3.3 Generating Digital Terrain Models

Digital Terrain Models (DTMs), sometimes called Digital Elevation Models (DEMs), are computer models of the surface of the Earth and are being increasingly used by scientists from many disciplines for tasks such as estimating slope gradient and aspect to operations such as analyzing the hydrological flow paths on the surface. Sources of data for creating DTMs on terrain height are arial photographs, contour maps and field survey.

The TIN (Triangulated Irregular Network) model represents a surface as a set of contiguous, non-overlapping triangles. Within each triangle a plane represents the surface. The triangles are made from a set of points called mass points. Mass points can occur at any location, the more carefully selected, the more accurate the model of the surface. Well-placed mass points occur where there is a major change in the shape of the surface, for example, at the peak of a mountain, the floor of a valley, or at the edge (top and bottom) of cliffs.

Hassanein (2002) developed a model, which automatically generates digital terrain models (DTMs) to represent the original ground topography and underlying soil strata. When estimating quantities of cut and fill, the model accounts for variations in swell and shrinkage factors of soils of these strata. Due to superior ability of TIN models to represent abrupt topography changes, DTMs are stored as TINs. TIN models are flexible and can provide more details in area where topography varies rapidly.

The first stage in developing a DTM from line theme is to generate the TIN nodes, which are taken along contour lines. Typically contour interval varies between 10 cm and 150 m depending on site area and required accuracy (Oloufa 1991). In order to develop a DTM, which does not place superfluous demand on the system memory, a procedure is developed to determine the intervals between developed nodes along contour lines. The procedure is iterative and generates nodes that are not regularly spaced. Initially interval is assumed to be equal to the horizontal component of the distance to the nearest contour line, and the initial mesh is developed accordingly. Having developed the nodes, the

DTM is generated and volume of the earth between the generated DTM and the ground water table is computed. In the case where no water table is defined, a horizontal plane passing through the lowest point in the generated DTM is used as datum. The interval is then reduced to one half of its previous value and another set of nodes is generated, producing the revised DTM. The volume of earth contained between the revised DTM and the water table is recalculated and compared to that calculated in previous iteration. This process is repeated until the change in volume is less than a user-specific value, or 10%. The default value (i.e. 10%) is well below what is considered acceptable for earthwork computations (Meyer and Gibson 1980). This procedure generates an accurate DTM without placing unnecessary demands on the memory.

## 2.4 FPC Introduction

Fleet Production and Cost Analysis (FPC) is a software tool designed to estimate the productivity, cost and time required for a wide variety of earthmoving or other material handling Fleet moving materials from one location to another over one or more Courses.

A Fleet consists of specific quantities of haulers, loaders and support equipment. The productivity of the Fleet and time required to move specific quantities of materials is determined for the haulers and loaders (In some cases, the haulers are self-loading and do not require a loading tool). The material handling cost is the sum of the costs for the haulers, loaders and support equipment.

A Course defines the hauling conditions over which a specific quantity of material is transferred from its original location to a new desired location. Distance, rolling resistance, grades and any speed or passing restrictions for safety or comfort are the variables for the course.

Fleet Production and Cost Analysis is used for comparison and estimating purposes. A cost or production comparison can be made between fleets moving material over a single course (haul profile) or over a group of courses. Usually, in a comparison, the Fleet that can move the materials for the lowest cost within a prescribed time period would be most desirable. For estimating costs and equipment requirements for the earthmoving job, the material handling can be broken down into specified quantities moved from one location to another over defined courses. FPC will then estimate productivity, cost and time required to move these specific quantities with a single fleet or with different fleets for different courses. The objective here would be to determine total job material handling costs using various equipments in different fleet combinations.

Many scenarios can be easily run to determine the best Fleet combinations for parts or the entire job.

**Table 1: Equipment Types Included in FPC**
**Source: Caterpillar FPC Manual, 1998**

| **Equipment Types Included in FPC** | | |
|---|---|---|
| Haulers | Trucks | Off-highway Trucks<br>On-highway Trucks |
| | Dumpers | Articulated Dump Trucks |
| | Scrapers | Wheel Tractor Scrapers<br>Tractor Drawn Scrapers |
| | Loaders | Wheel Loaders (load and carry)<br>Track Loaders (load and carry)<br>Backhoe Loaders (load and carry) |
| | Customized | User Modified Haulers (Off-highway tractor-trailers or any other modified Hauler) |
| Loaders | Wheel Loaders | Wheel Loaders<br>Backhoe Loaders (front bucket) |
| | Track Loaders | Track Type Loaders |

|  |  |  |
|---|---|---|
|  | Excavators | Hydraulic Excavators Front Shovel<br>Log Loaders Backhoe Loaders (rear bucket) |
|  | Power Shovels |  |
|  | Push Tractors | Used for Push Loading Wheel Tractor Scrapers. |
|  | Others | User-added (Hopper, Holland Loader, etc.) |
| Support |  | Any user-added equipment or personnel |

## 2.5 MODELING TECHNIQUES FOR EARTHMOVING

### 2.5.1 Mass Diagram Method

A mass diagram method is a graphical representation of the cumulative volume of earth along the roadway (after adjustments for swell and/or shrinkage). Typically, the mass diagram is plotted between profiles of the route, with the ordinate at any station representing the sum of the volume of cut and fill up to that station. The most economical way to handle the distribution of earthwork volumes can be determined from the diagram (Mayer and Stark 1981).

As we can see in fig 2.3, the rising curve on the mass diagram indicates excavation and a descending curve indicates embankment. If a horizontal line is drawn to intersect the diagram at two points, excavation and embankment (after adjusting for shrinkage) will be equal between the two stations represented by the point of intersection. Such a horizontal line is called a balance line, because the excavation balances the embankment between the two points at its ends (Innes1995).

Since the ordinates represent the cumulative volume of cut and fill, the total volume of cut and fill will be equal where the final ordinate equals the initial ordinate. If the final ordinate is greater than the initial ordinate, there is an excess of excavation (as shown in the mass diagram); if it is less than the initial ordinate, the volume of cut is greater and additional material must be obtained to complete the fill.

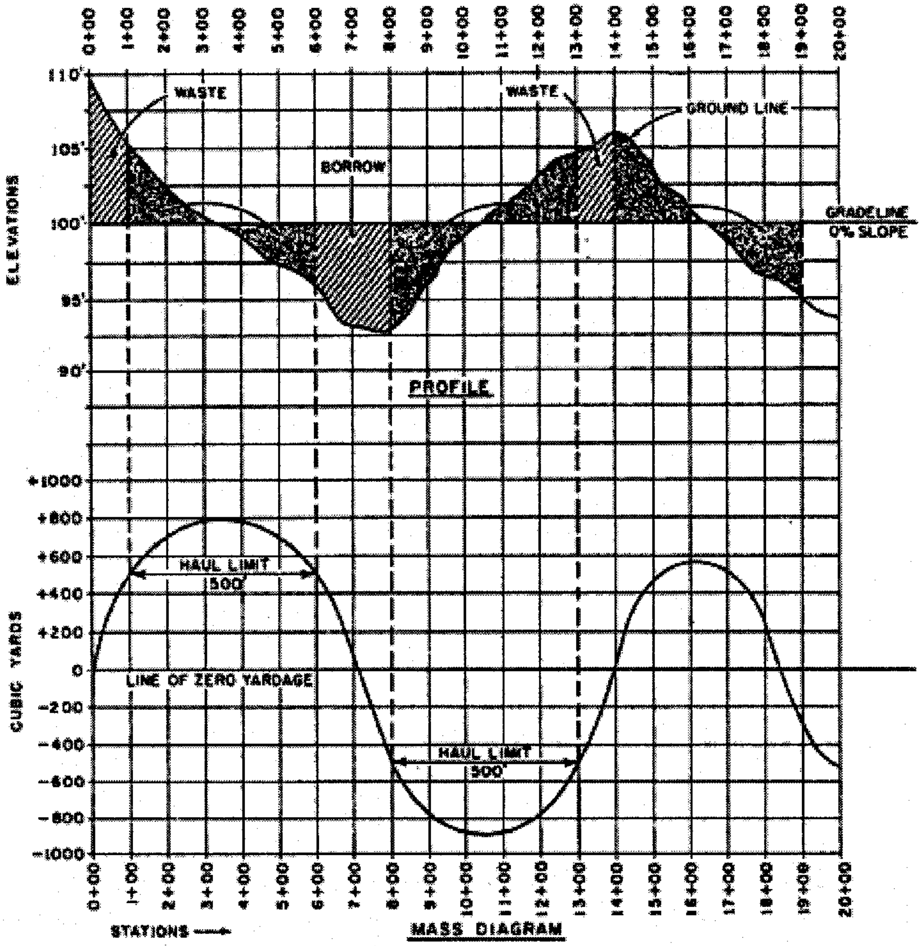


**Fig 2.3: Profile and mass diagram**
**Source: Innes, 1995**

The mass diagram approach can provide some answers to the "how much" and "where" questions when earthwork quantities are given. However, the quality of the answer (and, thus, its usefulness) diminishes in such practical solutions as the following (Stark and Mayer 1981):

1. When hauling costs are not directly proportional to the haul distance.

2. When soil characteristics vary along the roadway (particularly the percentage of swell and shrinkage).
3. When additional quantities of soil are available, or maybe disposed of, at off-the-roadway sites.

Mass diagram method does not tell which material to move from one section to another. It only provides guidelines. There is (theoretically) no preference between alternative possibilities chosen with the aid of the mass diagram.

### 2.5.2 Linear Programming-

Mathematical problems with a linear objective equation and linear constraints are called linear programming or, more accurately, linear optimization problems. That is, there are no exponents or multiplications of variables (Mayer and Stark 1981).

Ex: $4X1 + 3X2 <= 25$.

Linear programming, or LP, has an important and increasing industrial role. Hundreds of applications, as diverse as setting up automobile production lines, aiding oil refinery management, determining timber production, or preparing hospital menus, have been documented. New uses are still being discovered, and among them are applications to construction management.

Linear optimization or linear programming, as it is popular, is a tool used by managers to aid their decision. Although Linear Programming (LP) is not entirely new to the construction industry as Critical Path Methods, which is driven from linear programming, have been popular since 1950s, but LP does not have the prominent role in construction that it has in other industries (Stark and Mayer 1983). Mayer and Stark (1981) were among the early contributors in implementing linear programming in earthmoving operations. According to them, as minimum cost objective equation and related constraints are linear functions, so the technology of linear programming applied. Linear programming method can be extended to certain practical situations such as when haul costs and soil properties vary along the roadway, and when borrow and disposal sites are proposed (Mayer and Stark 1981).

Mayer and Stark (1981) pointed out unit cost assumption as the foremost limitation of this method. While actual costs are not likely linear, they may be often assumed to be approximately so. In fact, the mass diagram method assumes such linearity. Also, tendering practices involve unit price contracts, which provide for payment on a linear basis. A second consideration is that the format can become quite large as the number of roadway section increases. Of course, such magnitudes are very likely to be well within the capability of small computers, which can routinely solve linear programs involving thousands of variables and hundreds of constraints.

Nandgaonkar (1981) proposed a transportation model (which is a particular form of linear programming model) technique of Operation Research, which is an effective tool for arriving at the optimum solution in allocation of earthwork transportation from a set of origin to a set of destination and to reduce costs. Through the study presented in his paper, he brought out that the OR technique is suitable for arriving at the optimum estimated cost of the work at the precontract stage, and he recommended that a prepriced percentage rate tender form be used so as not to disturb the optimality of the solution for allocations already arrived at.

Easa (1987) investigated the factors that affect the variations of unit costs of earthwork activities and presented a Mixed-Integer Linear Programming (MILP) model of earthwork allocations that incorporates nonconstant unit costs. For that, a three-component stepwise unit cost function was considered. He developed a computer program, EARTHN, that solves the model by implicit enumeration, to determine the quantities of material to be moved from each cut section (or borrow pit) to each fill section (or disposal site). Easa (1988) formulated another earthwork example where unit cost function varies linearly with quantity. Easa (1988) used a QP model to solve that optimization example.

Jayawardane and Harris (1990) developed a linear programming model, which incorporates the project duration with minimizing the cost in earthwork optimization of road construction work. With their model, they attempted to optimize a comprehensive earthmoving system in road construction by comparing alternative fleets (from available fleets) to provide an optimum material distribution and appropriate plant fleets to complete a project within the specified time. The situation where different degree of compaction, availability of various soil strata at cut sections and borrow pits, and selection of borrow/disposal sites are also incorporated. Equipment sharing between fleets and sequence of operations present at cut and fill sections are examined by them as possible extensions. Although they took the project duration into account, their model ignores the sequence of operations at a cut or fill section, particularly when different soil strata are available and different degree of compaction are required. The model provide answer to questions like “from where”, “how much” and “by which fleet”.

### 2.5.3 Queuing Theory

Queuing theory (or waiting line theory) describes the stochastic or variable behavior of an operation or system that provides service for arriving demands. When the capacity of the service facility or server is exceeded by the demand for service, a queue or a waiting line forms. A queue is then a collection of arrivals or arriving units (customers) waiting for service.

Queues are commonplace in construction and mining operations; effective planning and management of the operations involve an examination of this queuing behavior. It is remarkable that queuing theory enjoyed a certain amount of popularity among engineers in the 1960's and 1970's but that the techniques of simulation has been favored in more recent years. There are several reasons for this shift in popularity. Firstly, early work in applying queuing theory to civil engineering and mining engineering struggled mainly with the exponential time distribution assumption. Secondly, the solution of the relevant queuing for every application was not feasible. Thirdly, simulation offers the prospect of being able to solve all operational problems. While acknowledging that simulation is a very useful technique, for many problems queuing theory can provide insight that is at times complementary to and at other times additional to that offered by simulation because of its fundamental analytical base (compared with a numerically based technique). As such queuing theory should be regarded as a base tool in the repertoire of any civil and mining engineer (Carmichael 1987). Moselmani (2002) developed FLSELECTOR, an earthmoving fleet selection tool using queuing method.

### 2.5.4 Expert Systems

In spite of the need and potential benefits, there are currently very few operational expert systems (i.e. in routine use by persons other than developers) in the field of construction. One reason for this may be a lack of awareness by the industry about what expert systems currently exist, what their capabilities are, and, who their developers and vendors are.

Discussion about expert system and its application in earthmoving operations have been done in the work of Alkass and Harris (1988). They presented a model for selecting earth-moving equipment in road construction. They developed a prototype computer program called ESEMPS (Expert System for Earth-Moving Plant Selection). The essence of this prototype is encoding of expert knowledge in a form usable by non-experts. It is based on the combination of the experience judgments of experts in the field for road construction and equipment rental specialists, known facts on ground conditions, weather conditions from past records, machine performance, work study, and cost data. A consultation begins by the user responding to questions posed by the system. Having received an answer to a question, the system locates the applicable rules by comparing the answers with the knowledge base and produces a decision giving a likely solution to the problem in hand.

### 2.5.5 Simulation

Simulation is applied widely as a tool for planning and analysis in many industries. However, in the case of construction processes, it has not yet emerged from the research stage into practice (Fente et al. 2000).

According to Shi and AbouRizk (1997), construction simulation has been mostly successful in academic research with limited successful applications in the industry. They attributed that to the complexities involved in constructing a model and the resultant time requirement.

Two general type of simulation system exist; general-purpose and special purpose simulation systems. General-purpose simulation tools and languages target a very broad domain and can be used to model almost any type of operation. In contrast, special-purpose simulations are tools that target a narrow domain such as ductile iron pipe installation (Martinez and loannou, 1999).

Moselhi and Marzouk (2002) presented a framework for multiobjective optimization of earthmoving operations using computer simulation and genetic algorithms, which aims at minimizing time and cost of earthmoving operations. The simulation process, in the proposed methodology, utilizes discrete event simulation and object oriented modeling. To assist in selecting near optimum fleet configurations, they developed a computer-based platform, SimEarth.

## 2.6 Variation of Unit Costs

### 2.6.1 Introduction

Earthwork activities consist of earthmoving related to cut sections and borrow pits. For earthwork between cut sections and fill sections or disposal sites, there are generally four unit costs:-unit cost of purchase (of disposal sites), excavation, haul and embankment. For earthwork between borrow pits and fill section, there are also four unit costs: - unit cost of purchase (of borrow pits), excavation, haul and embankment. Factors that affect these unit costs need to be investigated in order to determine those unit costs that depend on the (unknown) quantities of the earthwork allocations. Such unit costs would require a special formulation in the model of earthwork allocations. Other unit costs can be treated as constants (Easa 1987).

### 2.6.2 Factors affecting variations of unit cost of earthwork (Easa 1987)

Many factors affect the variations of unit cost of excavation, haul, and embankment for earthwork related to cut sections (or borrow pits) to fill sections (or disposal sites). Those factors are described briefly here-

- Unit Cost of Purchase (of borrow pits and disposal sites) – The unit cost of purchase of borrow pits or disposal sites would vary from place to place. The purchase cost may be fixed or may vary with the quantity purchased. The borrow pit or disposal sites may be a local farmhouse which is purchased by acreage regardless of the quantity of material excavated or dumped. In such situation, since the purchase cost is fixed, it should be added to the total cost if the borrow pit or disposal sites is used. Here, mixed-integer programming model presented by Mayer and Stark (1983) can be used. In other situation the purchase cost can be based on the quantity used and the associated unit cost may be constant or may vary with the quantity purchased or dumped. For the situation in which the unit cost varies with the quantity borrowed or dumped, total quantity is unknown and thus unit cost is also unknown. So a special formulation in earthwork allocations is needed. An example of a stepwise (discounting) unit cost function used in such situations is shown in fig. 3.10.

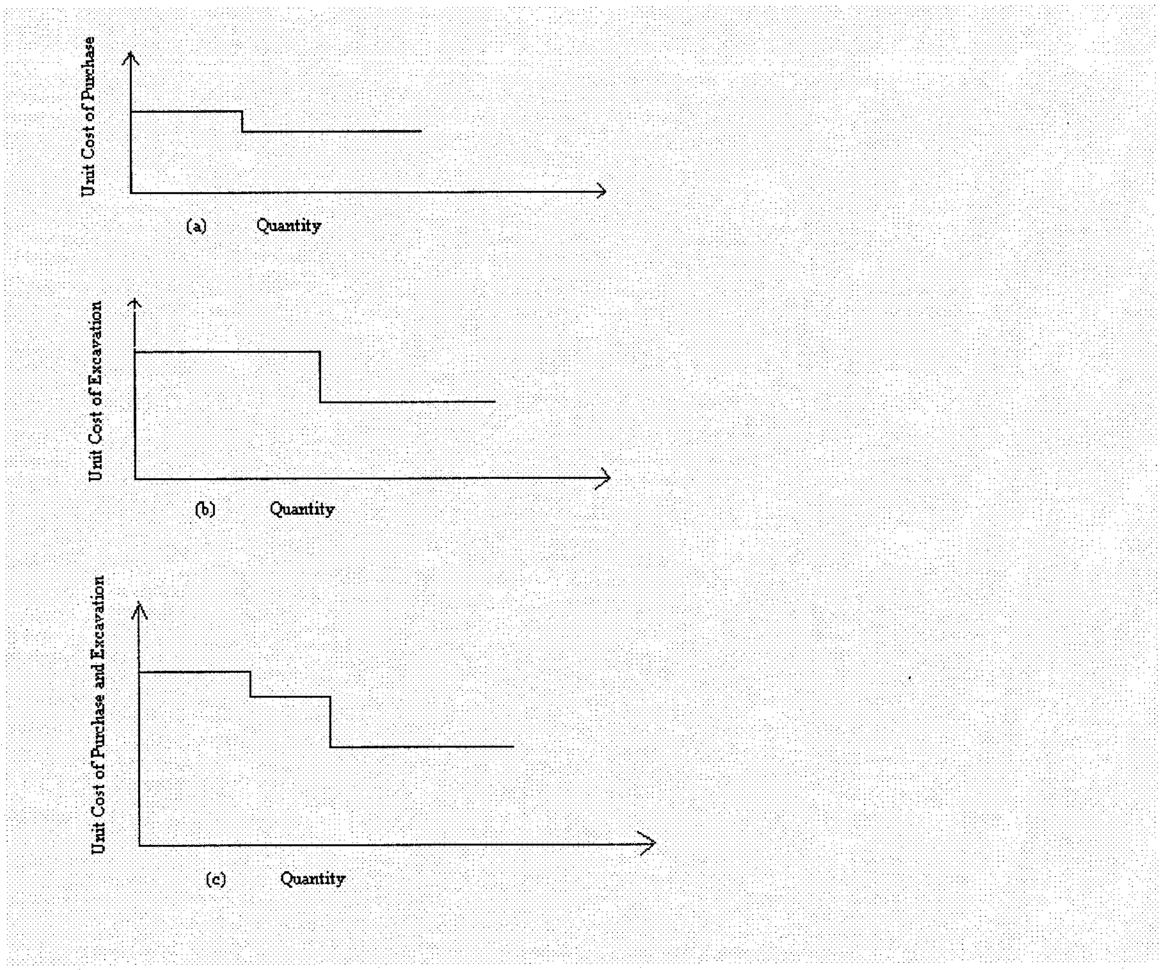


**Fig 2.4 – Unit Cost Functions of: (a) Purchase; (b) Excavation; and (c) Combined (of borrow pit)**
**Source: Easa, 1987**

- Unit Cost of Excavation. –The unit cost of excavation from a cut section or a borrow pit may be constant or may vary based on two main factors: the quantity of material to be excavated and the type of soil. The type of soil affects the determination of unit cost of excavation, with rock excavation being more expensive than soft or medium soil type. This unit cost is likely to be constant if the cut section or borrow pit consists of one type of soil. In this case, the unit cost is calculated based on the requirements of equipment and labor. The unit cost may depend on the quantity excavated, since the quantity to be excavated determines the type of equipment to be used. For small quantities, a tandem operation (of excavators, loaders, and trucks) is normally implemented resulting in a higher unit cost of excavation. For large quantities, a scraper operations used, resulting in a lower unit cost of excavation, (assuming that haul roads are available or can be constructed). A scraper will be an excellent machine for mass excavation as long as it is not needed to haul the load too far, around less than a mile. Thus, depending on the quantity level to be used from the cut section or borrow pit the contractor can decide the type of equipment to be used and the unit cost of excavation will vary with each quantity level. For this type of situations, unit cost function of excavation will be stepwise having two or more components, as shown in fig 3.10(b). Similarly, if the cut section or borrow pit consists of more than one type of soils, such as stiff clay followed by a soft soil, the unit cost of excavation will be different for different types of soil i.e. unit cost will again be multi component stepwise function. ). The unit cost of excavation from a borrow pit or cut section may also vary with the quantity used if the borrow pit consists of different types of soil with different unit costs of excavation (i.e., a stiff clay followed by a soft soil). The situation may be approximated by the stepwise unit cost function

For cut sections, the unit cost of excavation does not normally depend on the (unknown) quantity of material to be moved from a given cut section to a fill section or disposal site, but rather on the total (known) quantities of cut sections. Although the unit cost will not be constant, but the total quantity of excavation for a cut section is known. And thus we can find average unit cost, which can be used in cost estimation work. For borrow pit, the situation will be different as the quantity of material to be moved from a borrow pit to different fill sections is unknown. For that type of situation unit costs are formulated as stepwise function as shown in figure 3.10(b).

