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Innovative Methodology for Location-based Scheduling and Visualisation of Earthworks in Road Construction Projects

by

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Abstract

This thesis focuses on the development of an innovative location-based scheduling methodology and a computer-based model for improving earthwork operations in road construction projects. Analysis of existing planning and scheduling practices in road construction projects conducted in the course of this research concluded that planning, scheduling and resource allocation are largely dependent on subjective decisions. Also, shortcomings exist due to the distinct characteristics of earthworks, e.g. one-off projects with uncertain site conditions and soil characteristics, causing delays and cost overruns of projects.

The literature review found that existing linear scheduling methods provide inaccurate location-based information about earthworks and fail to integrate different productivity rates. A survey was used to capture and analyse industrial practices and issues related to delays and cost overruns. This analysis revealed that the accurate location-based information is vital for efficient resource planning and progress monitoring. Following these findings, a theoretical framework and specification were developed to automate location-based scheduling and visualisation of information. A prototype model was developed by integrating road design data, sectional quantities, productivity rates, unit cost, site access points, and arithmetic algorithms. The algorithms underpinning the model enable the generation of time-location plans automatically as a key output of the model. Weekly progress profiles, space congestion plans, and cost S-curves are the other outputs. A cut-fill algorithm was developed to identify optimum quantities of earthwork and its associated costs.

Experiments were conducted with design data provided by a road construction company to demonstrate the model's functionality. Sensitivity analysis was used to identify the critical factors relating to earthwork scheduling. It was found that the model is capable of generating time-location plans, considering the critical factors and location aspects. Finally, the model was evaluated using a case study and validated by road construction professionals using an indirect comparison method. It was concluded that the model is a valuable tool for producing location-based scheduling, optimising resource planning and assisting in the communication of scheduling information from the location viewpoints in the earthwork projects.

DEDICATION

To my parents

Sunandan and Sagar Devi

Who motivated and encouraged me at all times during the study

DECLARATION

No portion of this research referred to in this thesis has been submitted in support of an application for another degree or any other university. Other sources of information have been used by acknowledging them.

Signature:

Date:

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List of Abbreviations

4DCAD	Four-Dimensional Computer Aided Design
BoQ	Bill of Quantity
CPM	Critical Path Method
CPT	Construction Planning Technique
DGM	Data Generation Module
EBP	End Balance Point
EHD	Economical Haulage Distance
GDP	Gross Domestic Product
GVA	Gross Value Added
IT	Information Technology
LBMS	Location-based Management System
LBP	Location-based Planning
LBPS	Location-based Planning System
LBS	Location-based Scheduling
LCM	Linear Scheduling Method
LOB	Line-of-Balance
LP	Linear Programming
LPM	Last Planner Method
MHD	Mass Haul Diagram
NE	No Experience
NAO	National Audit Office
PERT	Programme Evaluation and Review Techniques
RPM	Repetitive Project Model
SBP	Start Balance Point
SCM	Space Congestion Module
SCP	Space Congestion Plan
SD	Standard Deviation
SQL	Structured Query Language
TDD	Time Distance Diagram
TILOS	Time Location Planning Software
TP	Turning Point

Chapter 1

INTRODUCTION

1.1 Introduction

The construction industry has distinct characteristics in comparison with other industries. These include one-off projects, site production, and temporary organisation (Koskela, 2000). The planning and scheduling processes of construction projects are challenging tasks and the decisions taken in the planning stage have a major impact on the success of project execution from its early imaginary stage to the project completion stage (Ahmed and Walid, 2002). Planning and scheduling tasks involve careful allocation of resources along with space/location in linear construction projects. Resource allocation includes the distribution of construction equipment, materials and workers at the correct locations when necessary throughout construction operations. Failure to select the optimum activities and the correct allocation of resources in relation to locations can have an adverse effect on project cost, duration, space congestion, and the safety of site works in construction projects (Mawdesley et al, 2004).

In order to innovate and to contribute to the enhancement of the scheduling process, this research study was undertaken to develop a methodology and a computerised model for the earthworks scheduling and visualisation of the scheduling information from a location viewpoint in road construction projects. The research study devises a decision-support tool to assist construction managers in resource scheduling and to communicate the scheduling information effectively in relation to location throughout earthwork construction operations. The study examines existing techniques and tools already used to develop a design specification for a prototype model, using Information Technology (IT) techniques relevant to the construction industry for information storage, processing, visualisation and communications.

The remainder of this chapter outlines the research background, statement of problem, objectives, methodology, contributions, scope and limitations, and organisation of this thesis, with a brief introduction to each chapter.

1.2 Research Background

This section presents the overview of the construction industry and road construction, and outlines the importance and characteristics of earthwork operations.

1.2.1 Overview of construction industry

The construction industry represents a significant part of the Gross Domestic Product (GDP) and employment worldwide. It plays an important role in reactivating economic cycles following a downturn and represents one of the key economic indicators. For example, the second largest output in the EU is the UK construction output, and construction contributes 8.2% of the national Gross Value Added (GVA) according to an annual report of UK construction statistics (BERR, 2007).

A report published by the National Audit Office (NAO) UK in 2005 indicated that 45% of construction projects carried out by government departments/agencies were over budget, and 37% of construction projects were delivered behind schedule. It revealed that a key contributory factor to the poor performance of construction projects was the lack of effective planning, streamlined procurement and communication amongst construction companies, consultants, clients, subcontractors and suppliers (NAO, 2005).

A report produced by Bourn (2007), and published by NAO, highlighted that road development and improvement projects costs were 40% higher than the initial cost estimates prepared before 2003 (considered as the base year). The largest increase in construction costs occurred due to inflation, design changes, underestimating of structural requirements, changes in interconnecting roads, meeting stakeholder requirements, increased complexity of projects, and unforeseen works such as the discovery of archaeological remains and weather patterns. The other major factors included in increased production costs were the cost of preliminary works (site setup, erection of temporary facilities and site transport), and the costs of re-routing utilities (gas, water and electricity). The Bourn report (2007) pointed out that accurate

estimating could reduce the variation in project cost and time. The development of an advanced planning and scheduling system for road construction projects can therefore be considered as an important contribution towards reducing construction cost by providing improved scheduling and visualisation of the processes involved.

1.2.2 Overview of road construction

Castro (2005) conducted a study that analysed a total of 145 road construction projects in both Europe and Africa, including new roads, refurbishing roads and upgrading roads, but excluding gravel roads, tunnels and bridges. He found that the earthworks component represented around 19.58% of the monetary value of all activities in road construction projects (see Table 1.1 below).