- Unit Cost of Haul. – The unit cost of haul varies depending on the type of hauling units, hauling distance, and a number of other factors. For example, scrapper operation is cost-effective for short hauling distance, while tandem operation would be so for greater distances.
- Unit Cost of Compaction. – The unit cost of compaction depends on the type of equipment used for compaction (road roller or sheep foot etc.), which is determined based on the level of compaction required, the type of soil to be compacted, and other operating conditions. The unit cost does not generally depend on the quantity of the fill to be compacted.

## 2.7 Linear Programming

### 2.7.1 Introduction

A Linear Programming problem is a special case of a Mathematical Programming problem. From an analytical perspective, a mathematical program tries to identify an extreme (i.e., minimum or maximum) point of a function $f(x_1,x_2,\ldots,x_n)$, which furthermore satisfies a set of constraints, e.g., $g(x_1,x_2,\ldots,x_n) >= b$. Linear programming is the specialization of mathematical programming to the case where both function f - to be called the objective function - and the problem constraints are linear(Mayer and Stark 1981).

From an applications perspective, mathematical (or linear) programming is an *optimization* tool, which allows the rationalization of many managerial and/or technological decisions required by contemporary techno-socio-economic applications. An important factor for the applicability of the mathematical programming methodology in various application contexts is the computational tractability of the resulting analytical models. Under the advent of modern computing technology, this tractability requirement translates to the existence of effective and efficient algorithmic procedures able to provide a systematic and fast solution to these models. For Linear Programming problems the Simplex algorithm provides a powerful computational tool, able to provide fast solutions to very large-scale applications, sometimes including hundreds of thousands of variables (i.e., decision factors). In fact, the Simplex algorithm was one of the first Mathematical Programming algorithms to be developed (George Dantzig, 1947), and its subsequent successful implementation in a series of applications significantly contributed to the acceptance of the broader field of *Operations Research* as a scientific approach to decision making.

### 2.7.2 General Linear Programming Form (Mayer and Stark 1983)

In general, all linear programming problems can be expressed in the following form:

Minimize (or maximize):

$$Z = c_1X_1 + c_2X_2 + \dots\dots\dots\dots\dots\dots + c_nX_n \qquad \text{objective equation (1)}$$

$$\text{Such that:}\quad \left.\begin{array}{l} a_{11}X_1 + a_{12}X_2 + \dots\dots\dots\dots\dots\dots a_{1n}X_n <= b_1 \\ \quad\vdots \\ a_{k1}X_1 + a_{k2}X_2 + \dots\dots\dots\dots\dots\dots a_{kn}X_n <= b_k \\ \quad\vdots \\ a_{m1}X_1 + a_{m2}X_2 + \dots\dots\dots\dots\dots\dots a_{mn}X_n <= b_m \end{array}\right\} \text{constraints (2)}$$

And $X_1 >= 0, X_2 >= 0, \dots\dots\dots, X_n >= 0$ non negativity condition (3)

Where the quantities $a_{11}, a_{12,\dots\dots}a_{mn,}$ $b_{1,\dots}$ $b_{k,\dots\dots,}$ $b_m$ and $c_1, c_{2,\dots\dots\dots,}c_n$ are constants. Note that the constraints [Eq. (2)] can be of less than, greater than or equality types. The problem is to select the values of the decision variables $X_1$ , $X_{2,\dots\dots}$ $X_n$ that minimize (or maximize, as appropriate) the objective equation [Eq. 1] and satisfy the constraints [Eq. 2] and the nonnegative condition [Eq. 3].

While the objective equation will usually represent a total cost that is to be minimized or a total profit to be maximized, that is not always the case.

Each of the three distinct types of constraints arises in applications:

1. Less-than constraints are usually used to indicate an upper limit on the availability of resources, such as work force, machinery, materials, or money.
2. Greater-than constraints, on the other hand, indicates lower limits on resource utilization or production.
3. Equal-to constraints, or equality constraints as they are called, occur less frequently. In construction, equality constraints arise to express the requirement that the sum of the parts must be equal the whole.

The nonnegative condition [Eq. 3] requires that decision variables not assume values that are negative. The nonnegative condition is not as restrictive as it appears.

Every managerial problem has an objective and every practical problem has constraints. Often these problems can be expressed in the general linear programming form [Eq. 1 – Eq 3.] which nearly always has simple, efficient, and relatively inexpensive techniques available for its solution.

### 2.7.3 LP's in ``standard form"

To further exploit the previous characterization of extreme points as the solution to *n* binding linearly independent constraints, we must define the concept of LP's in *``standard form"*. An LP is said to be in *``standard form"*, if: (i) all *technological constraints* are *equality* constraints, and (ii) all the variables have a *nonnegativity sign restriction*.

Every LP can be brought into ``standard form" through the following transformations:

- An inequality constraint:

$$a_1X_1 + a_2X_2 + \ldots + a_nX_n \begin{pmatrix} \leq \\ \geq \end{pmatrix} b$$

  can be converted into an equality one, through the introduction of a *slack (excess)* variable

$$S\ (E) \geq 0$$

$$a_1X_1 + a_2X_2 + \ldots + a_nX_n + \begin{pmatrix} S \\ -E \end{pmatrix} = b.$$

- A variable $X_i$ with sign restriction $X_i <= 0$ can substituted by $X_i = -X_i'$ with $X_i' >= 0$.
- Finally, a *urs* variable $X_i$ can be substituted by $X_i = X_i' - X_i''$ with $X_i', X_i'' >= 0$.

**Definition** Consider the system AX = b of m linear equations in N variables, corresponding to the technological constraints of an LP in "standard form".

1. A basic solution to this system is obtained by setting N – m variables equal to zero, and solving for the values of the remaining m variables. This assumes that setting the N – m variables equal to zero yields unique values for the remaining m variables are linearly independent. The m variables which are not bound to zero, are the b
2. Basic varibles (or equivalently, they define the basis) of the basic solution under consideration.
3. Any basic solution to AX = b in which all variables are nonnegative is a basic feasible solution (bfs).

The characterization of the extreme points of the feasible region of an LP as basic feasible solutions for its ``standard form" representation provides the analytical means for organizing the search for an optimal extreme point performed by the Simplex algorithm.

Because of their structural simplicity, the main limitations on the size of LP problems that can be solved are time, memory, and the possibility of numerical "instabilities" which are the cumulative result of the small errors intrinsic to finite precision computer arithmetic. The larger the model, the more likely it is that numerical instabilities will be encountered in solving it. Most large LP models are sparse in nature: While they may include thousands of decision variables and constraints, the typical constraint will depend upon only a few of the variables.

### 2.6.4 Summery

GIS is increasingly being used in transportation engineering, highway management, evaluation of alternatives for highway route alignment, groundwater modeling as well as construction industry. Jeljeli et al (1993) addresses issues such as utilizing GIS to select equipment based on soil type and work conditions. Hassanein (2002) developed a GIS based model for estimating quantities of cut and fill, which accounts for variations in swell and shrinkage factors of soils.

Mayer and Stark (1981) were one of the early contributors in implementation of linear programming in earthmoving operations. According to them Linear programming method can be extended to certain practical situations such as when haul costs and soil properties vary along the roadway, and when borrow and disposal sites are proposed. In these types of situation mass haul diagram does not fit well. Easa made some valuable contribution in this area by presenting a Mixed-Integer Linear Programming (MILP) model of earthwork allocations that incorporates nonconstant unit costs. Easa did not consider duration of the project and productivity of equipment as constraint in optimization model. Jayawardane and Harris (1990) developed a linear programming model, which incorporates the project duration with minimizing the cost in earthmoving operations of road construction work.

But they missed nonconstant nature of unit costs. Other researchers who contributed in the field of use of Linear Programming in earthmoving operations were Nandgaonkar (1981), Son J., Mattila K. G. and Myers D. S. (2005).

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

This chapter describes a presented methodology of integrated system for Quantity Take-off, Fleet selection and Optimization of Earthmoving Operations. Earthmoving optimization involves determining the optimum quantity of earth to be moved from different cut sections (or borrow pits) to fill sections (or disposal sites) using best Fleet. Mixed Integer Linear programming theory is adopted to optimize the earthmoving operations. In this model, unit cost function of purchase and excavation of borrow pits has been considered as stepwise having two components. The solution of this model yields among other things the minimum cost of completing the project within project duration using the best fleet.

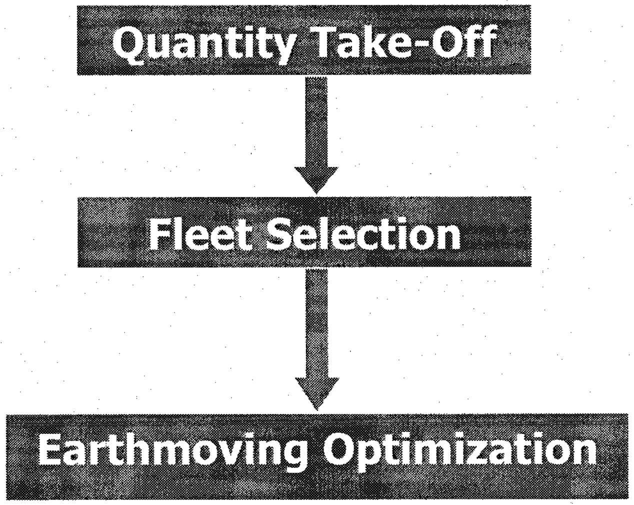


**Fig 3.1: Methodology Flow Chart**

## 3.2 Areas concerning earthwork estimation

The required elements for determining an earthwork estimate are: the quantity of earth to be moved, the haul distances to move the material and the grade that the material must haul over (Peurifoy and Schexnayder 2002).

Earthwork estimating has four major areas of concern:

1. Determining earthwork quantities for different sections.
2. Selecting appropriate types of construction equipments needed for particular earthmoving work.
3. Determining optimum quantity of material to be moved between different sections.
4. Determining optimum hauls distance and direction of haul.

To determine earthwork quantities for different sections, many commercial earthworks estimating software programs are available; most of them gives nearly exact cut and fill quantities. Nowadays, GIS (Geographical Information System) software is also being used effectively in determining the earthwork quantities. Previous investigation work, done by Price (1999) in this direction, showed that ArcView's 3D Analyst ® can be readily utilized to determine cut and fill quantities.

Information for types of construction equipment needed for earthmoving work can be got from performance database of different manufacturers of equipment, for example, caterpillar provides performance data for all types of Caterpillar equipments in their performance handbook. The objective here would be to determine total job material handling costs using various equipments in different fleet combinations. Many scenarios can be easily run to determine the best Fleet combinations for parts or the entire job.

Earthwork optimization aims at minimizing cost, maximizing production, finishing work on time and meeting the specification requirements. For optimizing the earthwork material movement, many researchers have developed different mathematical model, mostly based on linear programming, which can be executed in any linear programming software in modern computers very easily.

## 3.3 Quantity Take-Off

### 3.3.1 Proposed Algorithm for determining Longitudinal Interval

Consider a road segment, as shown in figure 3.2, for which earthwork allocations are required. Let us start by taking $N_o$ number of longitudinal intervals for a cut or fill part of road segment i.e. there will be $N_o$ number of sectional volume to be determined. Find the area of each sectional end by simplifying the end section to determine the equation of line of best fit. To determine the equation of line of best fit we can use the theory of least square or by using an alternate method, presented by Easa (1987), which can be employed for curved section of the embankment Then calculate volume of each section by applying any of suitable volume determination formula, e.g. Average end-area method, Prismoidal method, Pyramid frustum formula, Pappus' model or any mathematical model. Adding volumes of all section for that part of road segment will give the total volume of cut or fill required. Then divide that part of road segment into

$2N_o$ number of intervals and calculate areas and volumes for each section in the same way. Add all volumes again to get new total volume of cut or fill required for that part of road segment. There will be some difference in determined volume for $N_o$ interval and $2N_o$ intervals cut or fill part. If this difference is very less i.e. within tolerance limit then we will keep $N_o$ number of regular intervals for that part of road segment i.e. there will be $N_o$ number of sectional areas. But if this difference is more than tolerance limit then we will take $3N_o$ numbers of regular intervals and again check for tolerance limit between $2N_o$ and $3N_o$ interval parts. This is repeated for all cut and fill parts of road segments.

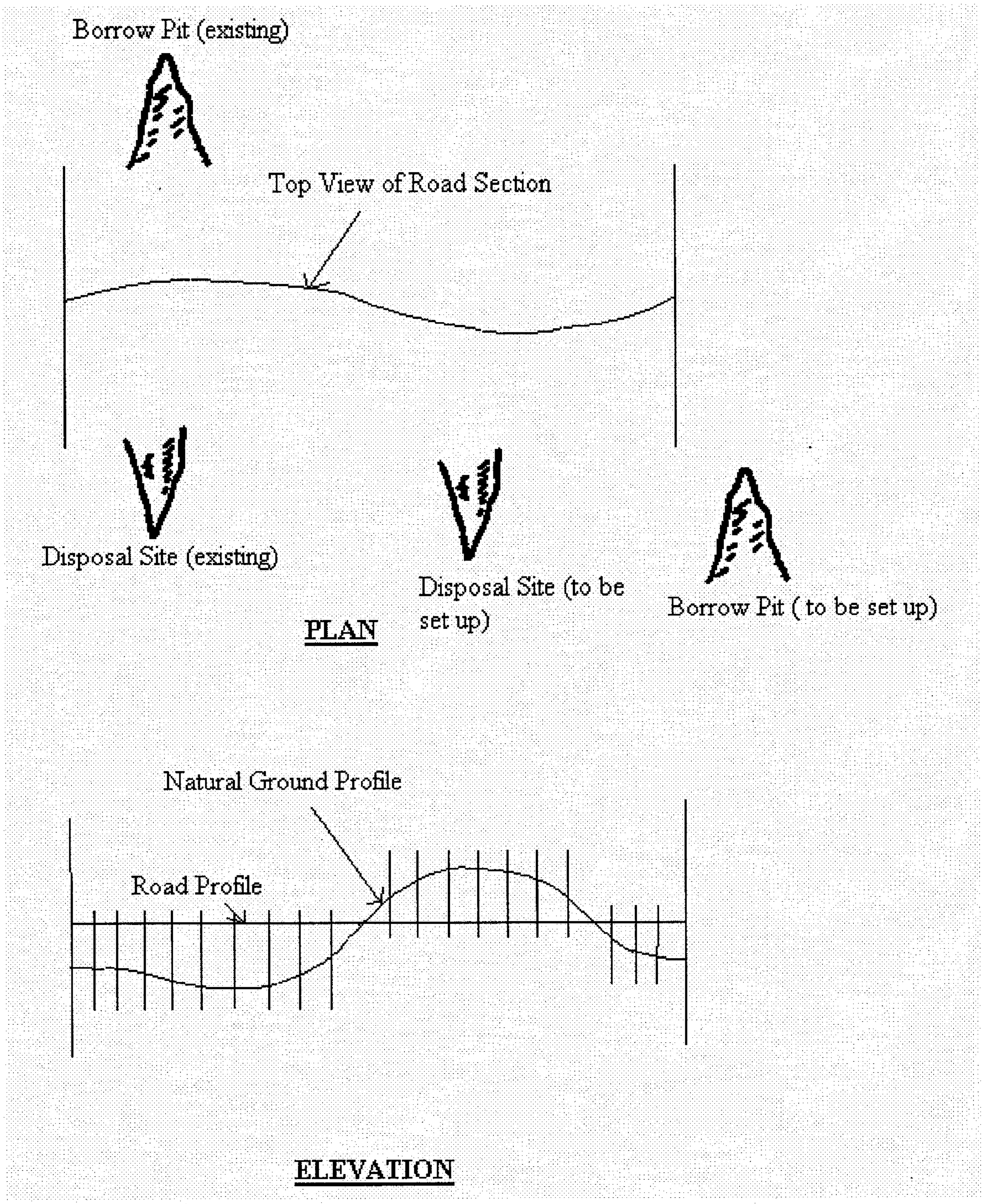


**Fig 3.2: Plan and Elevation of a road segment**

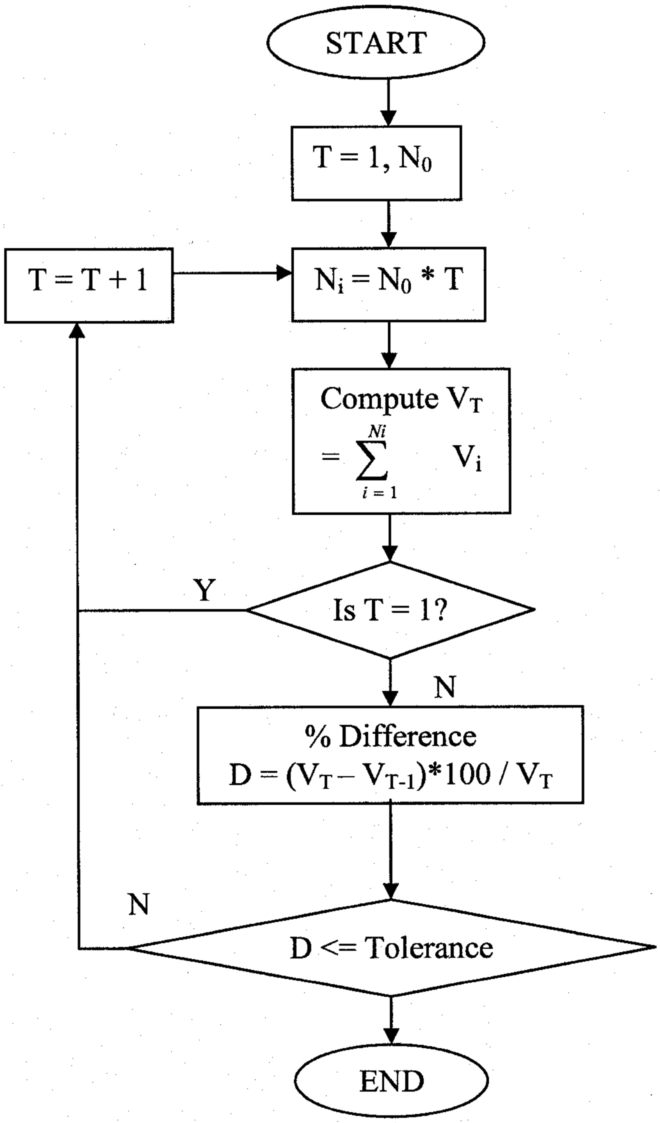


**Fig 3.3: Flow chart for longitudinal interval**

### 3.3.2 Earthwork Volume Determination

Earthwork volume for cut and fill sections can be determined using Geographic information system (GIS) technology. In this model ArcGIS, GIS application software, has been used for estimating total quantities of cut and fill required for different sections.

Drawing of proposed road profile is superimposed over the three dimensional contour map of natural ground profile to generate Digital Terrain Model (DTM). DTM can be made using data from any of compatible data format of different data acquisition technologies e.g. AutoCAD, GPS, 3D Laser scanner or by manual survey. In ArcGIS, DTM (Digital Terrain Model) is created using TIN (Triangulated Irregular Network). For that we have to use 3D Analyst extension of ArcGIS where TINs are created from features as in figure 3.4.

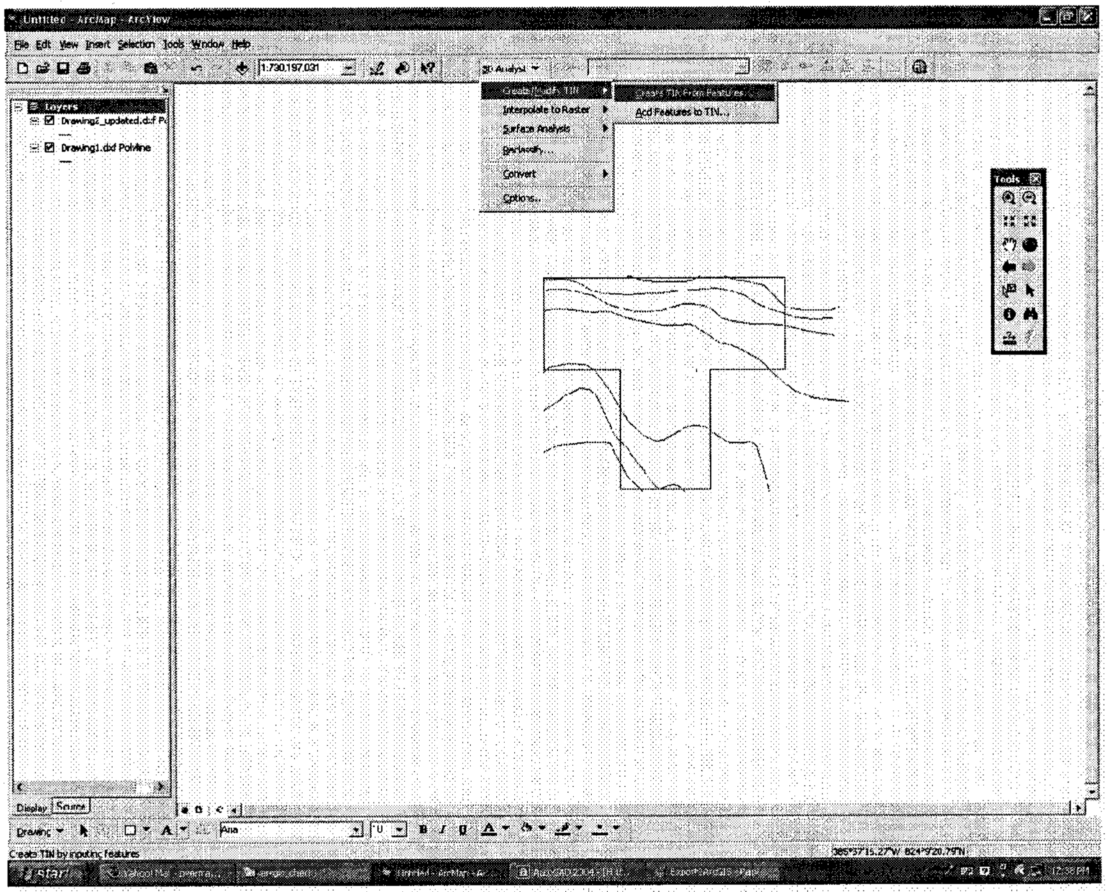


Fig 3.4: TIN creation

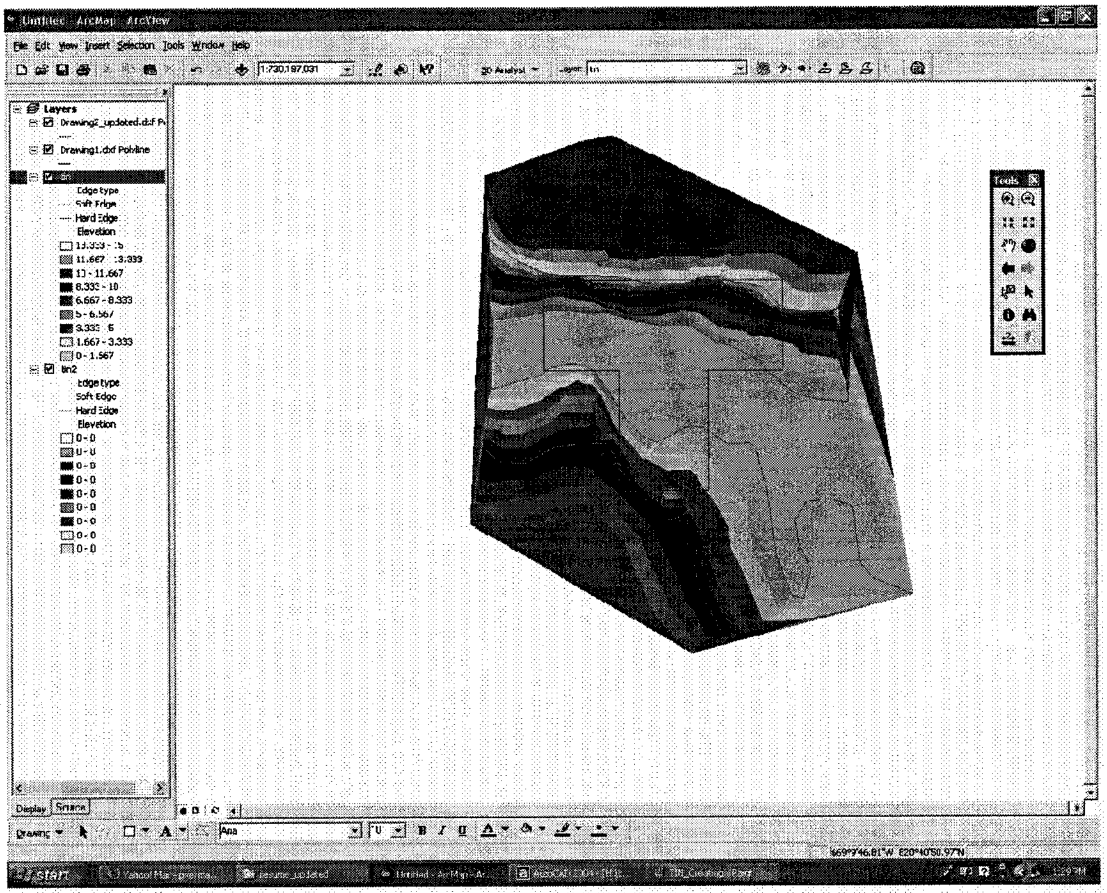
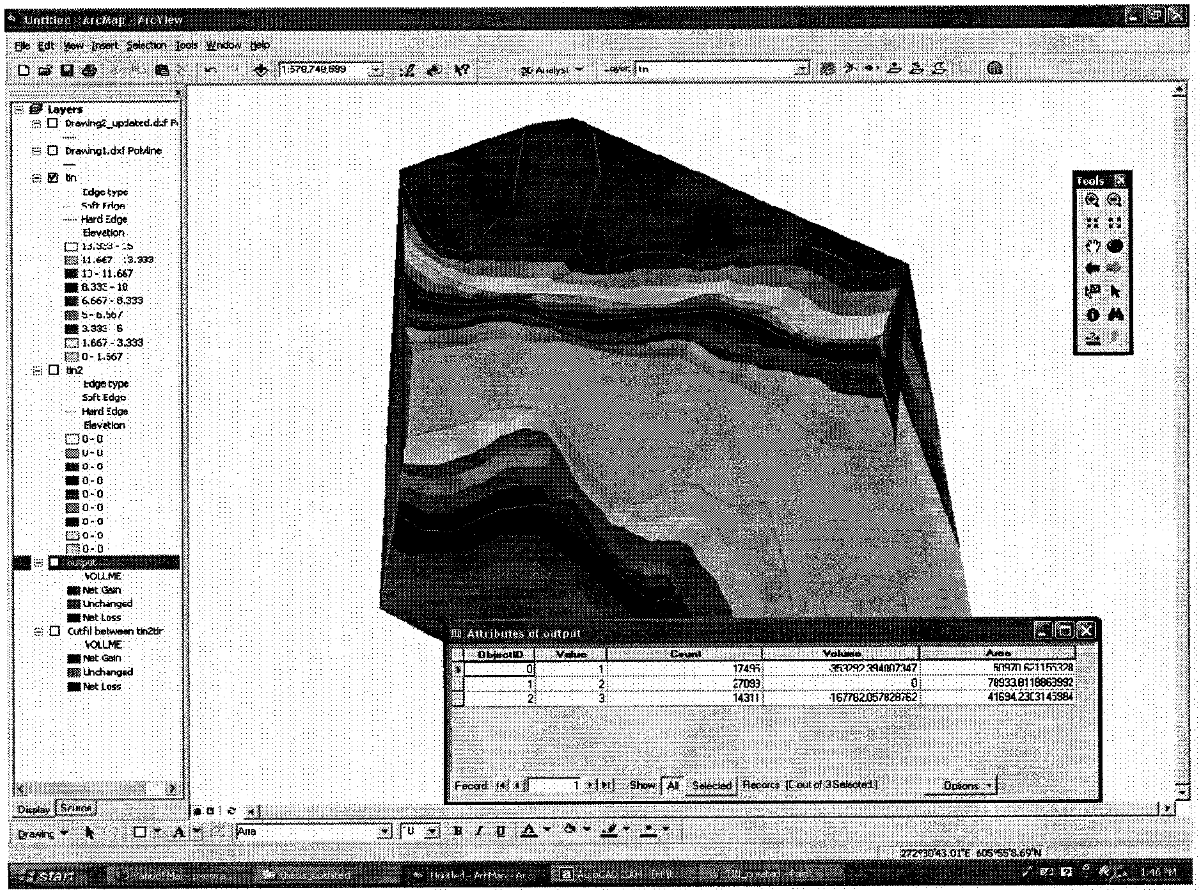


**Fig 3.5: DTM created**

Created DTM is shown in figure 3.5 where different colors are used to represent different contour levels. Now, using cut/fill tool of ArcGIS, cut and fill determination work is done by using Cut/Fill tool which will give total quantity of cut and fill required for different sections. This can be seen in automatically created table as shown in figure 3.6.



Attributes of output

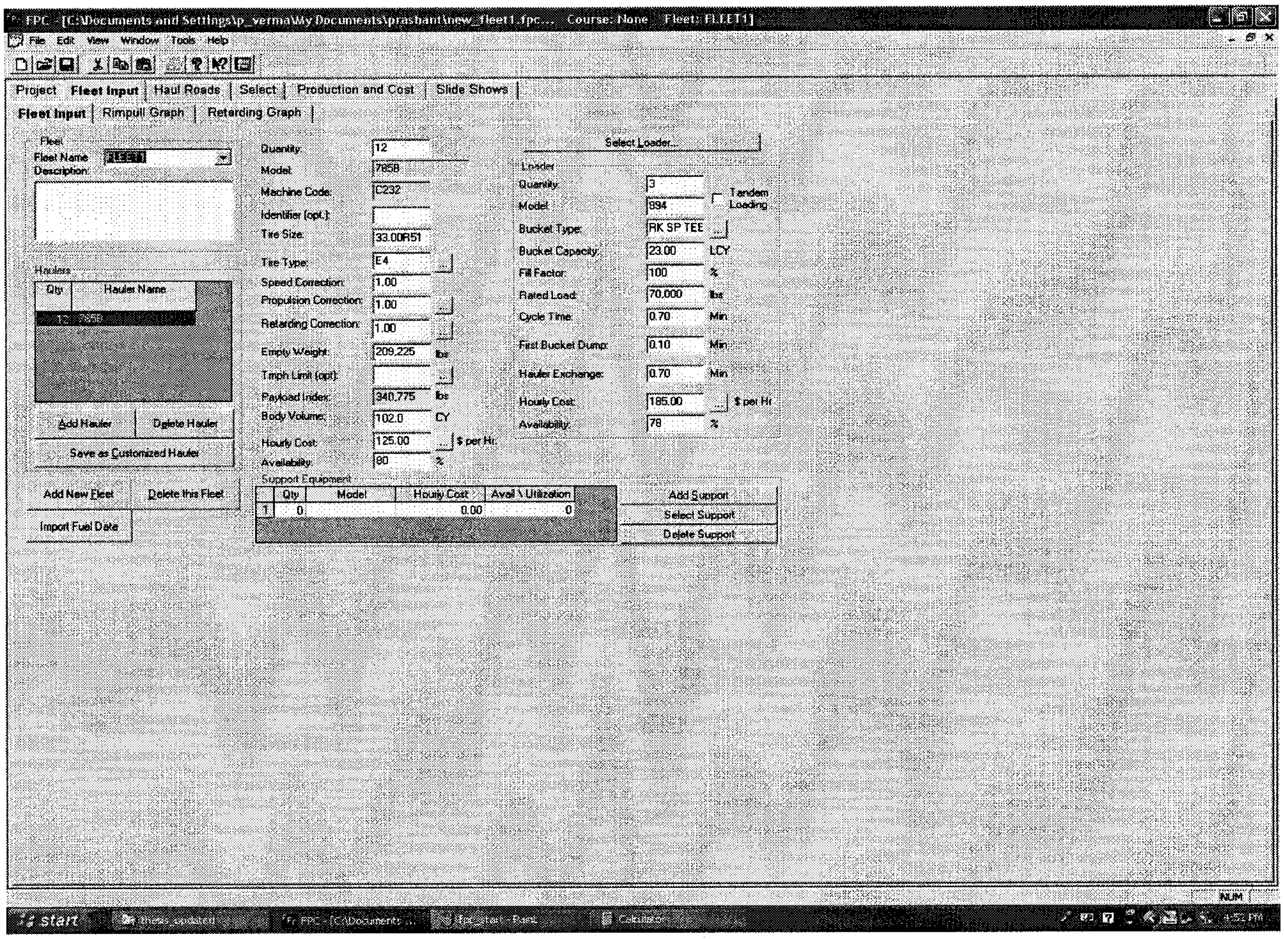
| ObjectID | Value | Count | Volume | Area |
|---|---|---|---|---|
| 0 | 1 | 17495 | -353292.394007347 | 50970.621155328 |
| 1 | 2 | 27093 | 0 | 78933.8118863992 |
| 2 | 3 | 14311 | 167782.057828762 | 41694.2303145984 |

Record: 1 Show: All Selected Records (0 out of 3 Selected.) Options

Fig 3.6 : Cut/Fill determinations

### 3.4 Fleet Selection

Fleet Production and Cost Analysis (FPC) is used for cost or production comparison between fleets and estimating purposes. A Fleet consists of specific quantities of haulers, loaders and support equipment. Usually, in a comparison, the Fleet that can move the materials for the lowest cost within a prescribed time period would be most desirable. In FPC, type and characteristics of haulers and loaders are taken as input data as shown in fig 3.7. Also we need to provide data of hauling road profile for example distance, rolling resistance, percentage grade, maximum speed limit etc. as shown in figure 3.8.



Fleet

Fleet Name: FLEET1

Description:

Haulers

| Qty | Hauler Name |
|---|---|
| 12 | 785B |

Quantity: 12
Model: 785B
Machine Code: C232
Identifier (opt.):
Tire Size: 33.00R51
Tire Type: E4
Speed Correction: 1.00
Propulsion Correction: 1.00
Retarding Correction: 1.00
Empty Weight: 209,225 lbs
Tmph Limit (opt):
Payload Index: 340,775 lbs
Body Volume: 102.0 CY
Hourly Cost: 125.00 $ per Hr.
Availability: 80 %

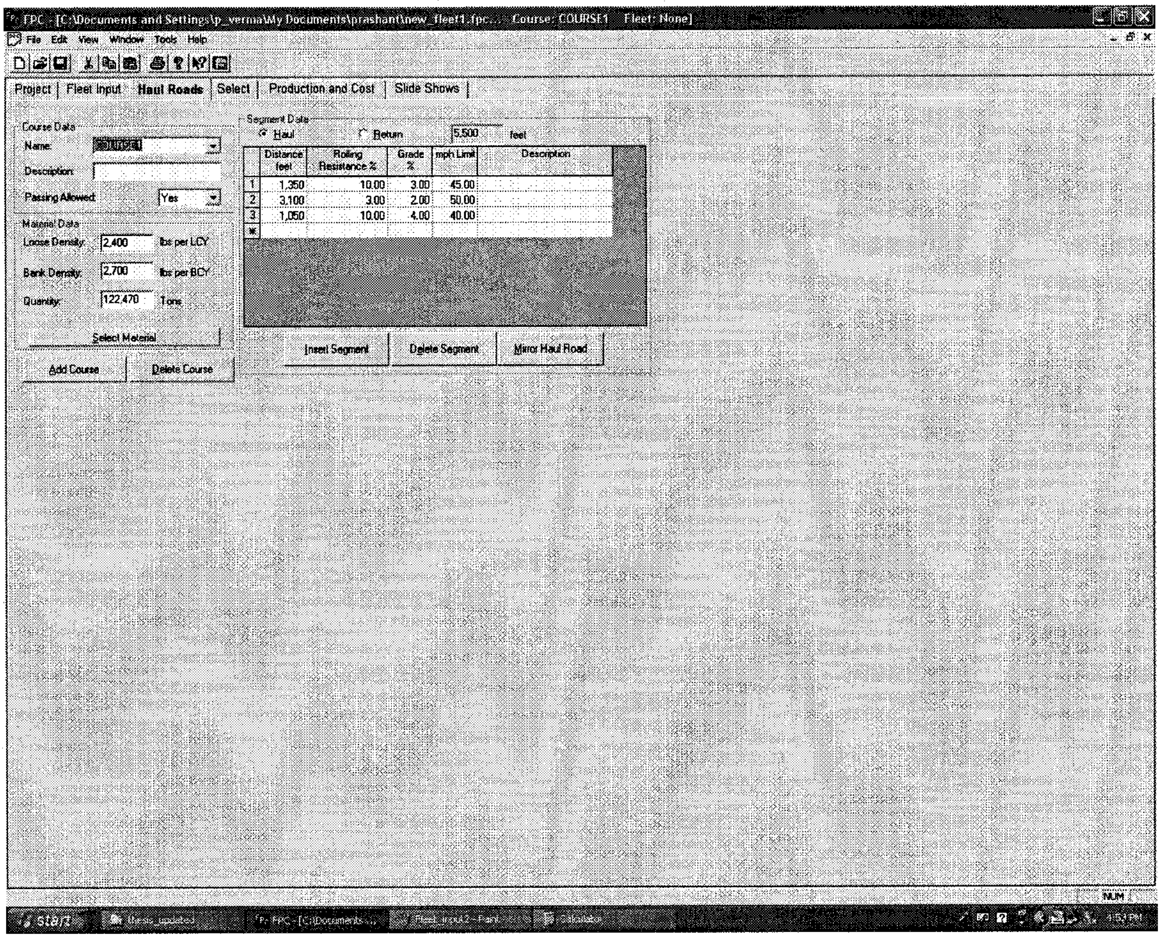
Loader

Quantity: 3
Model: 994
☐ Tandem Loading
Bucket Type: RK SP TEE
Bucket Capacity: 23.00 LCY
Fill Factor: 100 %
Rated Load: 70,000 lbs
Cycle Time: 0.70 Min
First Bucket Dump: 0.10 Min
Hauler Exchange: 0.70 Min
Hourly Cost: 185.00 $ per Hr
Availability: 78 %

Support Equipment

|  | Qty | Model | Hourly Cost | Avail \ Utilization |
|---|---|---|---|---|
| 1 | 0 |  | 0.00 | 0 |

Fig 3.7: Fleet Input



Course Data
Name: COURSE1
Description:
Passing Allowed: Yes

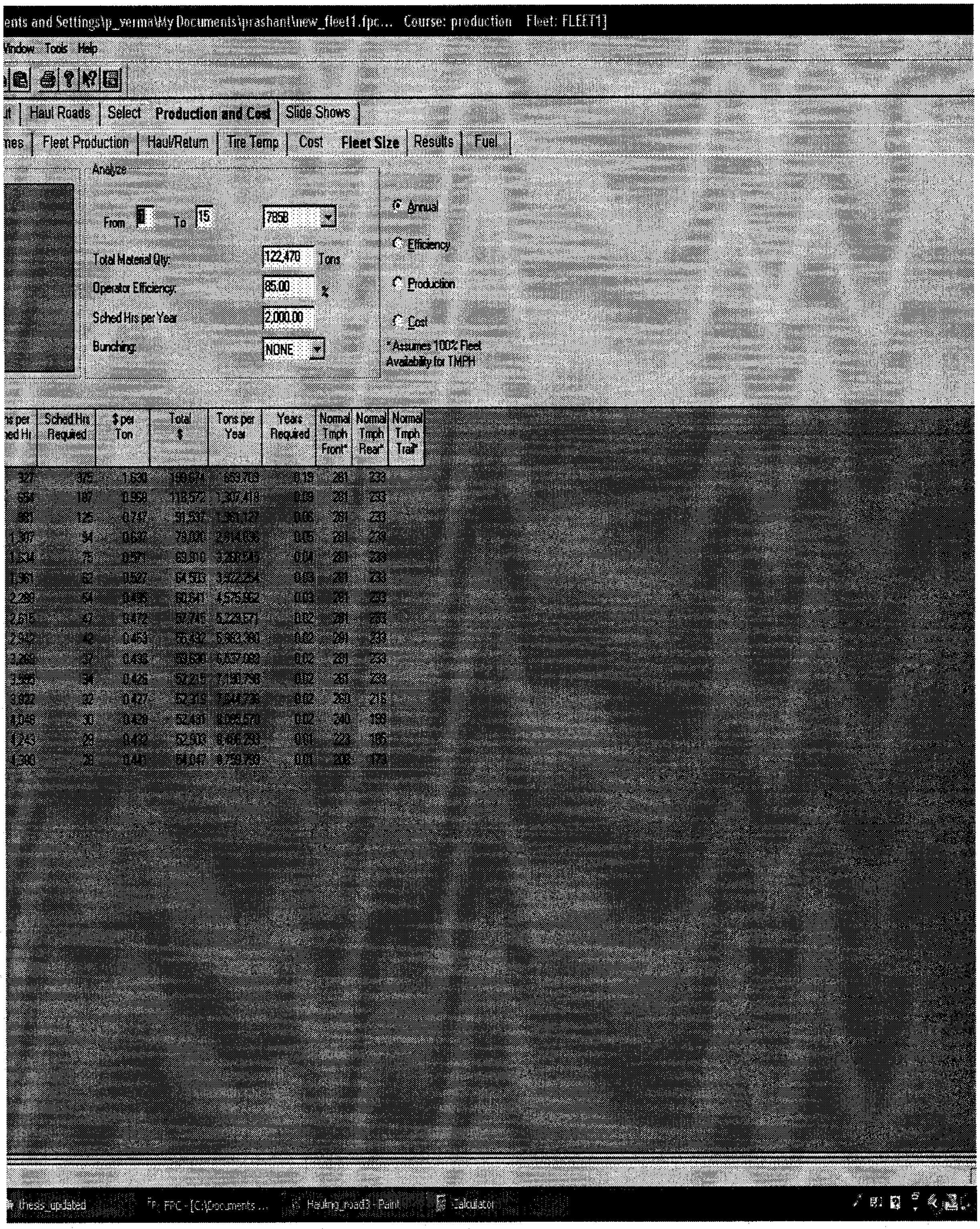
Material Data
Loose Density: 2,400 lbs per LCY
Bank Density: 2,700 lbs per BCY
Quantity: 122,470 Tons

Segment Data
● Haul ○ Return 5,500 feet

| | Distance feet | Rolling Resistance % | Grade % | mph Limit | Description |
|---|---|---|---|---|---|
| 1 | 1,350 | 10.00 | 3.00 | 45.00 | |
| 2 | 3,100 | 3.00 | 2.00 | 50.00 | |
| 3 | 1,050 | 10.00 | 4.00 | 40.00 | |
| * | | | | | |

**Fig 3.8: Road Profile Input**

At the end, we will get unit cost in $ per Ton, Tons per schedule hr., total schedule hr, total $ as output for different Fleet (combinations of haulers and loaders) as shown in fig 3.9. Fleet with minimum unit cost ($ per Ton) will be selected for optimization work.