Table 1.1 Percentage of earthworks, drainage and pavement in road works (Castro, 2005)

Earthworks	Drainage	Pavement	Road Furniture	Minor Structures	Miscellaneous	Site Establishment
19.58%	11.78%	44.58%	6.10%	4.35%	8.89%	4.72%
					Total	100%

However, the earthworks component in terms of monetary value was found to be different when the main contracts included only three activities: earthworks, drainage, and pavement separately (see Table 1.2).

Table 1.2 Percentage of earthworks, drainage and pavement in road works (Castro, 2005)

Type of works	Area	Earthworks	Drainage	Pavement
New Road	Europe	41.22	15.85	42.93
	Africa	26.26	22.22	51.52
Rehabilitation	Europe	4.99	12.50	82.51
	Africa	1.09	7.69	91.22
Up-Grading	Europe	21.28	20.30	58.42
	Africa	11.68	17.21	71.11

The results shown in Table 1.2 indicate that the earthworks component represents 41.22% in the new road projects, 4.99% in the rehabilitation or refurbishment projects, and 21.28% in the road upgrading projects in Europe; in Africa, the

earthworks component represented 26.26% in new road projects, 1.09% in rehabilitation, and 11.68% in upgrading projects (Castro, 2005).

The values presented in Table 1.2 confirm that the percentage of the earthworks component varies according to the topographical location and type of construction project. Earthwork activity is the most important activity because it controls overall progress; it contributes the highest cost, and affects the sequence of other activities. Exploration of earthworks operations in detail is needed to develop a computer-based model. The following section outlines the activities undertaken.

1.2.3 Overview of earthwork operations

Earthwork activities are the most uncertain and changeable in road construction due to exposure to unpredictable factors during construction operations; for example, weather factors, geotechnical alterations, water table variations, site constraints and environmental restrictions. They involve a wide range of activities: excavation, hauling, spreading, and compacting of the soil mass to achieve the desired ground level characteristics in a construction project. Figure 1.1 presents a workflow map of construction activities that take place, from start to finish.

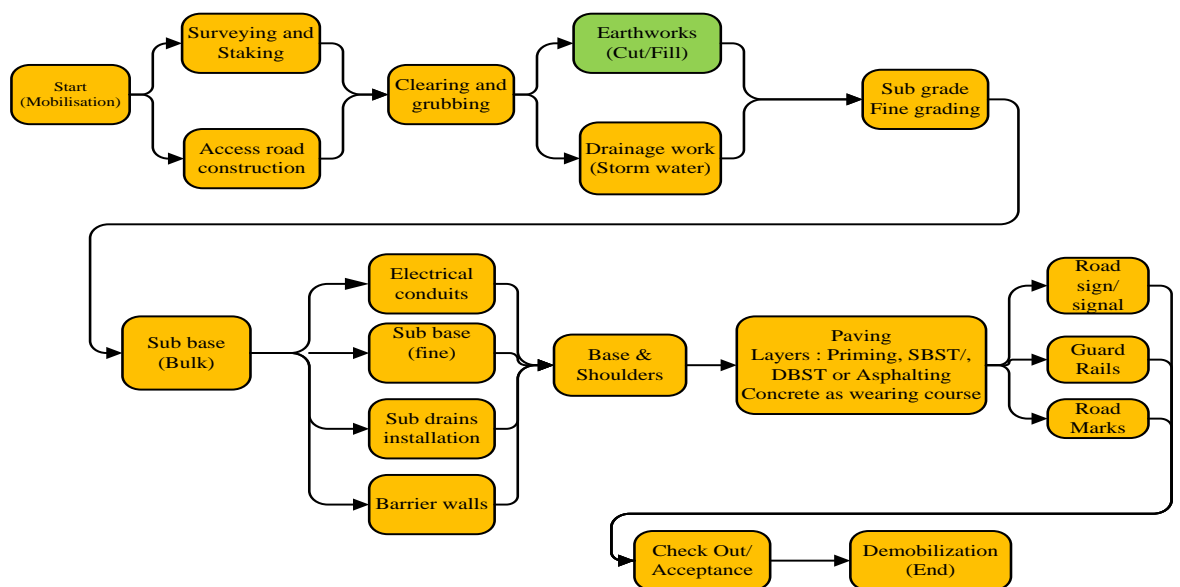


Figure 1.1 Map of workflow of tasks in a road construction project (Hassanein and Moselhi, 2004)

According to Kim and Russell (2003), the earthwork operations are subdivided into three major phases (see Figure 1.2). The figure outlines the sequence of earthwork processes arranged under three phases: site preparation, grade development (cut-fill operations), and finish works.

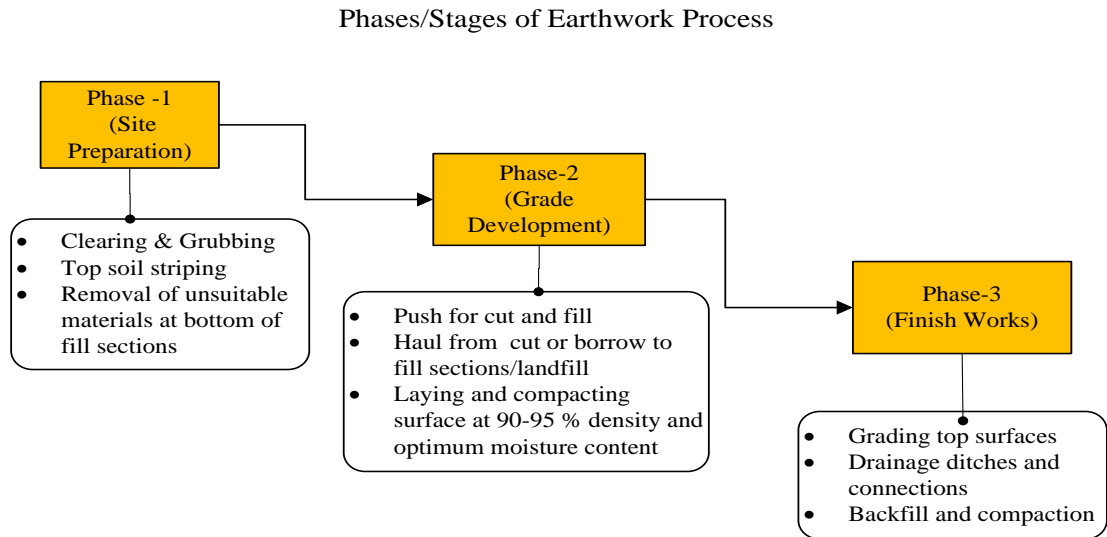


Figure 1.2 Process mapping of earthwork operations with detailed activities (Kim and Russell, 2003)

The earthwork activity also affects the rest of project performance (Kim and Russell, 2003). Therefore, it is necessary to enhance earthwork planning and scheduling processes by considering location aspects in road construction projects.