From 1 To 15 7858

Total Material Qty: 122,470 Tons

Operator Efficiency: 85.00 %

Sched Hrs per Year: 2,000.00

Bunching: NONE

● Annual

○ Efficiency

○ Production

○ Cost

*Assumes 100% Fleet Availability for TMPH

| ns per ned Hr | Sched Hrs Required | $ per Ton | Total $ | Tons per Year | Years Required | Normal Tmph Front* | Normal Tmph Rear* | Normal Tmph Trail* |
|---|---|---|---|---|---|---|---|---|
| 327 | 325 | 1.630 | 199,674 | 653,709 | 0.19 | 281 | 233 | |
| 654 | 187 | 0.968 | 118,572 | 1,307,418 | 0.09 | 281 | 233 | |
| 981 | 125 | 0.747 | 91,537 | 1,961,127 | 0.06 | 281 | 233 | |
| 1,307 | 94 | 0.637 | 78,026 | 2,614,836 | 0.05 | 281 | 233 | |
| 1,634 | 75 | 0.571 | 69,910 | 3,268,545 | 0.04 | 281 | 233 | |
| 1,961 | 62 | 0.527 | 64,503 | 3,922,254 | 0.03 | 281 | 233 | |
| 2,288 | 54 | 0.495 | 60,641 | 4,575,962 | 0.03 | 281 | 233 | |
| 2,615 | 47 | 0.472 | 57,745 | 5,229,671 | 0.02 | 281 | 233 | |
| 2,942 | 42 | 0.453 | 55,492 | 5,883,380 | 0.02 | 281 | 233 | |
| 3,268 | 37 | 0.438 | 53,696 | 6,537,089 | 0.02 | 281 | 233 | |
| 3,595 | 34 | 0.426 | 52,215 | 7,190,798 | 0.02 | 281 | 233 | |
| 3,922 | 32 | 0.427 | 52,319 | 7,844,726 | 0.02 | 260 | 216 | |
| 4,046 | 30 | 0.428 | 52,431 | 8,093,570 | 0.02 | 240 | 199 | |
| 4,243 | 29 | 0.432 | 52,909 | 8,486,290 | 0.01 | 223 | 185 | |
| 4,380 | 28 | 0.441 | 54,047 | 8,759,790 | 0.01 | 208 | 173 | |

**Fig 3.9: FPC output**

## 3.5 Earthmoving Optimization

### 3.5.1 Modeling of Variations

From the previous analysis, it is clear that the only unit costs that require special modeling in earthwork allocations are those of purchase and excavation from a borrow pit. These unit costs depend on the quantity to be used from the borrow pit and this quantity is unknown. All other unit costs can be established prior to the earthwork allocations and then treated as constants in the model. It should be noted that the unit costs of purchase and excavation typically constitute 30-40% of the total unit cost of the entire earthwork from a borrow pit. Therefore, precise representation of the variations of these unit costs is warranted.

Let us assume that unit cost of purchase and excavations are two component stepwise functions. The variation of the unit costs of purchase and excavation can be modeled by adding the respective unit costs function of fig 3.10(a-b). The combined unit cost function will be three-component stepwise function as shown in fig 3.10(c). As noted, this combined function has a decreasing unit cost for the second and third components. However, combined unit cost function could take any form depending on the shape of the unit cost functions of purchase and excavation. The model presented in the following section is applicable to any shape of three-component stepwise function. It should be noted that stepwise function of fig10(c) may also arise if the unit cost of purchase is constant and the unit cost of excavation is a three-component function and vice versa. Function with more than three components can be approximated by three components.

### 3.5.2 Model Development:

This section presents an optimization methodology for earthmoving operations that incorporate non constant stepwise unit cost function of purchase and excavation for borrow pits. Unit costs of other activities of earthwork are constant. In this section definition of the system, formulation of the model and the solution are presented.

#### System Definition

As explained by Jayawardane and Harris (1990), incorporation of different plant fleets is necessary in order to compare the production time and facilitate the incorporation of the project duration. For each haulage operation, there can be several possible plant fleets which can affect the duration and cost of haulage operation.

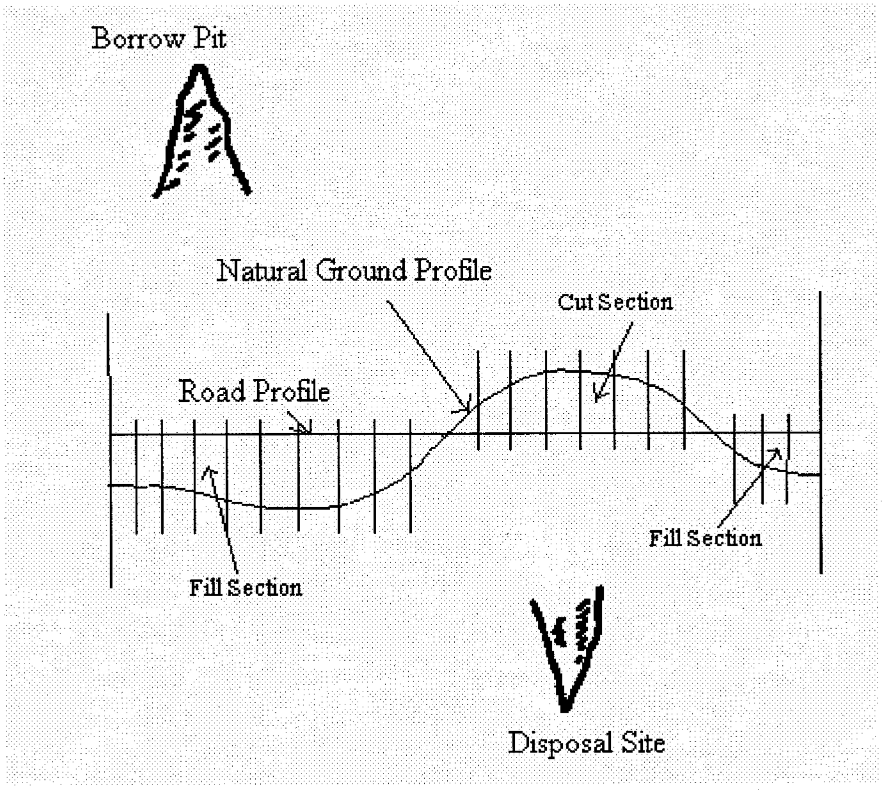


**Fig 3.10: Roadway segment for Earthwork Allocations**

Consider the roadway segment shown in figure 3.11 for which earthwork allocations are required. Let F be the set of identification numbers [F= (1,2,3,,………T)] corresponding to all the fleets available to a contractor and let $F_{i,j}$, which is a subset of F, be the possible fleet-identification numbers to be used between cut section i and fill section j, where i=1,2,3,…m and j=1,2,….n. Let X(i,j,f) be the amount of cut (in cubic yards) to be hauled from cut section i to fill section j by fleet having the identification number f, which is an element of $F_{i,j}$ which is a subset of F (i.e. $f \varepsilon F_{i,j} \subset F$ ). Let there are p number of sites (or landfills) are available for disposing excess materials, $X_d(i,k,f)$ is the amount of material (in cubic yards) to be disposed from cut section i to disposal site k, where k=1,2,…,p; using fleet f. Let there are q number of sites are available for borrowing needed material. $X_b(h,j,f)$ is the amount of material (in cubic yards) to be borrowed from borrow pit h, where h=1,2,…q, to fill section j, using fleet f. The capacities of disposal site k and borrow pit h are $D_k$ and $B_h$, respectively.

If U (i, j, f) is the total unit cost of earthmoving (i.e. excavation, haul and compaction), in dollars per cubic yard, from cut section i to fill section j by fleet f, then

$U(i,j,f) = u_e(i,f) + S_{ij}^h[u_h(i,f)*d(i,j) + u_c(i,j,f)]$……………………………………..(1)

Where the unit cost of excavation by fleet f, in dollars per cubic yard, including loading is $u_e(i,f)$, of haul in dollars per Cubic yard per unit distance, as $u_h(i,f)$ and of embankment (including placing and compaction), in dollars per cubic yard as $u_c(i,j,f)$], $d_{ij}$ is the distance between the centers of mass of the cut section i and fill section j and $S_{ij}^h$ is the swell (or shrinkage) factor in haul for material excavated from section i to be compacted in section j.

We can see that total cost of earthmoving work i.e. excavation, haul and compaction, from cut section i to fill section j, for one cubic yard of material, U (i,j,f), is linearly proportional to the haul distance.

In the same way, total cost of earthmoving work, i.e. excavation, haul and compaction, of one cubic yard of earth from cut section i to disposal site k using fleet f, i.e. $U_d(i,k,f)$ can be found as

$U_d(i,k,f) = u_e(i,f) + S_{ik}[u_h(i,f)*d(i,k) + u_c(i,k,f)]$ ………………………… ……(2)

And, total cost of haul and compaction of one cubic yard of material from borrow pit h to fill section j using fleet f, i.e. $U_b(h,j,f)$, can be found as

$U_b(h,j,f) = S_{hj}[u_h(h,f)*d(h,j) + u_c(h,j,f)]$ ………………………………………(3)

Thus total cost of earthmoving work from cut section i to fill section j using fleet f will be

$U(i,j,f) * X(i,j,f)$ ……………………………………………………(4)

By using the Mixed Integer Programming Model presented by Mayer and Stark (1981), suppose the purchase cost of a disposal site d is $P_d(k)$, then total cost of using disposal site k will be

$\lambda_d(k) * P_d(k) + \sum_{i=1}^{m} U_d(i,k,f) * X_d(i,k,f)$ ………………………………(5a)

$\lambda_d(k) \varepsilon (0,1)$ ……………………………………………………………(5b)

The constraint can be put for the number of disposal site, i.e. maximum one number of disposal site can be used, which can be written as

$\sum_{h=1}^{l} \lambda_d(k) <= 1$ ………………………………………………………(5c)

The capacity constraint can be put as

$$\sum_{i=1}^{m} \sum_{f \in Fi,k} S_{i,k,f}\, X_d(i,k,f) - \lambda_d(k) * M_d(k) <= 0 \ldots\ldots (5d)$$

Total cost of haul and compaction of earthmoving work from borrow pit h to fill section j will be

$$U_b(h,j,f) * X_b(h,j,f) \ldots\ldots (5e)$$

The production rate, in bank cubic yard per day, in moving earth from cut section i to fill section j by fleet f, R (i,j,f), is calculated by dividing the fleet-hire charge, in $ per day, by unit cost of haul from cut section i to fill section j using fleet f, i.e. U(i,j,f), in dollars per cubic yard. Similarly production rate for moving earth from cut section i to disposal site k and from fill section j to borrow pit h using fleet f, i.e. $R_d(i,k,f)$ and $R_b(h,j,f)$ are calculated.

## Model Formation

To formulate equations for three components stepwise functions of earthwork from borrow pit, the model developed by Easa (1987), for nonconstant unit costs, is very effective. Let us assume that unit cost of purchasing and excavation of a borrow pit is three component, as shown in figure 3.11.

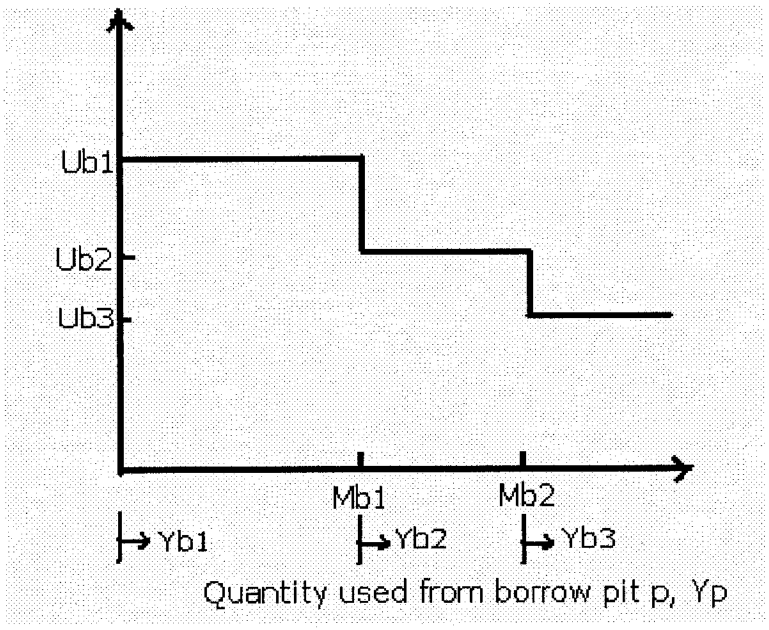


**Fig 3.11: Stepwise unit cost function for purchase and excavation (for borrow pit)**

The unit cost varies with the quantity used and has two break points quantities, $M_{b1}(h)$ and $M_{b2}(h)$ for borrow pit. If the total quantity of materials used from the borrow pit h, i.e. $Y_b(h)$, is less than $M_{b1}(h)$, i.e. $Y_b(h) = Y_{b1}(h)$ then the unit cost of purchase and excavation will be $U_{b1}(h)$ and total cost of purchase and excavation will be $U_{b1}(h) * Y_{b1}(h)$. If the total quantity used, $Y_b(h)$, is between $M_{b1}(h)$ and $M_{b2}(h)$ cubic yard i.e. $Y_b(h) = M_{b1}(h) + Y_{2p}(h)$, then unit cost of purchase will be $U_{b2}(h)$. And thus total cost will be $(M_{b1}(h) + Y_{2p}(h)) * U_{b2}(h)$. And if the total quantity used, $Y_b(h)$, is more than $M_{b2}(h)$, i.e. $Y_b(h) = M_{b2}(h) + Y_{3p}(h)$ then unit cost will be $U_{b3}$ and thus total cost will be $(M_{b2}(h) + Y_{3p}(h)) * U_{b3}(h)$.

Since the total quantity used from borrow pit h, $Y_h$, is equal to the sum of the quantities sent to various fill sections, then

$$Y_{b1}(h) + Y_{b2}(h) + Y_{b3}(h) = \sum_{j=1}^{n} X_b(h,j) \ldots\ldots (6)$$

In addition, the following logical conditions must be satisfied.

If $0<= Y_{b1}(h) < M_{b1}(h)$, then $Y_{b2}(h) = 0$ and $Y_{b3}(h) = 0$……………………(7)

If $0<= Y_{b2}(h) < (M_{b2}(h) - M_{b1}(h))$, then $Y_{b1}(h) = M_{b1}(h)$ and $Y_{b3}(h) = 0$..(8)

If $0<= Y_{b3}(h)$ then $Y_{b1}(h) = M_{b1}(h)$ and $Y_{b2}(h) = M_{b2}(h) - M_{b1}(h)$……….(9)

Such logical constraints can be handled by the use of binary variables. Introducing for each borrow pit p two binary variables, $\lambda_p(h)$ and $\gamma_p(h) \varepsilon (0,1)$, the constraints of Eqs. 7-9 can be replaced by

$Y_{b1}(h) <= M_{b1}(h)$……………………………………………………………(10)

$Y_{b1}(h) -(\lambda_b(h) + \gamma_b(h)) M_{b1}(h)>=0$…………………………………………….(11)

$Y_{b2}(h) -(\lambda_b(h) + \gamma_b(h)) (M_{b2}(h) - M_{b1}(h)) <=0$…………………………………(12)

$Y_{b2}(h) - \gamma_b(h) (M_{b2}(h) - M_{b1}(h)) >=0$…………………………………………(13)

$Y_{b3}(h) - \gamma_b(h) (M_{b2}(h) - M_{b1}(h)) <=0$…………………………………………(14)

$Y_{b3}(h) >=0$……………………………………………………………………(15)

$\lambda_b(h) + \gamma_b(h) <= 1$……………………………………………………………(16)

$\lambda_b(h) , \gamma_b(h) \varepsilon (0,1)$…………………………………………………………………(17)

The constraints of Equations 10-17 satisfy the conditions of Equations 7-9. From Equations 16 and 17 it is clear that at most one of the binary variables would be equal to 1.therefore the possible combinations of these variables are ($\lambda_b(h) = 0, \gamma_b(h) =0$), ($\lambda_b(h) = 1, \gamma_b(h) =0$), and ($\lambda_b (h)= 0, \gamma_b(h) =1$). These combinations correspond to the cases in which the quantity used from the borrow pit is within the first, second, and third components of the stepwise unit cost function, respectively. It is clear that the three combinations of $\lambda_b(h)$ and $\gamma_b (h)$ satisfy the conditions of Eqs 7-9. For ($\lambda_b(h) = 0, \gamma_b(h) =0$), Eqs 10 and 11 result in $0<= Y_{1b}(h) <= M_{b1}(h)$, Eqs. 12 and 13 yield $Y_{2b}(h) =0$, and

Eqs 14 and 15 yield $Y_{3b} = 0$. Thus, the condition of Eq. 7 is satisfied. Similarly, for the other two combinations, the conditions of Equations 8 and 9 are also satisfied.

Then the total cost for utilizing a borrow pit h will be

$$\sum_{j=1}^{n} \sum_{f\in Fh,j} U_b(h,j,f) * X_b(h.j,f) + [U_{b1}(h)*Y_{b1}(h) + U_{b2}(h)*Y_{b2}(h) + U_{b3}(h)*Y_{b3}(h) + (U_{b2}(h)-$$

$$U_{b1}(h))M_{b1}(h)*\lambda_b(h) + \{(U_{b2}(h)-U_{b1}(h))M_{b1}(h) + (U_{b3}(h)-U_{b2}(h))M_{b2}(h)\}\gamma_b(h)] \ldots\ldots(18)$$

Where the first term is the cost of haul and compactions of earthwork between borrow pits and fill sections. Second term represents the cost of purchase and excavation for borrow pits. In the second term, it is noted for ($\lambda_b(h)= 0$, $\gamma_b(h) =0$), the cost component is equal to $U_{b1}(h)*Y_{b1}(h)$. For ($\lambda_b(h)= 1$, $\gamma_b(h) =0$), this component is equal to $(M_{b1}(h)+ Y_{b2}(h))* U_{b2}(h)$. Similarly, for ($\lambda_b(h) = 0$, $\gamma_b(h) =1$), this cost component is equal to $(M_{b2}(h) +Y_{3b})* U_{b3}(h)$, as it should be.

The values of the decision variables, $X(i,j,f)$, $X_d(i,k,f)$ and $X_b(h,j,f)$ are limited by the required quantities of cut and fill, and the capacities of the landfills and borrow pits. For cut sections, constraints for the quantity will be

$$\sum_{j=1}^{n} \sum_{f\in Fi,j} X(i,j,f) + \sum_{k=1}^{r} \sum_{f\in Fi,k} X_d(i,k,f) = C(i) \ldots\ldots(19)$$

where C(i) is the quantity of cut required in section i.

For fill sections, constraints for the quantity will be

$$\sum_{i=1}^{m} \sum_{f\in Fi,j} S_{i,j,f} * X(i,j,f) + \sum_{h=1}^{l} \sum_{f\in Fh,j} S_{h,j,f} * X_b(h,j,f) = F(j) \ldots\ldots(20)$$

where F(j)is the quantity of fill required in section j.

For disposal sites, constraints for the quantity will be

$$\sum_{i=1}^{m} \sum_{f \in Fi,k} S_{i,k,f} X_d(i,k,f) - \lambda_d(k) * D(k) <= 0 \ldots\ldots(21)$$

Where D(k) is the capacity of the disposal site k and $\lambda_d(k)$ ε (0,1)

$$\sum_{k=1}^{r} \lambda_d(k) <= 1 \ldots\ldots(22)$$

Thus, the number of possible solutions corresponds to the following combinations of integer variables $(\lambda_1=0,\lambda_2=0,\lambda_3=0, \ldots\ldots, \lambda_l=0)$, $(\lambda_1=1,\lambda_2=0,\lambda_3=0, \ldots\ldots, \lambda_l=0)$, $(\lambda_1=0,\lambda_2=1,\lambda_3=0, \ldots\ldots, \lambda_l=0)$, ………………… $(\lambda_1=0,\lambda_2=0, \lambda_3=0, \ldots\ldots, \lambda_l=1)$.

For borrow pits, constraints for the quantity will be

$$\sum_{j=1}^{n} \sum_{f \in Fh,j} X_b(h,j,f) <= B(h) \ldots\ldots(23)$$

Where B(h) is the capacity of the borrow pit h.

Jayawardane and Harris (1990) have explained the way to formulate the constraint for plant fleet utilization, which has been used here. For each plant fleet f, the total utilization time for different haulage operation, i.e. moving materials from cut to fill sections, cut to disposal sites and from borrow pit to fill sections, will be equal to or less than the duration of the project. If no solution is found, the available plant fleet cannot be utilized on their own for project completion as scheduled and need to be changed.

$$\sum_{i=1}^{m} \sum_{j=1}^{n} \{ X(i,j,f)\} / P(i,j,f) \} + \sum_{h=1}^{l} \sum_{j=1}^{n} \{ X_b(h,j,f)\} / P(h,j,f) \} + \sum_{i=1}^{m} \sum_{k=1}^{r} \{ X(i,k,f)\} / P(i,k,f) \} <= D \ldots\ldots(24)$$

To complete project within project duration, there is chance of concurrent use of more than one fleet for a particular haulage operation, which may create congestion. To avoid this problem Jayawardane and Harris (1990) have suggested to add one more constraint, i.e. total time spent on any particular source and destination by all possible plant fleets should be less than or equal to the total project duration, thereby enabling the use of different plant fleets sequentially between a source and a destination, for project completion as scheduled.

So, for each haulage operation between cut and fill sections, i.e. for any combination of i and j,

$\{ X(i,j,f) / P(i,j,f) \} <= D$……………………………………………………(25)

Similarly, for each haulage operation between cut and disposal sites, i.e. for any combination of i and k,

$\{ X(i,k,f) / P(i,k,f) \} <= D$……………………………………………………(26)

And for each haulage operation between borrow pits and fill sections i.e. for any combination of h and j,

$\{ X_b(h,j,f) / P(h,j,f) \} <= D$……………………………………………………(27)

There will be non-negativity condition for each decision variable, i.e.

$X(i,j,f)$, $X_d(i,k,f)$ and $X_b(h,j,f) >= 0$ ……………………………………………(28)

The objective of optimization model is to minimize the total cost of earthmoving operation. The total cost is the sum of the cost of moving earth among cut and fill sections, from cut sections to the disposal sites and from borrow pits to fill sections. The objective function can be written as

$$
\begin{aligned}
\text{Minimize } Z = & \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{f \in Fi,j} C(i,j,f)\, X(i,j,f) + \sum_{k=1}^{p} \lambda_d(k) * P_d(k) + \sum_{i=1}^{m} \sum_{k=1}^{p} \\
& \sum_{f \in Fi,k} U_d(i,k,f) * X_d(i,k,f) + \sum_{h=1}^{l} \sum_{j=1}^{n} \sum_{f \in Fh,j} U_b(h,j,f) * X_b(h.j,f) + \sum_{h=1}^{l} [U_{b1}(h) * Y_{b1}(h) + \\
& U_{b2}(h) * Y_{b2}(h) + U_{b3}(h) * Y_{b3}(h) + (U_{b2}(h) - U_{b1}(h)) M_{b1}(h) * \lambda_b(h) + \{(U_{b2}(h) - U_{b1}(h)) M_{b1}(h) \\
& + (U_{b3}(h) - U_{b2}(h)) M_{b2}(h)\} \gamma_b(h)] \ldots\ldots (29)
\end{aligned}
$$

The first term in above Eq (29) represent the cost of earthwork from cut sections to fill sections, second and third term from cut to disposal sites and the rest fourth and fifth terms represent cost of earthwork from borrow pits to the fill sections.

Summing up the objective function and constraints -

**Objective Function**

$$
\begin{aligned}
\text{Minimize } Z = & \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{f \in Fi,j} U(i,j,f) * X(i,j,f) + \sum_{k=1}^{p} \lambda_d(k) * P_d(k) + \sum_{i=1}^{m} \sum_{k=1}^{p} \\
& \sum_{f \in Fi,k} U_d(i,k,f) * X_d(i,k,f) + \sum_{h=1}^{l} \sum_{j=1}^{n} \sum_{f \in Fh,j} U_b(h,j,f) * X_b(h.j,f) + \sum_{h=1}^{l} [U_{b1}(h) * Y_{b1}(h) + \\
& U_{b2}(h) * Y_{b2}(h) + U_{b3}(h) * Y_{b3}(h) + (U_{b2}(h) - U_{b1}(h)) M_{b1}(h) * \lambda_b(h) + \{(U_{b2}(h) - U_{b1}(h)) M_{b1}(h) \\
& + (U_{b3}(h) - U_{b2}(h)) M_{b2}(h)\} \gamma_b(h)] \ldots\ldots (30)
\end{aligned}
$$

**Constraints**

$$
\sum_{j=1}^{n} \sum_{f \in Fi,j} X(i,j,f) + \sum_{k=1}^{r} \sum_{f \in Fi,k} X_d(i,k,f) = C(i) \ldots\ldots (31)
$$

$$
\sum_{i=1}^{m} \sum_{f \in Fi,j} S_{i,j} * X(i,j,f) + \sum_{h=1}^{l} \sum_{f \in Fh,j} S_{h,j} * X_b(h,j,f) = F(j) \ldots\ldots (32)
$$

$$
\sum_{i=1}^{m} \sum_{f \in Fh,j} [S_{i,k}\, X_d(i,k,f) - \lambda_d(k) * D(k)] <= 0 \ldots\ldots (33)
$$

$$\sum_{h=1}^{l} \lambda_d(k) <= 1 \ldots\ldots (34)$$

$$\sum_{j=1}^{n} \sum_{f \in Fh,j} X_b(h,j,f) <= B(h) \ldots\ldots (35)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} \{ X(i,j,f) / P(i,j,f) \} + \sum_{h=1}^{l} \sum_{j=1}^{n} \{ X_b(h,j,f) / P(h,j,f) \} + \sum_{i=1}^{m} \sum_{k=1}^{r} \{ X(i,k,f) / P(i,k,f) \} <= D \ldots\ldots (36)$$

$$\{ X(i,j,f) / P(i,j,f) \} <= D \ldots\ldots (37)$$

$$\{ X(i,k,f) / P(i,k,f) \} <= D \ldots\ldots (38)$$

$$\{ X_b(h,j,f) / P(h,j,f) \} <= D \ldots\ldots (39)$$

$$Y_{b1}(h) + Y_{b2}(h) + Y_{b3}(h) = \sum_{j=1}^{n} X_b(h,j) \ldots\ldots (40)$$

$$Y_{b1}(h) <= M_{b1}(h) \ldots\ldots (41)$$

$$Y_{b1}(h) - (\lambda_b(h) + \gamma_b(h)) M_{b1}(h) >= 0 \ldots\ldots (42)$$

$$Y_{b2}(h) - (\lambda_b(h) + \gamma_b(h)) (M_{b2}(h) - M_{b1}(h)) <= 0 \ldots\ldots (43)$$

$$Y_{b2}(h) - \gamma_b(h) (M_{b2}(h) - M_{b1}(h)) >= 0 \ldots\ldots (44)$$

$$Y_{b3}(h) - \gamma_b(h) (M_{b2}(h) - M_{b1}(h)) <= 0 \ldots\ldots (45)$$

$$Y_{b3}(h) >= 0 \ldots\ldots (46)$$

$$\lambda_b(h) + \gamma_b(h) <= 1 \ldots\ldots (47)$$

$$\lambda_b(h), \gamma_b(h), \lambda_d(k) \ \varepsilon \ (0,1) \ldots\ldots (48)$$

$$X(i,j), X_d(i,k) \text{ and } X_b(h,j) >= 0 \ldots\ldots (49)$$

## 3.6 Methodology

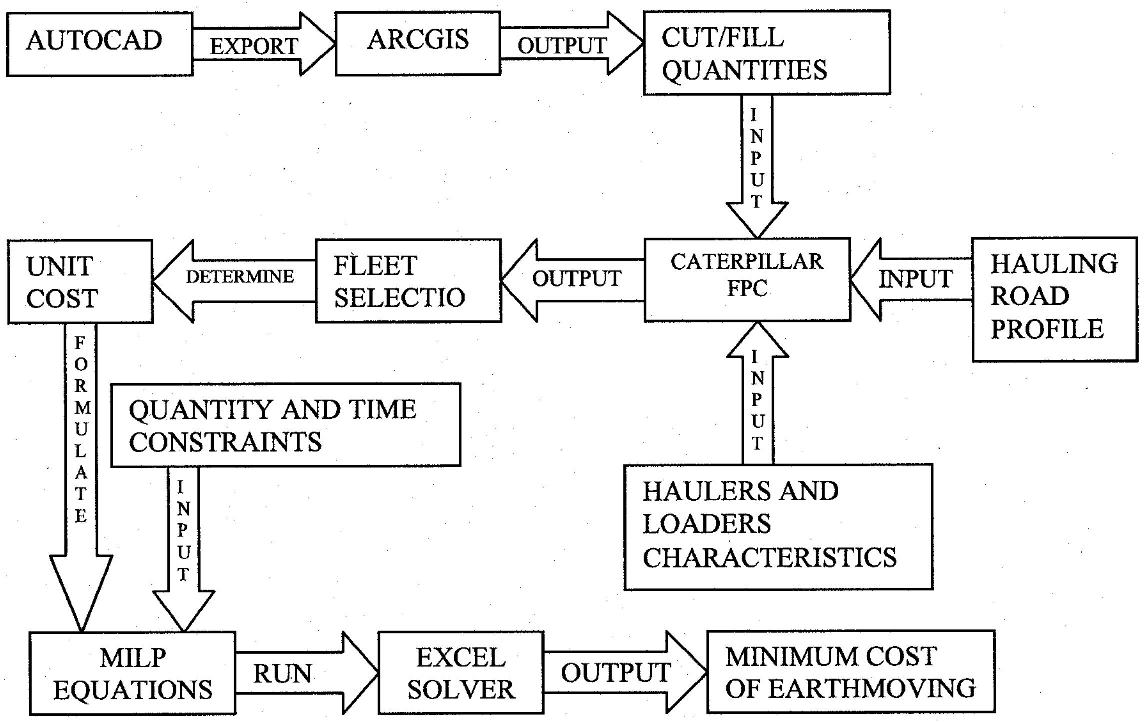


**Fig 3.12: Integrated System Flow Chart**

In above flow chart, we tried to show how the data can flow between different components of the integrated system. We can use AutoCAD for drawing three dimensional contour map of the natural ground profile which can be superimposed over map of proposed ground profile. This AutoCAD file (in dwg. format) can be exported to ArcGIS where DTM is generated using TIN networks. Using 3D-Analyst extension of ArcGIS, we can get cut/fill quantities for different sections which can be used as input in FPC, apart from hauling road profile data and haulers and loaders characteristics, to select best fleet. In FPC, we will also get unit cost for the selected fleet. These unit costs for material movements between different cut and fill sections, borrow pits and disposal sites are used to formulate Mixed-Integer Linear Programming equations. Required quantities of cut and fill, the capacities of the landfills and borrow pits and duration of project are considered as constraints. This MILP model can be run on Microsoft Excel add-in software, Solver, to get optimum quantities of materials to be moved between different sections so as to have minimum cost of earthmoving.

# CHAPTER 4

# MODEL IMPLEMENTATION

## 4.1 Introduction

This chapter presents the computer implementation of the presented integrated system for quantity take-off, fleet selection and optimization of earthmoving operation. Mixed Integer Linear Programming method has been used to solve the optimization model which has been implemented using Microsoft Excel Solver.

## 4.2 Special case

Let us assume that purchase cost of disposal sites are very small compare to other costs and so it has been neglected in the objective equation i.e. $\sum_{k=1}^{p} \lambda_d(k) * P_d(k) = 0$.

Also assume that combined unit cost of purchase and excavation have only two components with a break-point quantity $M_{b1}(h)$. This is possible if the unit cost component of purchase or excavation is constant or their break-point quantities are same. In this case only one binary variable $\lambda_b(h)$ would be needed and the Eq 30 is written as follows

$$\sum_{h=1}^{l} [U_{b1}(h)*Y_{b1}(h) + U_{b2}(h)*Y_{b2}(h) + (U_{b2}(h)-U_{b1}(h))M_{b1}(h)*\lambda_b(h)]$$

Thus the objective equation 30 and constraints for equation 40-49 can be written as -

$$\text{Minimize } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{f \in Nh,j} C(i,j,f)\, X(i,j,f) + \sum_{i=1}^{m} \sum_{k=1}^{p} \sum_{f \in Ni,k} U_d(i,k,f) * X_d(i,k,f) +$$

$$\sum_{h=1}^{l} \sum_{j=1}^{n} \sum_{f \in Nh,j} U_b(h,j,f) * X_b(h.j,f) + \sum_{h=1}^{l} [U_{b1}(h)*Y_{b1}(h) + U_{b2}(h)*Y_{b2}(h) + (U_{b2}(h)-$$

$$U_{b1}(h))M_{b1}(h)*\lambda_b(h)\,] \ldots\ldots (51)$$

$$Y_{b1}(h) + Y_{b2}(h) = \sum_{j=1}^{n} X_b(h,j) \ldots\ldots (52)$$

$$Y_{b1}(h) <= M_{b1}(h) \ldots\ldots (53)$$

$$Y_{b1}(h) - \lambda_b(h)\, M_{b1}(h) >= 0 \ldots\ldots (54)$$

$$Y_{b2}(h) - \lambda_b(h)\, (M_{b2}(h) - M_{b1}(h)) <= 0 \ldots\ldots (55)$$

$$Y_{b2}(h) >= 0 \ldots\ldots (56)$$

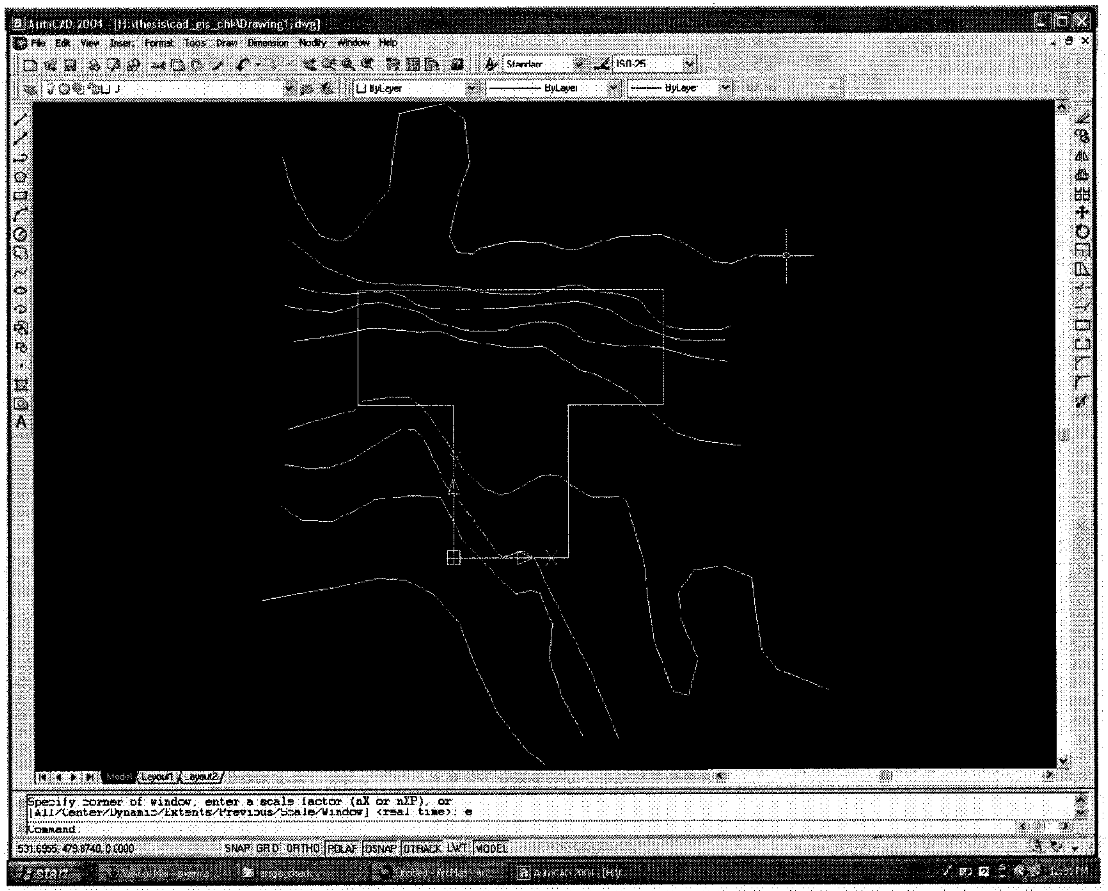
$$\lambda_b(h),\ \lambda_d(k)\ \varepsilon\ (0,1) \ldots\ldots (57)$$

### 4.3 Model Verification

In order to demonstrate the capabilities of the presented model, data from different source has been used to verify the output of GIS and MILP components of the model.

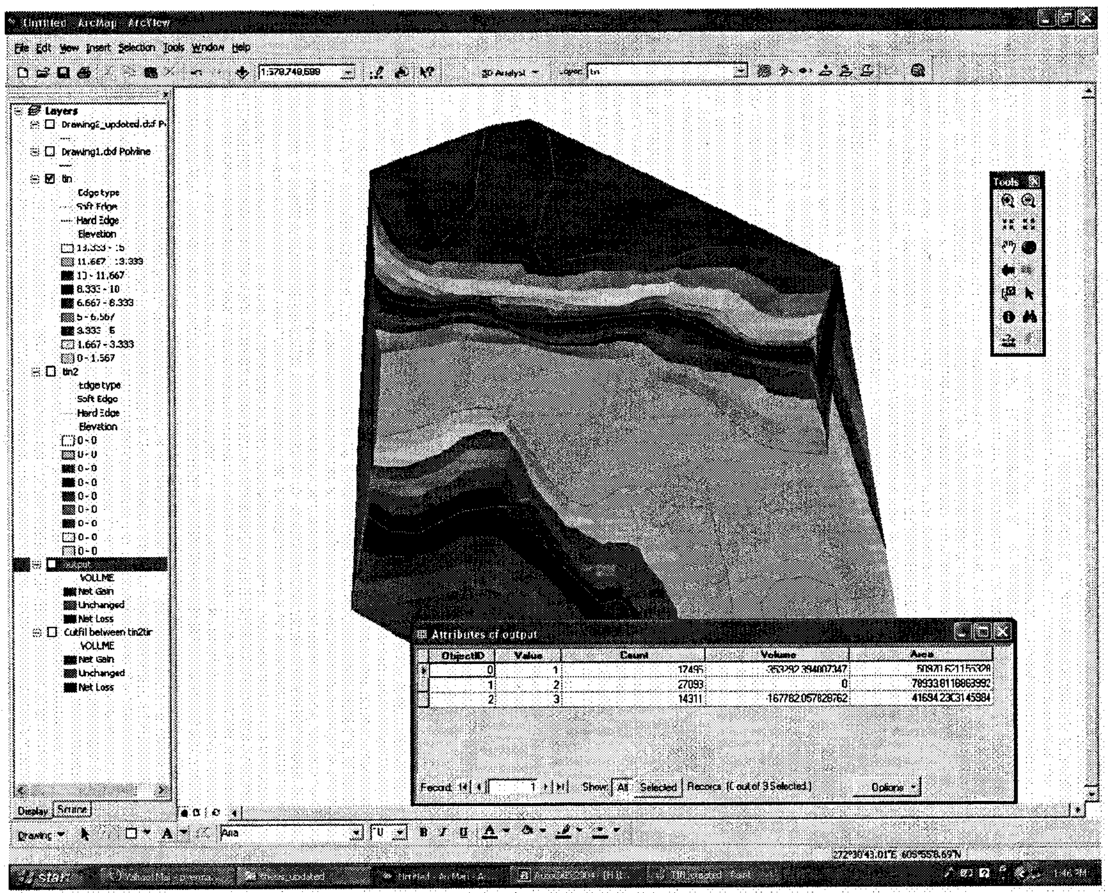
#### 4.3.1 GIS Component

Here, we have used AutoCAD dwg. file of an industrial warehouse as input to find volume of excavation needed (shown in fig 4.1). This AutoCAD file is imported in ArcGIS using 'add data' toolbar. Then Digital Terrain Model (DTM) is created in ArcGIS by using 3D-Analyst, which gives cut and fill volume needed for different sections as output. Comparison of this result of ArcGIS has been done with the manual calculation for cut and fill volume determination as shown in table 4.1.



```
Specify corner of window, enter a scale factor (nX or nXP), or
[All/Center/Dynamic/Extents/Previous/Scale/Window] <real time>: e
Command:
```

Fig 4.1: AutoCAD drawing file.