1.3 The Research Rationale

Earthworks have unique characteristics and take place at the early stages of construction, particularly in linear construction projects such as roads, railways, and pipelines. They constitute a major component in road construction projects, absorb high costs, and there is a need to deal with haul distances for balancing cutting and filling quantities in a cost-effective manner. These activities also direct the sequencing of the rest of the road activities. Decisions taken during the planning stage of earthwork operations have a high impact on the overall performance of the project (Kim and Russell, 2003; Mawdesley et al, 2004).

Space or location congestion occurs when the space requirements of an activity interfere with another activity's space requirement. Space congestion causes several

problems, including delay in work progress, loss in productivity, and incremental increase of resource wastage at construction sites (Akinici et al, 2002 and Dawood et al, 2006).

Moreover, Jongeling and Olofsson (2007) highlighted that location-based scheduling provides an alternative solution for planning of workflow, resources and crews in construction projects. Andersson and Christensen (2007) conducted three case studies and found that three important applications of location-based scheduling improved schedule overview, establishment of workflows and project control. They also found that the location-based scheduling has a practical application in the site management of building projects.

According to Kenley and Seppanen (2010, p123), the main significance of location-based planning is to arrange the productivity of work activities according to locations. It assists in organising both activity and work sequence for production efficiency. Location-based scheduling can be used to determine the impact of control actions taken to recover from a delay from the original schedule. The location-based scheduling tools are also important for time claim assessment with regard to costs in construction projects.

With consideration of the previous factors, the development of an effective simulation model will help project planners and construction managers make decisions using a systemic approach rather than using 'rule of thumb'/previous experiences.

1.4 The Problem Statement

The effective applications of planning and scheduling techniques such as Critical Path Method (CPM), and Programme Evaluation and Review Technique (PERT) are limited because the activities associated with linear construction projects such as roads, railways and pipelines are fundamentally different from building projects. Most of the work activities in road construction projects are linear activities. A linear scheduling method has the potential to provide significant enhancement in terms of

visual representation of working locations, and to progress monitoring because the method allows the project schedulers and construction managers to plan road construction projects visually and determine the controlling activity path and locations (Hamerlink and Yamin, 2000).

Arditi et al (2002) argued that earthwork projects require a separate planning task for each project individually due to the distinctive characteristics of earthworks. CPM networks are more suitable for large complex projects; however, Line-of-Balance (LOB) and Linear Scheduling Method (LSM) are more practical for the repetitive and linear construction projects (Mawdesley et al, 2004).

Arditi et al (2002) identified that the CPM algorithm is designed for duration optimisation rather than dealing with resource constraints associated with repetitive construction projects. The CPM algorithm fails to ensure the smooth transfer of crews from unit to unit without conflicts in activities, space/location and resource idleness. This results in problems in the hiring and procurement of equipment, labour and materials during linear project activity.

According to Mattila and Park (2003), the subjective division of repetitive activities from location to location, the inability to schedule the continuity of resources and display the activity rates of progress, and failure to provide any information on performed work on a project site are key limitations of CPM. The LSM is used to reduce the interruption of continuous or repetitive activities, to maintain resource continuity, and to determine the working locations during progress on any given day from the schedule.

DynaRoadTM(2006) developed a computer model (software) for producing a mass-haul plan and location-based schedule for earthwork activities, particularly in linear construction projects. This model failed to generate a sufficiently detailed location-based schedule capable of providing accurate information of weekly locations throughout construction operations. In earthwork operations, the quantities of cutting and filling vary from location to location in a road section and therefore the resources needed to manage the processes vary according to the quantities of earthwork required at each location.

From the above observations, it was derived that innovative research efforts to date, attempting to address earthwork planning problems and scheduling issues, have failed to produce sufficiently precise scheduling of tasks from a location perspective. The research background and problems presented above show that there is a need for an effective location-based planning and scheduling system for earthwork operations. This research study, therefore, focuses on improving linear scheduling methods by developing a prototype model that can provide weekly or daily information relating to working locations throughout the earthwork operations. The next section includes the study's aim, objective, research methodology, scope, limitations and contribution to knowledge.

1.5 Research Descriptions

The following subsections describe the research undertaken in this thesis and include research hypothesis, research aim and objectives, research methodology, research scope and limitations, and research contributions.

***Research Hypothesis:** “A location-based schedule generated by a prototype model provides accurate scheduling information of working locations on a weekly or daily basis. The location-based schedule assists construction managers in allocating the critical resources and communicating the scheduling information from the location aspects.”*

1.5.1 Research aim and objectives

The aim of this research study is to enhance earthworks scheduling and to visualise the scheduling information from location aspects by developing a methodology and a prototype model. The model helps to analyse the effects of locations in resource planning from location viewpoints of earthworks components in road construction projects.

To achieve this aim, the following objectives were set:

1. To review the state-of-the-art techniques and tools utilised in earthwork planning, scheduling and visualisation of construction processes, and to identify knowledge gaps in the application of such techniques and tools.
2. To review the existing practices and limitations, and to encapsulate construction site knowledge of earthwork operations, in linear construction projects.
3. To design a framework of a prototype by integrating productivity data, road design data and construction site knowledge of earthwork operations in road projects.
4. To develop a prototype model to semi-automate the generation of location-based scheduling (time-location plan), space congestion plans, progress profiles and location-based costing for the earthwork component.
5. To develop an algorithm using linear programming techniques and integrating it with the prototype model to optimise planning parameters such as cut-fill quantities and locations.
6. To perform experiments and sensitivity analysis using case studies derived from road construction projects for validating the functionalities of the prototype model.