Attributes of output

| ObjectID | Value | Count | Volume | Area |
|---|---|---|---|---|
| 0 | 1 | 17495 | -353292.394007347 | 50970.521155328 |
| 1 | 2 | 27093 | 0 | 78933.8118863992 |
| 2 | 3 | 14311 | -167782.057828762 | 41694.2303145984 |

Record: 1 Show: All Selected Records (0 out of 3 Selected.) Options

**Figure 4.2 Cut/Fill determinations using ArcGIS**

#### 4.3.1.1 Comparing GIS output with manual output

**Table 4.1: Manual output Vs GIS output**

| Total Volume of | Manual Results (Cu ft) | GIS results (Cu ft) |
|---|---|---|
| Cut | 508000 | 521074 |
| Fill | 0 | 0 |

Percentage difference in calculating cut volume = (521074 – 508000) / 508000 = 2.6% which is very less. So we can say that there is not much difference in manual and

GIS output. Volume calculation using GIS is very fast and easy compare to manual calculation and there is very less chance of error in calculating volume using GIS.

### 4.3.2 MILP Component

For solving the presented optimization model, we can use any of the Mixed-integer Linear Programming algorithms. Linear Programming problems are generally solved via the Simplex method. Here in our research work, the standard Microsoft Excel Solver has been used to solve the presented MILP model. Microsoft Excel Solver uses a straightforward implementation of the Simplex method to solve LP problems which make it practical to solve LP problems with tens of thousands of variables and constraints very fast. The memory required by this Simplex code increases with the number of variables times the number of constraints, regardless of the model's sparsity (scattered).

#### 4.3.2.1 Example Problem

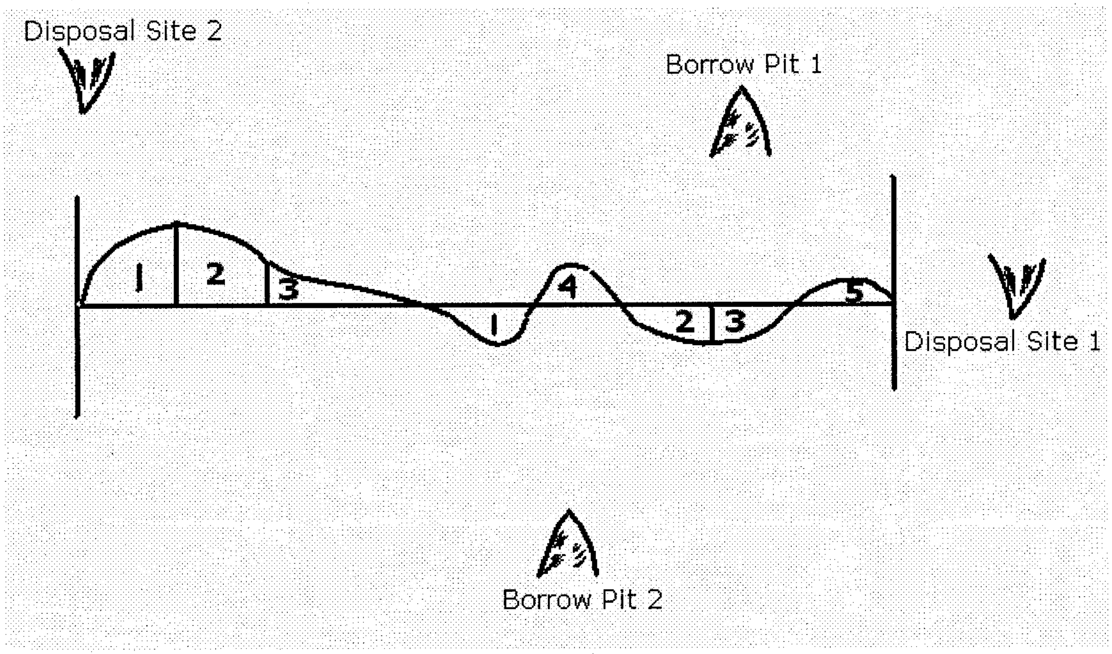


**Fig 4.3: Road Segment with available borrow pits and disposal sites**

Roadway earthwork allocation example used by Easa (1987) has been used to verify the performance of presented MILP model. The roadway section contains five cut sections and three fill sections with the earth quantities shown in figure 4.3.There are two borrow pits and two disposal sites available, the capacity of each borrow pit is 40,000 cu yd and disposal sites have unlimited capacity. The shrinkage factors in embankment for cut sections and borrow pits are also shown in Table 4.2. Assume that the unit costs (excavation, haul and embankment) for earthwork from cut sections to fill sections, based on Equation 1, are known and are shown in Table 4.3. Similarly, the unit costs (excavation, haul and embankment) for earthwork from cut sections to disposal sites are known (based on equation 2) and are shown in Table 4.3. For earthwork from borrow pits to fill sections, the unit costs of haul and compaction, base on Eq. 3, are constant, and are shown in Table 4.4. The unit cost of purchase and excavation for borrow pits are assumed to be two-component stepwise functions for simplification. The first and second components of the unit cost function and the breakpoint quantity are shown in Table 4.4. The stepwise unit cost function of purchase and excavation for borrow pit number 1 is increasing, while the borrow pit number 2 is decreasing. The increasing unit cost function of borrow pit number 1 is due to the presence of a different type of soil (after 10,000 cu yd), which is more expensive to excavate (the unit cost of purchase is constant). The decreasing unit cost function of borrow pit number 2 is due to a discounting unit cost of purchase (the unit cost of excavation is constant).

**TABLE 4.2: Data of Estimated Earth Quantities**

| Roadway sections | | Estimated quantities (1000 cu yard) | Shrinkage factor in embankment |
|---|---|---|---|
| Cut number | 1 | 30 | 0.80 |
| | 2 | 25 | 0.80 |
| | 3 | 10 | 1.00 |
| | 4 | 20 | 0.80 |
| | 5 | 15 | 0.75 |
| Fill number | 1 | 35 | -- |
| | 2 | 25 | -- |
| | 3 | 25 | -- |
| Borrow pit number | 1 | 40 | 0.90 |
| | 2 | 40 | 1.00 |
| Disposal site number | 1 | Unlimited capacity | -- |
| | 2 | Unlimited capacity | -- |

**Table 4.3: Estimated unit costs for earthwork between cut and fill sections ($ per 1,000 cu yd).**

| From cut section number | Unit cost to fill section number | | | Unit cost to disposal site number | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 |
| 1 | 7,400 | 8,600 | 9,200 | 3,700 | 970 |
| 2 | 5505 | 5815 | 6270 | 3245 | 1425 |
| 3 | 4050 | 4960 | 5415 | 4100 | 2900 |
| 4 | 3595 | 3595 | 4050 | 1134 | 2790 |
| 5 | 5280 | 4300 | 3810 | 570 | 4490 |

**Table 4.4: Estimated unit costs for earthwork between borrow pits and fill section ($ per 1,000 cu yd)**

| From borrow pit | Unit cost to fill section (Haul and Embankment) | | | Stepwise unit cost (Purchase and Excavation) | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | First Component | Second component | Break-point (* 1,000) |
| 1 | 3680 | 2840 | 1950 | 500 | 600 | 10 |
| 2 | 3700 | 2860 | 2460 | 410 | 100 | 10 |

Let us assume that all hauling works from cut to fill sections have been done by using fleet f having production level (1000 cu yd) is 4, from cut to disposal sites have been done by fleet f having production level (1000 cu yd) is 5 and from borrow pits to fill sections have been done by fleet f having production level (1000 cu yd) is 6.

#### 4.3.2.2 Problem Statement

As, in this example, we have two-component stepwise functions for purchase and excavation of borrow pits and constant unit costs for the disposal sites, we have to substitute the unit costs of Table 4.3 and 4.4 in the objective function of Eq 51. Thus we get,

$$
\begin{aligned}
\text{Minimize } Z = {} & 7400X(1,1,f) + 8600X(1,2,f) + 9200X(1,3,f) + 5505X(2,1,f) \\
& + 6270X(2,3,f) + 4050X(3,1,f) + 4960X(3,2,f) + 5415X(3,3,f) + 3595X(4,1,f) + \\
& 3595X(4,2,f) + 4050X(4,3,f) + 5280X(5,1,f) + 4300X(5,2,f) + 3810X(5,3,f) + \\
& 3700X_d(1,1,f) + 970X_d(1,2,f) + 3245X_d(2,1,f) + 1425X_d(2,2,f) + 4100X_d(3,1,f) + \\
& 2900X_d(3,2,f) + 1134X_d(4,1,f) + 2790X_d(4,2,f) + 570X_d(5,1,f) + 4490X_d(5,2,f) + \\
& 4680X_b(1,1,f) + 2840X_b(1,2,f) + 1950X_b(1,3,f) + 3700X_b(2,1,f) + 2860X_b(2,2,f) + \\
& 2460X_b(1,3,f) + 500Y_{11} + 600Y_{21} + 1000\lambda_1 + 410Y_{12} + 100Y_{22} - 3100\lambda_2
\end{aligned}
$$

subject to the constraints

$$
\begin{aligned}
Y_{11} + Y_{21} &= X_b(1,1) + X_b(1,2) + X_b(1,3) \\
Y_{11} &\le 10 \\
Y_{11} - 10\lambda_1 &\ge 0 \\
Y_{21} - 30\lambda_1 &\le 0 \\
Y_{12} + Y_{22} &= X_b(2,1) + X_b(2,2) + X_b(2,3) \\
Y_{12} &\le 10
\end{aligned}
$$

$Y_{12} - 10\lambda_2 \geq 0$
$Y_{22} - 30\lambda_2 \leq 0$
$Y_{21} , \quad Y_{22} \geq 0$
$\lambda_1 , \lambda_2 \quad \varepsilon \, (0,1)$

$X(1,1,f) + X(1,2,f) + X(1,3,f) + X_d(1,1,f) + X_d(1,2,f) = 30$

$X(2,1,f) + X(2,2,f) + X(2,3,f) + X_d(2,1,f) + X_d(2,2,f) = 25$

$X(3,1,f) + X(3,2,f) + X(3,3,f) + X_d(3,1,f) + X_d(3,2,f) = 10$

$X(4,1,f) + X(4,2,f) + X(4,3,f) + X_d(4,1,f) + X_d(4,2,f) = 20$

$X(5,1,f) + X(5,2,f) + X(4,3,f) + X_d(5,1,f) + X_d(5,2,f) = 15$

$0.8X(1,1,f) + 0.8X(2,1,f) + X(3,1,f) + 0.8X(4,1,f) + 0.75X(5,1,f) + 0.9X_b(1,1,f) + X_b(2,1,f) = 35$

$0.8X(1,2,f) + 0.8X(2,2,f) + X(3,2,f) + 0.8X(4,2,f) + 0.75X(5,2,f) + 0.9X_b(1,2,f) + X_b(2,2,f) = 25$

$0.8X(1,3,f) + 0.8X(2,3,f) + X(3,3,f) + 0.8X(4,3,f) + 0.75X(5,3,f) + 0.9X_b(1,3,f) + X_b(2,3,f) = 25$

#### 4.3.2.3 Computer Output

The above MILP optimization problems is solved using Microsoft Excel Solver which gives optimum value of decision variables, i.e., optimum quantity of materials need to be moved between different cut sections (or borrow pits) to fill sections (or disposal sites) to get optimum (minimum) cost of completing the project within project duration using a specific type of fleet.

## Table 4.5: Solver Output

**Microsoft Excel 10.0 Answer Report**
**Worksheet: [problem_solution1.xls]Sheet2**
**Report Created: 2/10/2005 12:36:50 AM**
**Result: Solver found a solution. All constraints and optimality conditions are satisfied.**
**Engine: Standard LP/Quadratic**

Target Cell (Min)

| Cell | Name | Original Value | Final Value |
|---|---|---|---|
| $C$24 | Z = Variables | 0 | 346775 |

Adjustable Cells

| Cell | Name | Original Value | Final Value |
|---|---|---|---|
| $D$7 | Variables x11 | 0 | 0 |
| $E$7 | Variables x12 | 0 | 0 |
| $F$7 | Variables x13 | 0 | 0 |
| $G$7 | Variables $x_d$11 | 0 | 0 |
| $H$7 | Variables $x_d$12 | 0 | 30 |
| $I$7 | Variables x21 | 0 | 0 |
| $J$7 | Variables x22 | 0 | 0 |
| $K$7 | Variables x23 | 0 | 0 |
| $L$7 | Variables $x_d$21 | 0 | 0 |
| $M$7 | Variables $x_d$22 | 0 | 25 |
| $N$7 | Variables x31 | 0 | 10 |
| $O$7 | Variables x32 | 0 | 0 |
| $P$7 | Variables x33 | 0 | 0 |
| $Q$7 | Variables $x_d$31 | 0 | 0 |
| $R$7 | Variables $x_d$32 | 0 | 0 |
| $S$7 | Variables x41 | 0 | 20 |
| $T$7 | Variables x42 | 0 | 0 |
| $U$7 | Variables x43 | 0 | 0 |
| $V$7 | Variables $x_d$41 | 0 | 0 |
| $W$7 | Variables $x_d$42 | 0 | 0 |
| $X$7 | Variables x51 | 0 | 0 |
| $Y$7 | Variables x52 | 0 | 0 |
| $Z$7 | Variables x53 | 0 | 0 |
| $AA$7 | Variables $x_d$51 | 0 | 15 |
| $AB$7 | Variables $x_d$52 | 0 | 0 |
| $AC$7 | Variables $x_b$11 | 0 | 0 |
| $AD$7 | Variables $x_b$21 | 0 | 5 |
| $AE$7 | Variables $x_b$12 | 0 | 0 |
| $AF$7 | Variables $x_b$22 | 0 | 25 |
| $AG$7 | Variables $x_b$13 | 0 | 16.66666667 |

| | | | |
|---|---|---|---|
| $AH$7 | Variables $x_b23$ | 0 | 10 |
| $AI$7 | Variables y11 | 0 | 10 |
| $AJ$7 | Variables y21 | 0 | 6.666666667 |
| $AK$7 | Variables y12 | 0 | 10 |
| $AL$7 | Variables y22 | 0 | 30 |
| $AM$7 | Variables $\lambda_1$ | 0 | 1 |
| $AN$7 | Variables $\lambda_2$ | 0 | 1 |

Constraints

| Cell | Name | Cell Value | Formula | Status | Slack |
|---|---|---|---|---|---|
| $C$10 | $C_3$ | 10 | $C$10=$B$10 | Binding | 0 |
| $C$11 | $C_4$ | 20 | $C$11=$B$11 | Binding | 0 |
| $C$12 | $C_5$ | 15 | $C$12=$B$12 | Binding | 0 |
| $C$13 | $F_1$ | 35 | $C$13=$B$13 | Binding | 0 |
| $C$14 | $F_2$ | 25 | $C$14=$B$14 | Binding | 0 |
| $C$15 | $F_3$ | 25 | $C$15=$B$15 | Binding | 0 |
| $C$16 | $X_b1$ | 0 | $C$16=0 | Binding | 0 |
| $C$17 | $X_b2$ | 0 | $C$17=0 | Binding | 0 |
| $C$8 | $C_1$ | 30 | $C$8=$B$8 | Binding | 0 |
| $C$9 | $C_2$ | 25 | $C$9=$B$9 | Binding | 0 |
| $AI$7 | y1 | 16.66666667 | $AI$7<=40 | Not Binding | 23.33333333 |
| $AJ$7 | y2 | 40 | $AJ$7<=40 | Binding | 0 |
| $D$7 | x11 | 0 | $D$7>=0 | Binding | 0 |
| $E$7 | X12 | 0 | $E$7>=0 | Binding | 0 |
| $F$7 | x13 | 0 | $F$7>=0 | Binding | 0 |
| $G$7 | $x_d11$ | 0 | $G$7>=0 | Binding | 0 |
| $H$7 | $X_d12$ | 30 | $H$7>=0 | Not Binding | 30 |
| $I$7 | x21 | 0 | $I$7>=0 | Binding | 0 |
| $J$7 | X22 | 0 | $J$7>=0 | Binding | 0 |
| $K$7 | X23 | 0 | $K$7>=0 | Binding | 0 |
| $L$7 | $x_d21$ | 0 | $L$7>=0 | Binding | 0 |
| $M$7 | $X_d22$ | 25 | $M$7>=0 | Not Binding | 25 |
| $N$7 | x31 | 10 | $N$7>=0 | Not Binding | 10 |
| $O$7 | X32 | 0 | $O$7>=0 | Binding | 0 |
| $P$7 | X33 | 0 | $P$7>=0 | Binding | 0 |
| $Q$7 | $X_d31$ | 0 | $Q$7>=0 | Binding | 0 |
| $R$7 | $X_d32$ | 0 | $R$7>=0 | Binding | 0 |
| $S$7 | x41 | 20 | $S$7>=0 | Not Binding | 20 |

| | | | | | |
|---|---|---|---|---|---|
| $T$7 | X42 | 0 | $T$7>=0 | Binding | 0 |
| $U$7 | X43 | 0 | $U$7>=0 | Binding | 0 |
| $V$7 | $X_d41$ | 0 | $V$7>=0 | Binding | 0 |
| $W$7 | $X_d42$ | 0 | $W$7>=0 | Binding | 0 |
| $X$7 | X51 | 0 | $X$7>=0 | Binding | 0 |
| $Y$7 | X52 | 0 | $Y$7>=0 | Binding | 0 |
| $Z$7 | X53 | 0 | $Z$7>=0 | Binding | 0 |
| $AA$7 | $X_d51$ | 15 | $AA$7>=0 | Not Binding | 15 |
| $AB$7 | $x_d52$ | 0 | $AB$7>=0 | Binding | 0 |
| $AC$7 | $x_b11$ | 0 | $AC$7>=0 | Binding | 0 |
| $AD$7 | $x_b21$ | 5 | $AD$7>=0 | Not Binding | 5 |
| $AE$7 | $x_b12$ | 0 | $AE$7>=0 | Binding | 0 |
| $AF$7 | $x_b22$ | 25 | $AF$7>=0 | Not Binding | 25 |
| $AG$7 | $x_b13$ | 16.66666667 | $AG$7>=0 | Not Binding | 16.66666667 |
| $AH$7 | $x_b23$ | 10 | $AH$7>=0 | Not Binding | 10 |
| $AI$7 | y1 | 16.66666667 | $AI$7>=0 | Not Binding | 16.66666667 |
| $AJ$7 | y2 | 40 | $AJ$7>=0 | Not Binding | 40 |

#### 4.3.3.4 Comparing MILP model output with EARTHN output

Easa (1987) used the same problem in his developed computer program EARTHN which has been compared with presented MILP model.

**Table 4.6: MILP model output Vs EARTHN output**

| | MILP model Results | EARTHN results |
|---|---|---|
| Total Cost ($) | 346775 | 353597 |

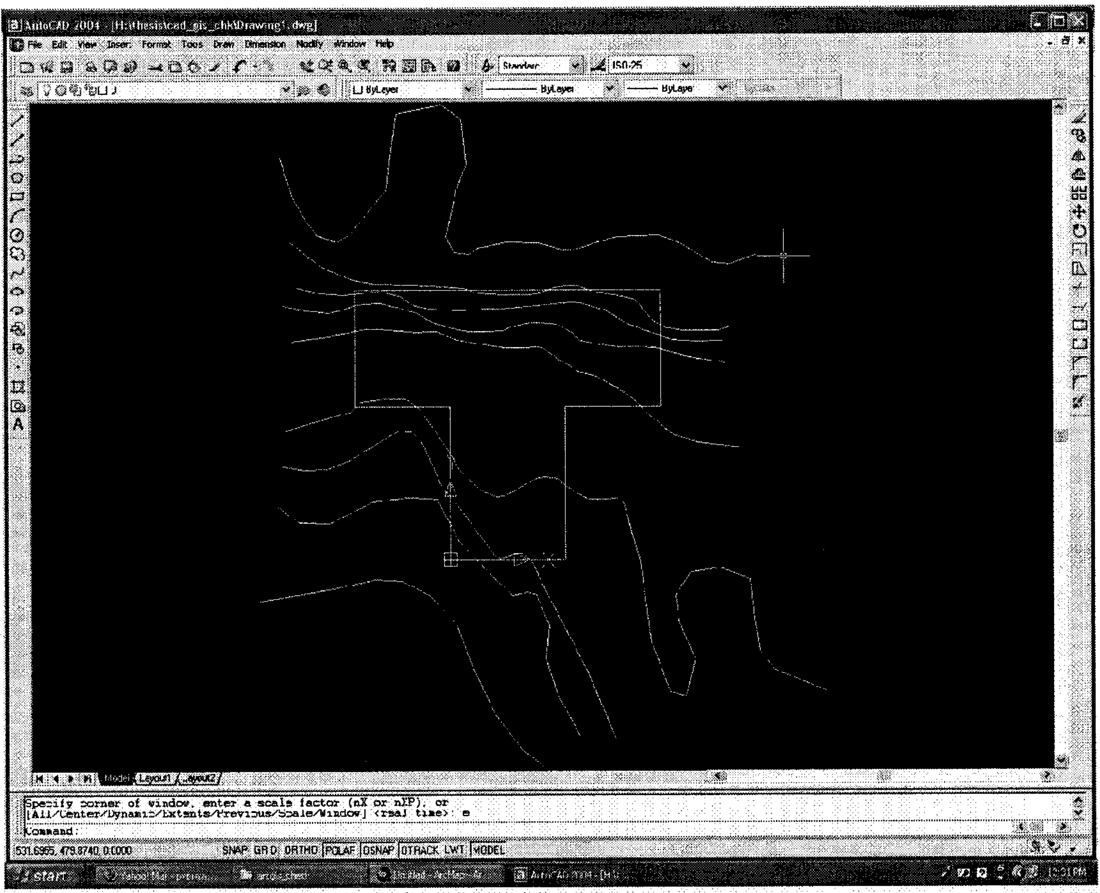
Percentage difference in calculated cost using two model = (353,597– 346,775) / 346,775 = 1.97 % which is negligible and thus verify the set up of equations in the model.

## 4.4 Case Study

To verify our proposed integrated system we have used two different examples as part of our case study. First example is a Graduate course assignment problem in which quantity determination and optimum earthmoving cost determination is to be done for a given T section. Second example is taken from Easa's work, which is basically optimization of earthmoving operations in excavation work.

### 4.1 Case Study 1

Here, we have used AutoCAD drawing file (figure 4.3), of the T section superimposed over contour map, which we had used earlier in verification work. Using 3D-Analyst extension of ArcGISs we have calculated the required volume of cut and fill for the given T section.



```
Specify corner of window, enter a scale factor (nX or nXP), or
[All/Center/Dynamic/Extents/Previous/Scale/Window] <real time>: e
Command:
```

**Fig 4.4: AutoCAD drawing files of T section**

Total Volume of cut required - 521074 Cu ft

Total Volume of fill required - 0

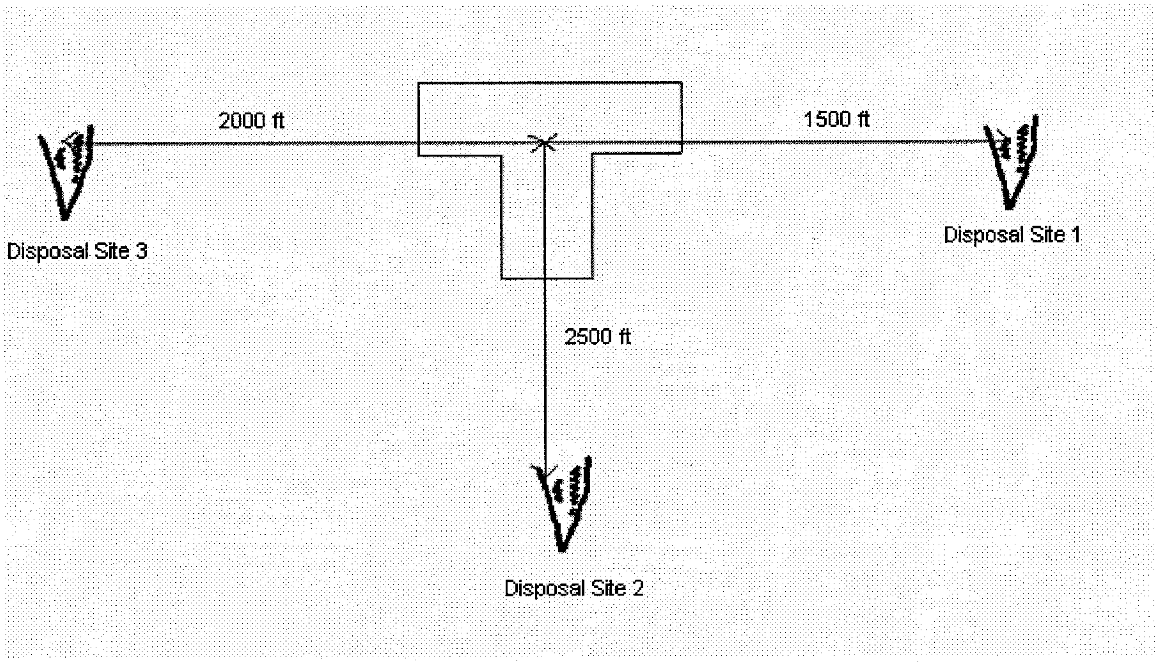


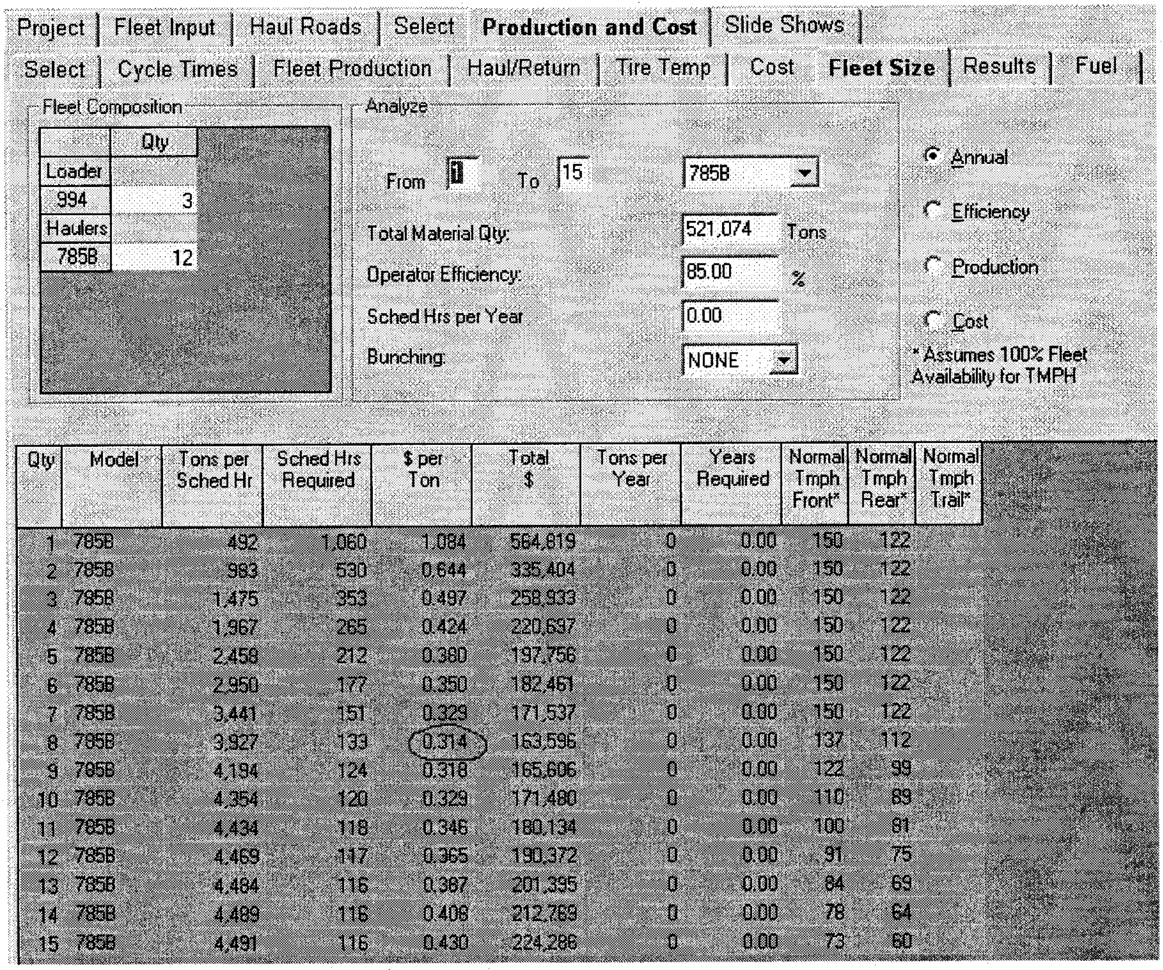
**Fig 4.5: Location of Disposal sites**

We have three disposal sites available, to dispose earth materials from T section, each having different hauling road profile and direction of haul as shown in figure 4.2. The material is dry, loose sand, weighing 2500 lb per bcy.

The earth will be excavated with a wheel load 994. The average elevation of the project is 5500 ft above sea level. Weather condition is of Temperature equal to $+6^0$ F, wind speed equal to 15 miles/hour, and no precipitation. Operator efficiency will be equal to 85%. Loader availability is 80% and cost/h is $185.

Using FPC (Fleet production and Cost Analysis), Caterpillar's commercial software, we analyzed these three options to determine most economical way of disposing excavated materials.

**Option 1 (from the centre of T section to the Disposal Site 1)** - 1500 ft with average grade of 4%, average rolling resistance of 8%, coefficient of traction of 0.40 and maximum allowable speed of 35 mph.



| | Qty |
|---|---|
| Loader | |
| 994 | 3 |
| Haulers | |
| 785B | 12 |

From 1 To 15 785B

Total Material Qty: 521,074 Tons

Operator Efficiency: 85.00 %

Sched Hrs per Year 0.00

Bunching: NONE

● Annual
○ Efficiency
○ Production
○ Cost

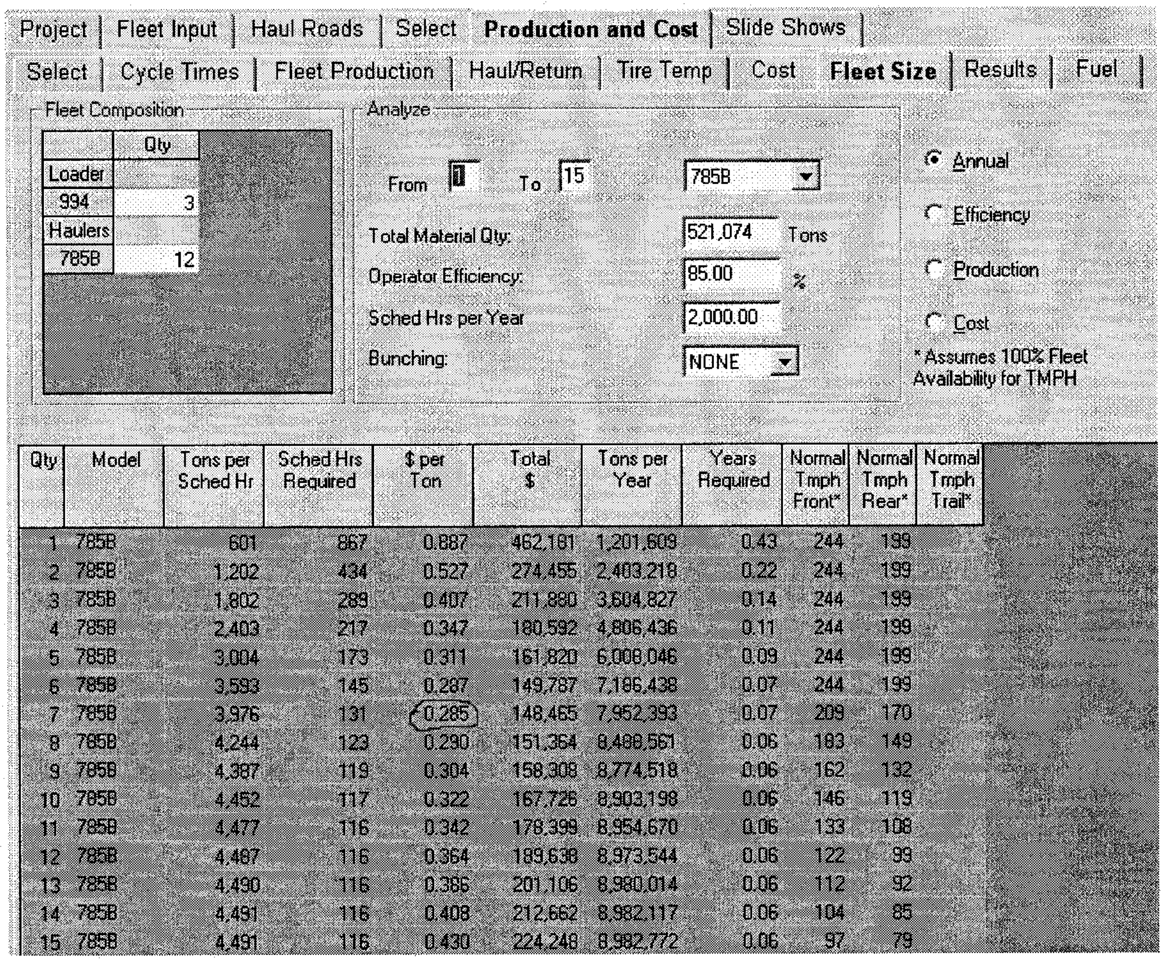
* Assumes 100% Fleet Availability for TMPH

| Qty | Model | Tons per Sched Hr | Sched Hrs Required | $ per Ton | Total $ | Tons per Year | Years Required | Normal Tmph Front* | Normal Tmph Rear* | Normal Tmph Trail* |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 785B | 492 | 1,060 | 1.084 | 564,819 | 0 | 0.00 | 150 | 122 | |
| 2 | 785B | 983 | 530 | 0.644 | 335,404 | 0 | 0.00 | 150 | 122 | |
| 3 | 785B | 1,475 | 353 | 0.497 | 258,933 | 0 | 0.00 | 150 | 122 | |
| 4 | 785B | 1,967 | 265 | 0.424 | 220,697 | 0 | 0.00 | 150 | 122 | |
| 5 | 785B | 2,458 | 212 | 0.380 | 197,756 | 0 | 0.00 | 150 | 122 | |
| 6 | 785B | 2,950 | 177 | 0.350 | 182,461 | 0 | 0.00 | 150 | 122 | |
| 7 | 785B | 3,441 | 151 | 0.329 | 171,537 | 0 | 0.00 | 150 | 122 | |
| 8 | 785B | 3,927 | 133 | 0.314 | 163,596 | 0 | 0.00 | 137 | 112 | |
| 9 | 785B | 4,194 | 124 | 0.318 | 165,606 | 0 | 0.00 | 122 | 99 | |
| 10 | 785B | 4,354 | 120 | 0.329 | 171,480 | 0 | 0.00 | 110 | 89 | |
| 11 | 785B | 4,434 | 118 | 0.346 | 180,134 | 0 | 0.00 | 100 | 81 | |
| 12 | 785B | 4,469 | 117 | 0.365 | 190,372 | 0 | 0.00 | 91 | 75 | |
| 13 | 785B | 4,484 | 116 | 0.387 | 201,395 | 0 | 0.00 | 84 | 69 | |
| 14 | 785B | 4,489 | 116 | 0.408 | 212,769 | 0 | 0.00 | 78 | 64 | |
| 15 | 785B | 4,491 | 116 | 0.430 | 224,286 | 0 | 0.00 | 73 | 60 | |

**Fig 4.6: FPC output for Option 1**

In the above figure 4.3, lowest unit cost (in $ per Ton) of earthmoving for option 1 will be 0.314 $ per Ton having fleet combination of 3 loaders and 8 haulers.

**Option 2 (from the centre of T section to the Disposal Site 2)** - 2500 ft with average grade of 2.5%, average rolling resistance of 6%, coefficient of traction of 0.45 and maximum allowable speed of 45 mph.



|  | Qty |
|---|---|
| Loader |  |
| 994 | 3 |
| Haulers |  |
| 785B | 12 |

From 1 To 15 785B

Total Material Qty: 521,074 Tons

Operator Efficiency: 85.00 %

Sched Hrs per Year 2,000.00

Bunching: NONE

● Annual
○ Efficiency
○ Production
○ Cost

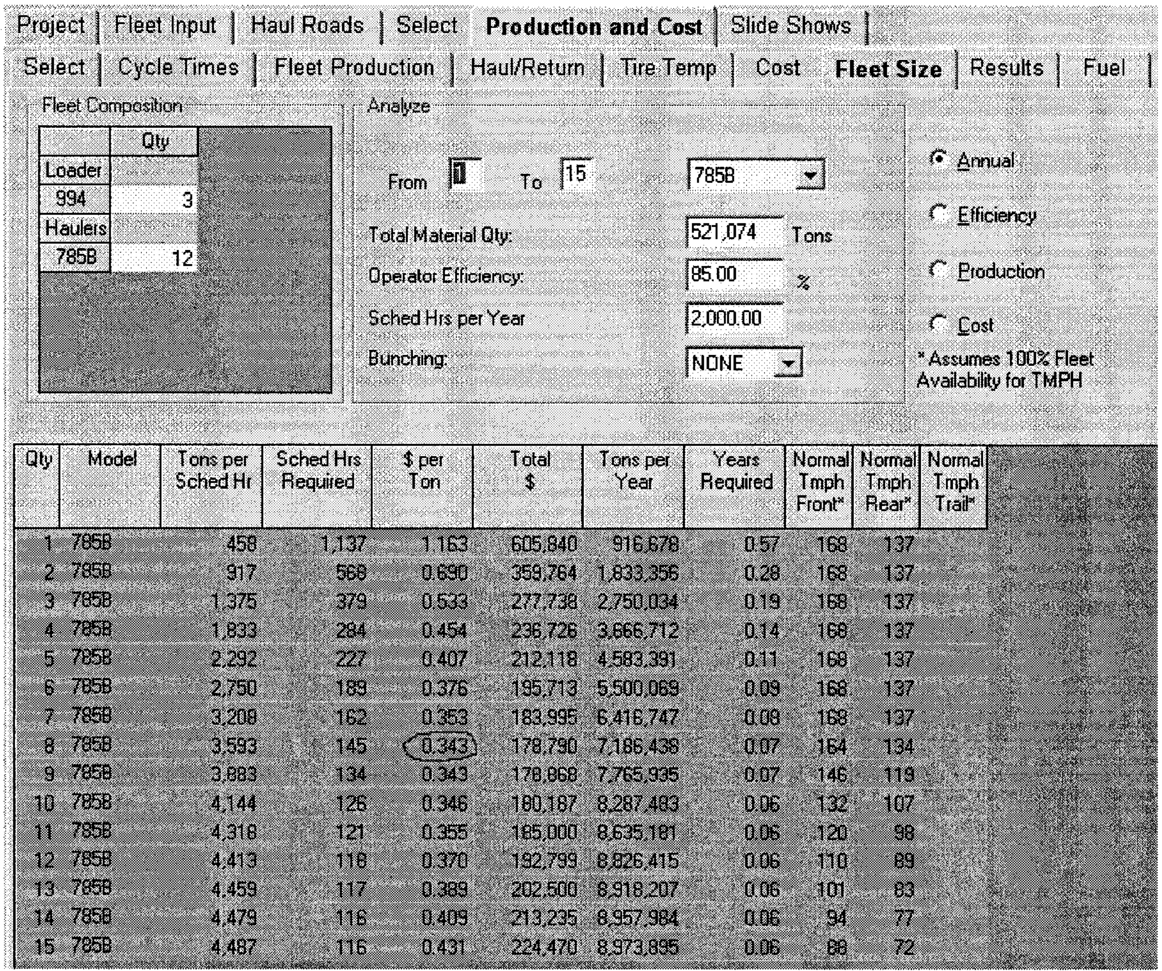
*Assumes 100% Fleet Availability for TMPH

| Qty | Model | Tons per Sched Hr | Sched Hrs Required | $ per Ton | Total $ | Tons per Year | Years Required | Normal Tmph Front* | Normal Tmph Rear* | Normal Tmph Trail* |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 785B | 601 | 867 | 0.887 | 462,181 | 1,201,609 | 0.43 | 244 | 199 |  |
| 2 | 785B | 1,202 | 434 | 0.527 | 274,455 | 2,403,218 | 0.22 | 244 | 199 |  |
| 3 | 785B | 1,802 | 289 | 0.407 | 211,880 | 3,604,827 | 0.14 | 244 | 199 |  |
| 4 | 785B | 2,403 | 217 | 0.347 | 180,592 | 4,806,436 | 0.11 | 244 | 199 |  |
| 5 | 785B | 3,004 | 173 | 0.311 | 161,820 | 6,008,046 | 0.09 | 244 | 199 |  |
| 6 | 785B | 3,593 | 145 | 0.287 | 149,787 | 7,186,438 | 0.07 | 244 | 199 |  |
| 7 | 785B | 3,976 | 131 | 0.285 | 148,465 | 7,952,393 | 0.07 | 209 | 170 |  |
| 8 | 785B | 4,244 | 123 | 0.290 | 151,364 | 8,488,561 | 0.06 | 183 | 149 |  |
| 9 | 785B | 4,387 | 119 | 0.304 | 158,308 | 8,774,518 | 0.06 | 162 | 132 |  |
| 10 | 785B | 4,452 | 117 | 0.322 | 167,726 | 8,903,198 | 0.06 | 146 | 119 |  |
| 11 | 785B | 4,477 | 116 | 0.342 | 178,399 | 8,954,670 | 0.06 | 133 | 108 |  |
| 12 | 785B | 4,487 | 116 | 0.364 | 189,638 | 8,973,544 | 0.06 | 122 | 99 |  |
| 13 | 785B | 4,490 | 116 | 0.386 | 201,106 | 8,980,014 | 0.06 | 112 | 92 |  |
| 14 | 785B | 4,491 | 116 | 0.408 | 212,662 | 8,982,117 | 0.06 | 104 | 85 |  |
| 15 | 785B | 4,491 | 116 | 0.430 | 224,248 | 8,982,772 | 0.06 | 97 | 79 |  |

**Fig 4.7: FPC output for Option 2**

In the above figure 4.4, lowest unit cost (in $ per Ton) of earthmoving for option 2 will be 0.285 $ per Ton having fleet combination of 3 loaders and 7 haulers.