1.5.2 Research methodology

Kothari (2008, p5) suggested that there are two basic research approaches: quantitative and qualitative. The quantitative approach involves the generation of data in quantitative form by quantitative analysis in a proper and rigid way, whereas the qualitative approach deals with subjective judgment, i.e. attitudes, opinions and behaviour. The simulation approach, which is part of the quantitative approach, is useful in building models for understanding the future conditions. Fitzgerald et al (2002, p50) stated that prototyping is a technique and a philosophy for system

development. The prototyping approach is utilised widely and is popular in the development of computer-based modelling because of rapid delivery of the systems and the precise determination of system requirements (Dennis et al, 2008). Therefore, the prototyping approach was selected as the research methodology to accomplish the aim of this research study. Other techniques, including a literature review, a survey of construction industries using semi-structured interviews, development of a prototype model, and the demonstration and validation of the model functionalities with case studies, were utilised to achieve the research objectives. The research methods that are used in this research study are described as follows:

- A comprehensive literature review was carried out to identify the current trends and the state-of-the-art techniques utilised in the earthwork planning, scheduling, optimisation and visualisation of earthwork operations. The review was conducted by analysing the existing techniques in earthwork operations, thereby meeting the criteria of the first objective.
- A construction industries survey was conducted by designing a questionnaire circulated to 30 construction companies involved in linear construction projects, using random sampling. The survey was carried out by interviewing the companies and obtaining the responses via a questionnaire to identify issues in existing practices, critical factors affecting earthworks scheduling, and the potential application stage of the model proposed in earthwork operations. This satisfies the second objective.
- To further address the second objective, a review of construction processes was also carried out by interviewing a construction manager of a construction company to understand, in depth, the detailed processes involved in road construction projects and to identify the stages where the developed model could be applied in construction operations.
- A framework of a prototype was outlined by incorporating the findings from the literature review, industry review and construction industry survey. The framework was developed by integrating road design data, sectional quantity of

cuts and fills, variable productivity data, arithmetic algorithms for modelling earthwork operations, construction site knowledge, working lengths and site access points. The specification of the model was arranged into inputs, process and outputs. This addresses the third objective of the study.

- To meet the fourth objective, a prototype model was developed using a Microsoft Excel platform with a user interface developed through Visual Basic for Applications (VBA) programming language. The VBA was used in integration of the data generation module, the visualisation module, the “RoadSim” database, and Excel solver features. Various VBA macros were developed to provide the different functionalities of the model.
- The fifth objective was addressed by developing a cut-fill optimisation module, which was developed by integrating the mass haul diagram, unit cost data and Excel solver. The Excel solver has been developed using the Simplex algorithm. The mass haul diagram and construction knowledge were used to identify the possible site access points and to generate a cut-fill matrix table of earthwork.
- To meet the sixth objective, experiments were conducted with the developed prototype model using case studies and design data collected from recently completed road projects. The functionality of the model was validated by demonstrating it to road construction professionals. Sensitivity analysis was carried out to analyse the impacts of critical factors such as equipment type, soil characteristics and access points for resource planning and visualisation of weekly progress profiles.

1.5.3 Research contributions

The contributions to knowledge from this research study are as follows:

1. A prototype model constituted by a new methodology generates location-based schedules, space congestion plans, weekly progress profiles and the cost profiles of earthwork from location aspects throughout construction processes.

2. The model helps to analyse the impact of different factors associated with productivity data and location attributes by means of “what-if scenarios” in earthworks scheduling, and it helps to visualise the scheduling information of resources from the location viewpoint.
3. Location-based schedules generated by the prototype model assist construction managers in resource planning from a location aspect. This includes mobilising suitable sets of equipment and materials at correct locations and avoiding space congestion at an early stage of earthworks.
4. Development of a platform where the prototype model can be further tailored to extend to other road activities like pavements and road furniture, and to other linear construction projects like railways, canals, and pipelines.
5. Research contributions were presented, reviewed and validated by the publication of research papers in journals and in conference proceedings.

1.5.4 Research scope and limitations

The scope of this research study is limited to the earthworks component in new road construction projects. In the study, a typical cross-section, having regular side-slopes and a transverse-slope, was assumed for analysing and generating location-based scheduling and earthwork progress profiles. The modelling of rock excavation from the rest of earthwork operations was excluded in the development of the prototype. Other structures such as intersections, bridges and tunnels, which are considered as separate projects for the planning, design and construction purposes in road projects, are not included in the development of the prototype. The prototype is limited, with a sectional length of 1.5 to 7km for generating the location-based earthwork schedules, and provides a tool for the visualisation of scheduling information from the location aspects in a linear construction project.

The weather, which has a high influence in determining the rates of earthwork productivity, is excluded in the study because of the complexity in productivity simulation and the uncertainty of weather patterns according to the topographical

locations of a construction site. To mitigate the risk associated with adverse weather conditions, the effects of weather in the construction schedule are, however, considered by planners as a contingency plan by adding a few days. Considering the topographical conditions and the weather patterns of a construction site, the likely delay due to adverse weather is estimated, and the estimated duration is incorporated in the earthwork scheduling. The details of the assumptions made for the development of a prototype model are outlined in Chapter 4 of this thesis.

1.6 Structure of Thesis

The structure of this thesis is presented in Figure 1.3 and contains eight chapters followed by references and appendices. A brief outline of each chapter follows.

Chapter One presents the introduction and background of the research study; problem statement; aim and objectives; research methodology; significance and justification; scope and limitations; and a map of the thesis structure. It contains a diagram of the thesis structure and the relationships between the different chapters (see Figure 1.3).

Chapter Two presents the rigorous and critical review of the literature, including previous research studies in the field of construction planning, scheduling, simulation and visualisation technology applied in road construction projects. The review focused on recent academic and industry research studies dealing with the theory of 4D modelling and their applications in the construction industry, particularly the earthwork component of road projects.

Chapter Three provides a detailed description of the construction industry survey undertaken to identify existing practices in construction planning, scheduling and visualisation processes for earthwork operations in road construction projects. This chapter covers the questionnaire design; methodology for the data collection; the data analysis; and the presentation of the survey findings. The survey findings were utilised to develop the specification of a prototype model for earthwork planning and visualisation of road construction processes.

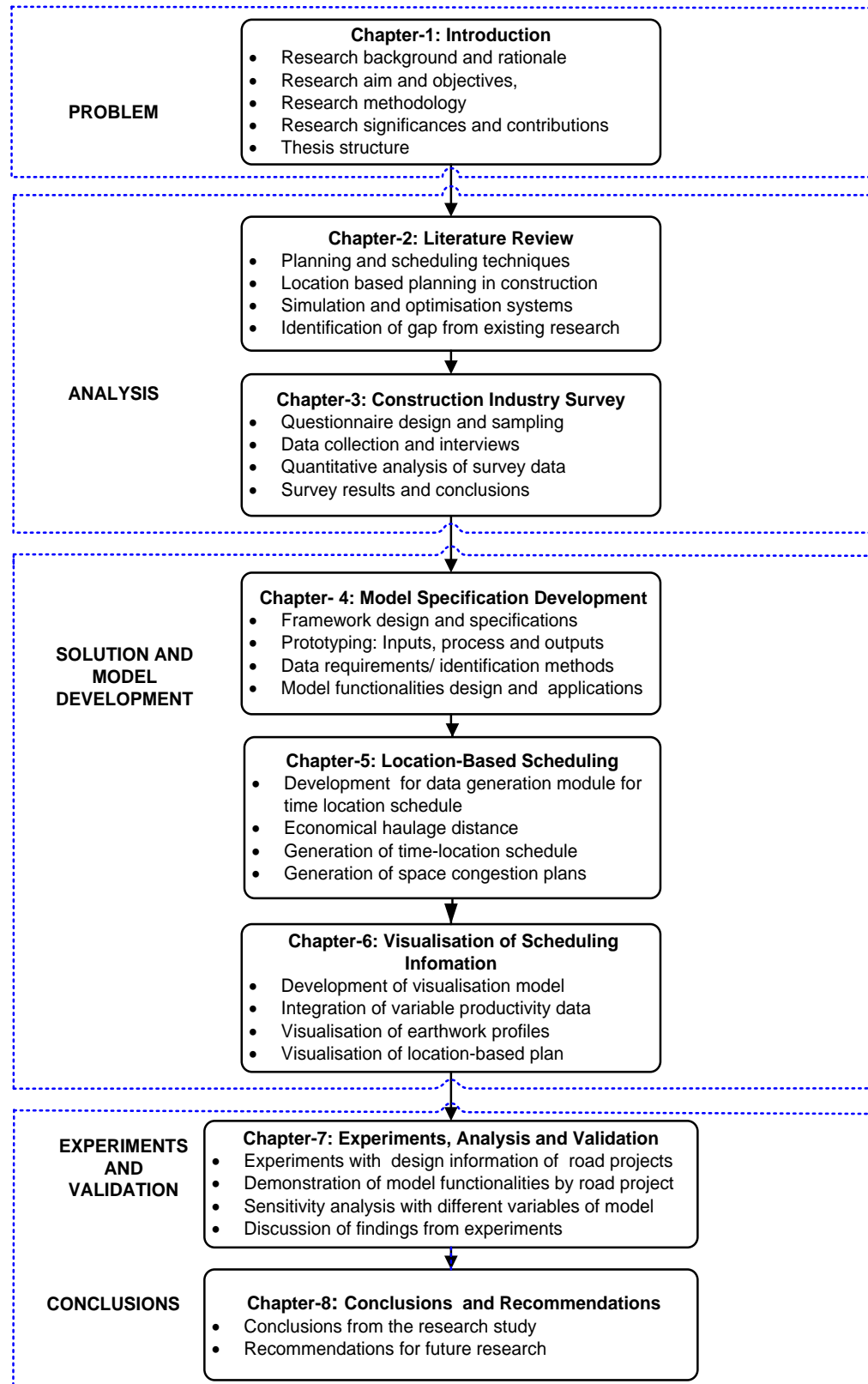


Figure 1.3 Thesis structure and the relationships between chapters of the thesis

Chapter Four outlines the development of the model specification by incorporating the findings from the literature review and the construction industry survey. The

framework of a prototype model was designed into three components: input, process and output. The conceptual diagrams of the data flow and the programming algorithms for the development of different functionalities of the prototype model are explained in this chapter. These functions include the automatic generation of weekly progress profiles, location-based cost profiles, time-location plans, space congestion plans, and optimisation of earthwork allocation quantities in the cut and fill sections.

Chapter Five presents a detailed explanation of the development of a prototype model that automates the generation of location-based schedules and space congestion plans. The detailed data flow diagram and arithmetic algorithms for the development of the model functionalities are presented. The development of a mass haul diagram and the identification of economical haulage-distance are discussed and the model functionality is demonstrated using road design data. The chapter also explains the logic and data flow diagram for soil layer identification algorithms at cutting sections and demonstrates the cut-fill optimisation module and soil layer identifications. A demonstration of model functionalities, location-based schedules and space congestion plans is also presented. The impacts on location-based schedules due to different factors such as site access points, equipment and soil characteristics are analysed and demonstrated.

Chapter Six discusses the visualisation aspects of the model outputs. This includes the logic and development process of the visualisation module to visualise the earthwork progress and cost profiles. The data flow diagram and programming languages used for the development of the visualisation engine are also explained. Additionally, this section includes the demonstration processes of the model functionalities: visualisation of weekly cost profiles, production of S-curve, time-location plan/location-based schedules and a space-congestion plan.

Chapter Seven explains the processes of the prototype model evaluation and validation including experimentation and sensitivity analysis of the model functionality with road design information. The data used was collected from road projects recently completed in Portugal. The chapter presents the results of the

experiments and the sensitivity analysis. Finally, the model functionalities were evaluated by the construction professionals and the findings are presented.

Chapter Eight summarises the conclusions and recommendations drawn from the research study, the research limitations, and offers possible future recommendations. The published research papers from the study, references and appendices are included at the end of the thesis.

1.7 Summary

This chapter discussed the research background and rationale, and provided a statement of problems to be addressed by the research study. Based on these factors, the research aim and objectives were set. The methodology utilised to achieve the research objectives and contributions of this study was discussed and contributions of the thesis were highlighted. The scope and limitations of the study were also presented.

The prototype model developed during the course of this study helps to analyse the impacts of critical factors associated with productivity values on earthwork scheduling and resource planning from a location viewpoint throughout construction operations. A number of critical factors including types of equipment, soil characteristics and site access points were identified; these influence the productivity values of earthworks, and the most important have been incorporated within the model in order to analyse their impacts.

In this research study, it is hypothesised that the location-based schedules generated by the developed prototype model assist in allocating the required resources to the correct locations on a weekly basis and in communicating the scheduling information of earthworks effectively to the site team members from location aspects in road construction projects. The thesis structure, together with a brief introduction of each chapter of the thesis, was presented. The remainder of the thesis follows the structure developed in Chapter One.

Chapter 2

Literature Review

2.1 Introduction

In this chapter, the previous research studies related to planning and scheduling techniques are examined. An identification of the state-of-the-art tools used in the simulation and visualisation of earthwork construction processes can then help to create the theoretical framework for the study. The literature review focuses largely on the recent academic and industrial publications, and on research projects dealing with the planning and scheduling techniques in linear construction projects such as roads, pipelines and railways.

This chapter reviews the theory of a location-based planning and scheduling system to understand the significance of location aspects, particularly in earthwork planning and scheduling. It also explores the gaps in knowledge associated with linear scheduling techniques for the earthwork components in road construction projects. The issues related to the use of computer modelling for earthworks' scheduling and the visualisation of the scheduling information are also outlined, along with the correspondent outcomes of the past studies undertaken by previous researchers.

The functionalities and limitations of existing commercial and research software that are appropriate in the planning, simulation, optimisation and visualisation of earthwork operations are highlighted. Gaps and limitations in the existing planning techniques and tools utilised in the earthwork operations are discussed and the arguments for the justification of this research study are presented. This chapter starts with an overview and a brief explanation of the characteristics and issues associated with earthwork planning in linear construction projects.