**Option 3 (from the centre of T section to the Disposal Site 3) -** 2000 ft with average grade of 4%, average rolling resistance of 10%, coefficient of traction of 0.35 and maximum allowable speed of 45 mph.



| | Qty |
|---|---|
| Loader | |
| 994 | 3 |
| Haulers | |
| 785B | 12 |

From 1 To 15 785B

Total Material Qty: 521,074 Tons

Operator Efficiency: 85.00 %

Sched Hrs per Year 2,000.00

Bunching: NONE

* Assumes 100% Fleet Availability for TMPH

| Qty | Model | Tons per Sched Hr | Sched Hrs Required | $ per Ton | Total $ | Tons per Year | Years Required | Normal Tmph Front* | Normal Tmph Rear* | Normal Tmph Trail* |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 785B | 458 | 1,137 | 1.163 | 605,840 | 916,678 | 0.57 | 168 | 137 | |
| 2 | 785B | 917 | 568 | 0.690 | 359,764 | 1,833,356 | 0.28 | 168 | 137 | |
| 3 | 785B | 1,375 | 379 | 0.533 | 277,738 | 2,750,034 | 0.19 | 168 | 137 | |
| 4 | 785B | 1,833 | 284 | 0.454 | 236,726 | 3,666,712 | 0.14 | 168 | 137 | |
| 5 | 785B | 2,292 | 227 | 0.407 | 212,118 | 4,583,391 | 0.11 | 168 | 137 | |
| 6 | 785B | 2,750 | 189 | 0.376 | 195,713 | 5,500,069 | 0.09 | 168 | 137 | |
| 7 | 785B | 3,208 | 162 | 0.353 | 183,995 | 6,416,747 | 0.08 | 168 | 137 | |
| 8 | 785B | 3,593 | 145 | 0.343 | 178,790 | 7,186,438 | 0.07 | 164 | 134 | |
| 9 | 785B | 3,883 | 134 | 0.343 | 178,868 | 7,765,935 | 0.07 | 146 | 119 | |
| 10 | 785B | 4,144 | 126 | 0.346 | 180,187 | 8,287,483 | 0.06 | 132 | 107 | |
| 11 | 785B | 4,318 | 121 | 0.355 | 185,000 | 8,635,181 | 0.06 | 120 | 98 | |
| 12 | 785B | 4,413 | 118 | 0.370 | 192,799 | 8,826,415 | 0.06 | 110 | 89 | |
| 13 | 785B | 4,459 | 117 | 0.389 | 202,500 | 8,918,207 | 0.06 | 101 | 83 | |
| 14 | 785B | 4,479 | 116 | 0.409 | 213,235 | 8,957,984 | 0.06 | 94 | 77 | |
| 15 | 785B | 4,487 | 116 | 0.431 | 224,470 | 8,973,895 | 0.06 | 88 | 72 | |

**Fig 4.8: FPC output for Option 3**

In the above figure 4.5, lowest unit cost (in $ per Ton) of earthmoving for option 3 will be 0.343 $ per Ton having fleet combination of 3 loaders and 8 haulers.

We found that lowest unit cost (in $ per Ton) of earthmoving will be 0.285 $ per Ton for option 2. So, it is concluded that most economical way of moving excavated material from the given T section will be disposing all material to disposal site 2.

**4.2 Case Study 2:** Roadway earthwork allocation example problem, used by Easa (1987), has been used to verify the performance of presented MILP model. The roadway section contains five cut sections and three fill sections as shown in figure 4.8.There are two borrow pits and two disposal sites available, the capacity of each borrow pit is 40,000 cu yard and disposal sites have unlimited capacity. The shrinkage factors in embankment for cut sections and borrow pits are also shown in Table 4.7.

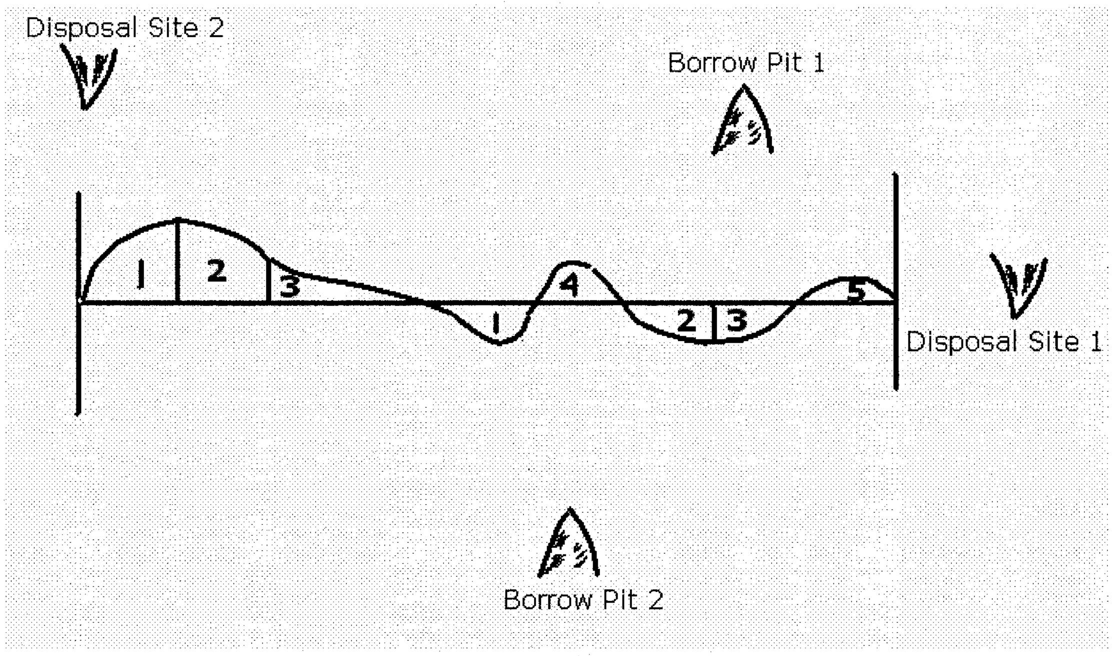


**Fig 4.9: Road Segment with available borrow pits and disposal sites**

**TABLE 4.7: Data of Estimated Earth Quantities**

| Roadway sections | | Estimated quantities (1000 cu yard) | Shrinkage factor in embankment |
|---|---|---|---|
| Cut number | 1 | 30 | 0.80 |
| | 2 | 25 | 0.80 |
| | 3 | 10 | 1.00 |
| | 4 | 20 | 0.80 |
| | 5 | 15 | 0.75 |
| Fill number | 1 | 35 | -- |
| | 2 | 25 | -- |
| | 3 | 25 | -- |
| Borrow pit number | 1 | 40 | 0.90 |
| | 2 | 40 | 1.00 |
| Disposal site number | 1 | Unlimited capacity | -- |
| | 2 | Unlimited capacity | -- |

In figure 4.8 distances between centers of consecutive cut/fill sections are 50 feet.

Distances from different borrow pits and disposal sites are:

**TABLE 4.8: Distances from borrow pits and disposal sites to the centre of T section**

| **From - To** | **Distance (ft)** |
|---|---|
| Borrow pit 1 – Fill section 1 | 250 |
| Borrow pit 1 – Fill section 2 | 150 |
| Borrow pit 1 – Fill section 3 | 100 |
| Borrow pit 2 – Fill section 1 | 100 |
| Borrow pit 2 – Fill section 2 | 100 |
| Borrow pit 2 – Fill section 3 | 150 |
| Cut Section 1 – Disposal site 1 | 450 |
| Cut Section 1 – Disposal site 2 | 100 |
| Cut Section 2 – Disposal site 1 | 400 |
| Cut Section 2 – Disposal site 2 | 150 |
| Cut Section 3 – Disposal site 1 | 350 |
| Cut Section 3 – Disposal site 2 | 200 |
| Cut Section 4 – Disposal site 1 | 250 |
| Cut Section 4 – Disposal site 2 | 300 |
| Cut Section 5 – Disposal site 1 | 100 |
| Cut Section 5 – Disposal site 2 | 400 |

We have used FPC to determine the best fleet which can move earth material between different sections. For getting FPC input, we have used the data of case example used in Alkass, El-Moslmani and AlHussein (2003) work.

The material is dry, loose sand, weighing 2700 lb per bcy. The earth will be excavated with a wheel load 994. The average elevation of the project is 6300 feet above sea level. Weather condition is of Temperature equal to $+5^0$ F, wind speed equal to 20 miles/hour, and no precipitation. Operator efficiency will be equal to 85%. Loader availability is 78% and cost/h is $185.

Assume that all hauling works from cut to fill sections have been done by using fleet f having production level (1000 cu yd) is 4, from cut to disposal sites have been done by fleet $f_d$ having production level (1000 cu yd) is 5 and from borrow pits to fill sections have been done by fleet $f_b$ having production level (1000 cu yd) is 6.

**Table 4.9: Calculated unit costs for earthwork between cut and fill sections ($ per 1,000 cu yd)**

| From cut section number | Unit cost to fill section number | | | Unit cost to disposal site number | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 |
| 1 | 6235 | 7500 | 8300 | 2735 | 460 |
| 2 | 4600 | 4920 | 5355 | 2740 | 875 |
| 3 | 3060 | 3800 | 4540 | 3205 | 1550 |
| 4 | 1870 | 1870 | 3070 | 670 | 1500 |
| 5 | 4300 | 3670 | 2800 | 360 | 3200 |

**Table 4.10: Calculated unit costs for earthwork between borrow pits and fill section ($ per 1,000 cu yd)**

| From borrow pit | Unit cost to fill section | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| 1 | 2465 | 1700 | 1125 |
| 2 | 2850 | 1980 | 1645 |

### 4.3.3.2 Problem Statement

Minimize $Z = 6235X(1,1) + 7500X(1,2) + 8300X(1,3) + 4600X(2,1) + 4920X(2,2) + 5355\,(2,3) + 3060X(3,1) + 3800X(3,2) + 4540X(3,3) + 1870X(4,1) + 1870X(4,2) + 3070X(4,3) + 4300X(5,1) + 4300X(5,2) + 3670X(5,3) + 2735X_d(1,1) + 460X_d(1,2) + 2740X_d(2,1) + 875X_d(2,2) + 3205X_d(3,1) + 1550X_d(3,2) + 670X_d(4,1) + 1500X_d(4,2) + 360X_d(5,1) + 3200X_d(5,2) + 2465X_b(1,1) + 1700X_b(1,2) + 1125X_b(1,3) + 2850X_b(2,1) + 1980X_b(2,2) + 1645X_b(1,3)$

Subject to the contraints

$$X(1,1) + X(1,2) + X(1,3) + X_d(1,1) + X_d(1,2) = 30$$

$$X(2,1) + X(2,2) + X(2,3) + X_d(2,1) + X_d(2,2) = 25$$

$$X(3,1) + X(3,2) + X(3,3) + X_d(3,1) + X_d(3,2) = 10$$

$$X(4,1) + X(4,2) + X(4,3) + X_d(4,1) + X_d(4,2) = 20$$

$$X(5,1) + X(5,2) + X(4,3) + X_d(5,1) + X_d(5,2) = 15$$

$$0.8X(1,1) + 0.8X(2,1) + X(3,1) + 0.8X(4,1) + 0.75X(5,1) + 0.9X_b(1,1) + X_b(2,1) = 35$$

$$0.8X(1,2) + 0.8X(2,2) + X(3,2) + 0.8X(4,2) + 0.75X(5,2) + 0.9X_b(1,2) + X_b(2,2) = 25$$

$$0.8X(1,3) + 0.8X(2,3) + X(3,3) + 0.8X(4,3) + 0.75X(5,3) + 0.9X_b(1,3) + X_b(2,3) = 25$$

$$X(1,1,f)/4 + X(1,2,f)/4 + X(1,3,f)/4 + X(2,1,f)/4 + X(2,2,f)/4 + X(2,3,f)/4 + X(3,1,f)/4 + X(3,2,f)/4 + X(3,3,f)/4 + X(4,1,f)/4 + X(4,2,f)/4 + X(4,3,f)/4 + X(5,1,f)/4 + X(5,2,f)/4 + X(5,3,f)/4 + X_d(1,1,f_d)/5 + X_d(1,2,f_d)/5 + X_d(2,1,f_d)/5 + X_d(2,2,f_d)/5 + X_d(3,1,f_d)/5 + X_d(3,2,f_d)/5 + X_d(4,1,f_d)/5 + X_d(4,2,f_d)/5 + X_d(5,1,f_d)/5 + X_d(5,2,f_d)/5 + X_b(1,1,f_b)/6 + X_b(1,2,f_b)/6 + X_b(1,3,f_b)/6 + X_b(2,1,f_b)/6 + X_b(2,2,f_b)/6 + X_b(2,3,f_b)/6 = 25$$

#### 4.3.3.3 Computer Output

The above optimization problems is solved using Microsoft Excel Solver which gives optimum value of decision variables, i.e., optimum quantity of materials need to be moved between different cut sections (or borrow pits) to fill sections (or disposal sites) to get optimum (minimum) cost of completing the project within project duration of 25 days.

**Table 4.11: Solver Output with 25 days project duration as constraint.**

**Microsoft Excel 10.0 Answer Report**

Target Cell (Min)

| Cell | Name | Original Value | Final Value |
|---|---|---|---|
| $C$24 | Z = Variables | 0 | 564671.9435 |

Adjustable Cells

| Cell | Name | Original Value | Final Value |
|---|---|---|---|
| $D$7 | Variables x11 | 0 | 18.75 |
| $E$7 | Variables x12 | 0 | 10.9375 |
| $F$7 | Variables x13 | 0 | 0 |
| $G$7 | Variables $x_d11$ | 0 | 0 |
| $H$7 | Variables $x_d12$ | 0 | 0.312500001 |
| $I$7 | Variables x21 | 0 | 0 |
| $J$7 | Variables x22 | 0 | 20.3125 |
| $K$7 | Variables x23 | 0 | 4.6875 |
| $L$7 | Variables $x_d21$ | 0 | 0 |
| $M$7 | Variables $x_d22$ | 0 | 0 |
| $N$7 | Variables x31 | 0 | 0 |
| $O$7 | Variables x32 | 0 | 0 |
| $P$7 | Variables x33 | 0 | 10 |
| $Q$7 | Variables $X_d31$ | 0 | 0 |
| $R$7 | Variables $X_d32$ | 0 | 0 |
| $S$7 | Variables x41 | 0 | 20 |
| $T$7 | Variables x42 | 0 | 0 |
| $U$7 | Variables x43 | 0 | 0 |
| $V$7 | Variables $X_d41$ | 0 | 0 |
| $W$7 | Variables $X_d42$ | 0 | 0 |

|  |  |  |  |
|---|---|---|---|
| $X$7 | Variables x51 | 0 | 0 |
| $Y$7 | Variables x52 | 0 | 0 |
| $Z$7 | Variables x53 | 0 | 15 |
| $AA$7 | Variables $x_d51$ | 0 | 0 |
| $AB$7 | Variables $x_d52$ | 0 | 0 |
| $AC$7 | Variables $x_b11$ | 0 | 0 |
| $AD$7 | Variables $x_b21$ | 0 | 0 |
| $AE$7 | Variables $x_b12$ | 0 | 0 |
| $AF$7 | Variables $x_b22$ | 0 | 0 |
| $AG$7 | Variables $x_b13$ | 0 | 0 |
| $AH$7 | Variables $x_b23$ | 0 | 0 |

Using Excel Solver, the optimum (minimum) cost of earthmoving for the above case example, with 25 days project duration as time constraint, has been estimated as $ 564671.9435. For that minimum cost, optimum quantities of materials to be moved between different sections can be seen in the above Excel table.

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATION

## 5.1 Conclusions

This study presents methodology for integrated systems for estimating earthmoving production, selecting fleet and optimizing earthmoving operation work in a computerized environment. To achieve these three objectives the model uses GIS, FPC and MILP as its three components. The model estimates the cut and fills quantities for earthmoving operations by using Arc View, GIS application software. FPC has been used for optimum fleet selection which can move the earth between different sections at minimum cost. Mixed-Integer Linear Programming is used for optimizing earthmoving operation between different cut sections or borrows pits and fill sections or disposal sites using selected fleet within the project duration.

In our integrated system methodology, we have used AutoCAD for drawing three-dimensional contour map of the natural ground profile, which has been superimposed over map of proposed ground profile. This AutoCAD file is exported to ArcGIS where DTM is generated using TIN networks. Using 3D-Analyst extension of ArcGIS, we get cut/fill quantities for different sections which is used as input in FPC, apart from hauling road profile data and haulers and loaders characteristics, to select best fleet. In FPC, we get different unit costs for the selected optimum fleet (having minimum unit cost) for different hauling road characteristics. These unit costs for material movements between different cut and fill sections, borrow pits and disposal sites, are used to formulate Mixed-

Integer Linear Programming equations. Required quantities of cut and fill, the capacities of the landfills and borrow pits and duration of project is considered as constraints. This MILP model is run on Microsoft Excel add-in software, Solver, to get optimum quantities of materials to be moved between different sections so as to have minimum cost of earthmoving.

## 5.2 Limitations

Physical integration of the three components of the presented system, GIS, FPC and MILP, is not done due to restriction in professional software.

## 5.3 Verifications

Three separate numerical examples are presented to verify the results of the three components of the presented system and highlight its capabilities. The first case result is compared with the manually calculated results and the percentage difference of two results is found to be 2.6% which is very less. Second case result is compared with FLSELECTOR results and the best fleet combination have minimum cost per Ton as 0.426 $ and 0.312 $ respectively. In the third case, comparing MILP model output with EARTHN output, difference in total cost calculation is found to be 1.97 % which is negligible.

## 5.4 Case Study

To verify our proposed integrated system we have used two different examples as part of our case study. First example is a Graduate course assignment problem for a given T section in which quantity determination has been done using ArcGIS software and optimum earthmoving cost determination has been done using FPC software. Second example is taken from Easa's work, which is basically cost optimization of earthmoving operations in road excavation work using Linear Programming.

### 5.5 Research Contributions

This study presents a methodology of integrated system for quantity take-off, fleet selection and cost optimization of earthmoving operations. The contributions of this study can be summarized as:

- Proposed an algorithm for determining longitudinal interval for a part of road segment.
- Quantity takeoff determination using ArcGIS.
- Fleet selection using Caterpillar FPC software.
- Presented an optimization methodology based on Mixed-Integer Linear Programming for earthmoving operations.
- Successfully run the presented methodology based on MILP in Microsoft Excel Solver and got satisfactory results.

The presented integrated system can assist engineers, contractors and clients of earthmoving projects in getting the accurate earthwork quantities, selecting best equipment fleet and getting optimum quantity of earthwork materials to be moved between different sections so as to finish the project in minimum time and within budget with optimum use of available resources.

## 5.6 Recommendations for Future Research work

- Research can be extended to find a way for physical integration of the three components of the presented system, i.e. GIS, FPC and MILP.
- Automated scheduling can be done using the optimization results of earthwork movements.
- Three dimensional (3D) movements of earth can be accommodated to get exact distance of haul.

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