2.2 Overview of Earthwork Activity

In road construction projects, earthwork activities usually involve significant haulage costs associated with the movement of soil mass. These activities also influence and restrict the sequencing of the rest of the work activities throughout the construction stage (Askew et al, 2002). Earthwork operations are affected by several factors such as weather, variations in the water table level, geotechnical alterations, hauling distances and site constraints. In practice, planning experts use the historical data of the weather patterns around a construction site, and consider the topographical locations of the proposed construction site, to estimate the possible duration of interruption that may affect the construction schedule. The estimated duration is then incorporated into the construction schedule of earthworks to reduce the impact of adverse weather in project delivery (Castro, 2005).

The site conditions and objectives of construction works influence the selection of planning and scheduling techniques, and the sequencing of the work activities. Earthwork projects require individual planning and scheduling tasks due to their unique characteristics (Arditi et al, 2002). In this context, the selection of a suitable planning technique plays an important role in the successful execution of the processes involved in the earthwork operations.

Mattila and Park (2003) suggested that the common planning and scheduling techniques are Bar Charts, Critical Path Methods (CPM), and Programme Evaluation and Review Techniques (PERT). These techniques are widely utilised in all types of construction projects, but they are less effective for construction projects that are linear or repetitive. Mawdesley et al (2004) stated that CPM networks are more suitable for large complex projects, whereas the Line-of-Balance (LOB) and the Linear Scheduling Method (LSM)/Time-location charts are more practical for the repetitive and the linear construction projects. The time-chainage diagram is also known as LSM, and it is widely used in those linear construction projects that have a repetitive nature of work activities (Kenley, 2004). The next section explains the existing planning and scheduling techniques and the basic characteristics of these techniques in relation to construction projects. These techniques include CPM, PERT, LOB, LSM, and Last Planner Method (LPM).

2.3 Review of Planning and Scheduling Techniques

The selection of the correct planning and scheduling technique for a construction project is a crucial task for project management, particularly during the planning and execution phases. An efficient construction plan provides the foundation for the initial project cost and the success of the developed schedule of work activities. It requires a deep understanding and definition of the activities involved, particularly in an evaluation of the necessary resources and execution time of each task; the selection of expertise; and the identification of logical relationships amongst the different working tasks (Hendrickson and Tung, 2000). The next section explains the definitions, principles and characteristics of planning and scheduling techniques.

2.3.1 Definitions of planning and scheduling

Planning is defined as “a process of making plans for something” and scheduling is defined as “a process of arranging time for something” (Oxford Dictionary). According to Clough and Sears (1995, p53), planning construction operations involves the determination of what must be done, how it is to be performed and the sequential order in which it will be carried out, whereas scheduling determines the date for the start and completion of project works. In other words, planning refers to how, what and who, whereas scheduling refers to when and why.

Harris and McCaffer (2007) divided construction planning into two levels: strategic planning and operational planning. Strategic planning deals with the selection of project objectives, including scope, procurement routes, and timescales and financing options, whereas operational planning involves detailed project resource requirements and method statements of how the works will be executed. Tender planning, feasibility planning and construction planning are examples of operational planning. Both strategic and operational level planning task require various tools and techniques to optimise decision making for a successful project delivery. According to Hendrickson and Tung (2000) the planning and scheduling tools, if required, save time at the initial stage of the planning and re-planning phase. In the planning stage, managerial decisions are needed regarding the relationships between project participants, resource utilisation and the type of organisations that must be

incorporated in the construction project. Therefore, it is necessary to find the most suitable computer-based tools that can assist construction managers and project planners in the decision-making processes; particularly in earthworks planning and scheduling, where existing planning tools fail to provide detailed scheduling information of earthwork activity from a location aspect, especially at the execution stage.

Several studies (Jaafari, 1984; Johnston, 1981; Al Sarraj, 1990; Lutz and Halpin, 1992; Sriprasert, 2004) have been carried out in the area of planning and scheduling techniques and found different types of planning techniques. According to Harris and McCaffer (2007), however, the following are the major planning and scheduling techniques:

- Critical path method / Gantt chart
- Programme evaluation and review techniques
- Line-of-balance
- Linear scheduling method / Time-location chart
- Last planner method

These techniques are still being used in construction projects for the purpose of planning and scheduling processes. However, CPM, PERT, LOB, LSM and LPM are the most common planning and scheduling techniques used in construction projects and, therefore, they deserve a more detailed explanation which is given in the following sections.

2.3.2 Critical path method / programme evaluation and review techniques

In 1957, CPM was discovered as a network planning tool for the management of a project. It depends on a deterministic technique, which uses a fixed-time estimate for each activity. The CPM fails to incorporate the time variations of tasks and resource dependencies. It also does not focus on the non-critical tasks which have a significant impact on the completion time of a project. Despite this, the CPM is easy to understand and it is extensively used in planning processes (Cooke and Williams, 2009).

PERT is a network planning model which allows for randomness in activity completion time. In the 1950s, it was invented for the U.S. Navy's Polaris project, where thousands of contractors were employed. One of the key benefits of the PERT is the ability to decrease both time and cost impact for the successful delivery of any construction projects (Cooke and Williams, 2009).

Since the late 1950s, the CPM and PERT have been adopted in the construction industry. During the preparation of project proposals, project managers are fully familiar with CPM and PERT applications such as managing project personnel and resource planning; tracking delayed tasks; incorporating change orders; and co-ordinating with subcontractors (Jaafari, 1984). Roads, railways, tunnelling, high-rise buildings, housing projects, bridges, transmission lines and other types of linear construction projects have been characterised as repetitive projects (Sriprasert, 2004). The CPM and PERT are extensively utilised in construction projects for the following reasons:

1. CPM and PERT are simple and easy to use in most construction planning in both linear and repetitive projects, such as buildings, roads, tunnels, pipelines and railways.
2. They identify the critical path and activities where more attention is required.
3. They assist in determining the demand for resources such as workers and types of equipment in a construction project.
4. They also assist in making efficient decisions in order to maximise site productivity and operational profitability.

Arditi et al (2002) suggested that the CPM algorithm is designed for duration optimisation rather than dealing with resource constraints for repetitive projects. The CPM algorithm fails to ensure the smooth operation of crews from unit to unit without conflicting activities, working space and idle time for resources. This causes problem in producing the hiring and procurement schedule of equipment, including labour and materials, throughout the construction operations of linear projects.

Additionally, Mattila and Park (2003) pointed out that CPM was found to be unsatisfactory and ineffective for scheduling linear construction projects, although it has been used on numerous projects. The failure of the CPM technique to represent accurately the repetitive nature of linear construction projects has also been identified by several other studies (Stradel and Cacha, 1982; Chrzanowski and Johnston, 1986; Reda, 1990; Suhail and Neale, 1994; Harris and Ioannou, 1998; and Harmelink and Rowings, 1998 cited in Mattila and Park, 2003).

The subjective division of repetitive activities from location to location, the inability to schedule the continuity of resources and display the activity rates of progress, and the failure to provide any information on where the work is being performed on a project site, are the key limitations of the CPM (Mattila and Park, 2003). Several LSMs were proposed by different researchers to overcome the CPM scheduling limitations. These methods include the Line-of-Balance (Lumsden, 1968; Khisty, 1970; Carr and Meyer, 1974; Al Sarraj, 1990; Halpin and Riggs 1992), the Linear Scheduling Method (Johnston, 1981; Vorster et al, 1992) and the Vertical Production Method (O'Brien 1975; Barrie and Paulson, 1978 cited in Mattila and Park, 2003).

The linear schedule is used to reduce the interruption of repetitive activities, to maintain continuity in resource use, and to determine the location of tasks in progress on any given day (Mattila and Park, 2003). The LSM produces a graphical schedule that helps practitioners to understand more clearly the construction processes from the location aspects rather than the Network schedule. These schedules plot work activities on an X-Y graph, where the location attribute of the activities is on one axis and the duration is on the other axis. Taking into account the above points, the author considers that the LSM is more useful in providing detailed scheduling information of earthwork operations from the location aspects. Therefore, the LOB and LSM scheduling methods deserve a more detailed discussion, and are described below.

2.3.3 Line-of-balance

The previous research studies (Johnston, 1981; Lutz and Halpin, 1992) found that the theory of the LOB method was invented by a company called Goodyear at the start of the 1940s. However, it was only effectively utilised in the early 1950s by the

U.S. Navy, applied to both repetitive and non-repetitive construction projects to control construction plans.

Arditi et al (2001) suggested that the LOB has been known under different names; for example, the Construction Planning Technique (CPT) found by Peer and Selinger (1973); the Vertical Production Method (VPM) stated by O'Brien (1975); the LSM identified by Johnston (1981); the Time Space Scheduling Method (TSSM) found by (Stradal and Cacha, 1982); and the Repetitive Project Model (RPM) stated by Reda (1990).

The LOB is a project controlling tool used in project management to collect, measure and present details of a project's status concerning time, cost and achievement of construction activities (Johnston, 1981). These are measured against a detailed plan, and the LOB displays the information on progression, status, location and timing of project activities and provides a measuring tool with the following objectives:

- To compare actual progress with a pre-defined objective plan
- To examine the deviations from developed plans and determine their impact with respect to the rest of the activities in a project
- To collect timely information regarding problem areas and to indicate areas where appropriate corrective action is required
- To forecast future performance of the project

Lumsden (1965, cited in Cooke and William, 2009) pioneered the application of the LOB in construction and highlighted that the LOB was recognised as the best planning method for repetitive works, such as housing and flats. The LOB provides a visual display of the rate of working for different activities on a programme.

Research by Arditi et al (2001) showed that the LOB technique assumes that the production rate of an activity is consistent throughout the construction period. The rate of production of an activity is linear if time is drawn on a horizontal axis and units or stages of an activity on the vertical axis or vice versa. The rate of production is represented by the slope of the production line for an activity and it is indicated in terms of unit per time. The LOB method controls the estimation of working hours for an activity and it assists in optimisation of crew size. The anticipated rate of output

for each activity is determined after computing the number of crews, and the LOB chart is generated depending upon the output productivity (the likely numbers of production units are plotted against time). The slope of the parallel lines is equal to the actual rate of output and denoted by the starting and finishing times respectively, for each activity, for all of the production units from the first to the last throughout the production operation (Arditi et al, 2002). A typical example of an LOB is presented in Figure 2.1 below.

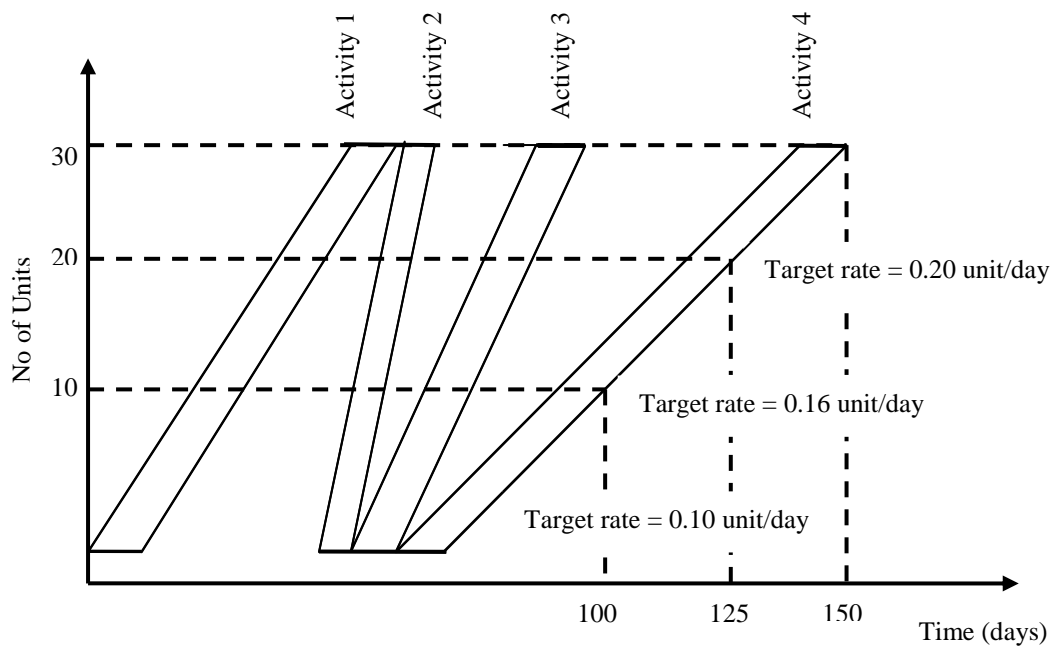


Figure 2.1 Typical view of line-of-balance (Arditi et al, 2002)

Arditi and Albulak (1986) applied LOB scheduling techniques in the pavement construction industry and dubbed it as an “LSM” for repetitive projects. They found that the LOB is extremely sensitive to errors in man-hours, crew size and activity duration estimates. The LOB, however, cannot be used as an LSM in earthwork activities because the earthwork quantity varies from location to location along a road section due to the variation in topography. The next section discusses the linear scheduling method in more detail.

2.3.4 Linear scheduling method/Time-location chart

The time-chainage diagram or time-location chart is a combination of the bar chart and the LOB scheduling method, and time-chainage principles have been developed

on these programming techniques (Cormican, 1985, cited in Cooke and William, 2009). After analysing the past research efforts in the linear scheduling method, Mattila and Abraham (1998) pointed out that planning linear construction projects from the location aspects is very important in order to mobilise the work crew and resources from location to location, without space conflict at a construction site. Several research studies were carried out in the area of linear scheduling techniques (Johnston, 1981; Garold et al, 2005; Harmelink and Rowings, 1998; Harris and Ioannou, 1998; and Mattila and Park, 2003). They concluded that time-location planning is a valuable scheduling technique for planning and monitoring the progress of linear construction projects such as roads, pipelines and railways.

According to Harris and McCaffer (2007), the time-space diagram / location-time chart was normally used for planning the construction works before the advent of the computer-based planning packages. This diagram is plotted in the form of two-dimensional graphs in which time is represented on one axis and space on the other axis. The diagram allows the identification of potential conflicts in the utilisation of resources and assists in communicating scheduling information of work activities in a project. It also assists in identifying the location of the progressing activities and their rates of production. For linear construction activities, the diagonal lines indicate the start and the end date, and the working locations, while the slope of the line indicates the rate of progress. In a road project, the existing time-location chart, however, is not capable of providing accurate information relating to the locations and the timetable required for the earthwork operations.

According to Cooke and William (2009), time-chainage diagrams are a graphical technique and have been widely applied to major road projects and motorways in the UK for many years. The technique was also used in the planning of tunnelling and equipment installation in the Channel Tunnel project (ICE, 1992). The time-chainage diagrams have distinct attributes that provide several types of information such as the order of activities or operations, working locations, activities progress in relation to direction and distance, and activities duration with key dates (start/end) of activities. In the existing time-location chart, earthworks and structure, including bridges and culverts, were displayed as a block of works at different locations. In such cases, the

chart lacks to display the productivity and locations information of work activities, particularly in the cut-fill operations of earthworks.

The LSM is also known as a time-chainage graph, as a time-distance chart, or as location-based scheduling (Kenley, 2004; Kenley and Seppanen, 2010). A time-location chart or an LSM is a very useful scheduling method for monitoring the progress in linear construction projects from location to location. The line corresponding to each activity in a time-location chart has a slope representing the respective productivity. A typical example of a linear schedule for a road project is shown in Figure 2.2 below.

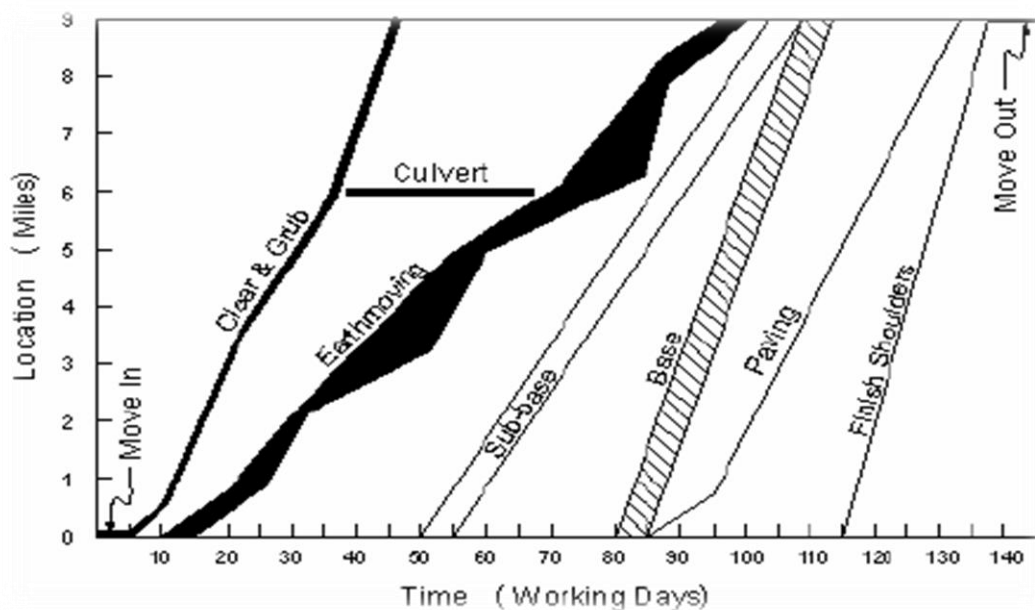


Figure 2.2 Example of linear schedule used in road projects (Garold et al, 2005)

Garold et al (2005) recommended that different scheduling methods are used according to the nature of projects; these are summarised and presented in Table 2.1.

Table 2.1 Type of scheduling method for different types of projects

S. N.	Type of Project	Scheduling Method	Main Characteristics
1	Linear and Repetitive Projects: Roads /Highways, Pipelines, Railways, Tunnels	LSM	<ul style="list-style-type: none"> • Few activities • Executed along a linear path • Complex sequence logic • Work continuity crucial for effective performance

2	Multiunit Repetitive Projects (housing complexes or residential buildings)	LOB	<ul style="list-style-type: none"> • A group of similar units as final product • Same activities in all projects • Balance between different activities achieved to reach targeted production
3	High Rise Buildings	LOB	<ul style="list-style-type: none"> • Repetitive activities • Hard logic for some activities but soft for other activities • Every floor is considered a production unit • Suitable for a large number of activities
4.	Refinery, Oil and Gas and other complex projects	PERT/CPM	<ul style="list-style-type: none"> • Extremely large number of activities • Complex design • Activities discrete in nature • Crucial to keep project in critical path
5	Simple Projects (of any kind)	Bar/Gantt Chart	<ul style="list-style-type: none"> • Indicates only time dimension (when to start and end activities) • Relatively suitable for few activities

The previous research studies presented earthwork activity as a linear activity and developed a time-distance chart by representing it through a single line for the period of the earthwork sections. In real practice, however, earthwork activities do not progress in a uniform rate along a road section because the earthwork quantities vary from station to station (chainage to chainage) in construction sites according to the topography of the terrain surface along a road project. Therefore, a detailed schedule is required to manage the daily or weekly activities of earthworks from the location aspects. The daily or weekly schedule of earthwork activities is applied at site-level planning. The Last Planner method is commonly used for short-term planning and site-level planning in construction projects.

2.3.5 Last Planner method

The LPM focuses on short-term planning (weekly) at crew level using the concept of lean construction, which includes increasing productivity, decreasing wastage, and variability (Ballard, 2000; Seppanen et al, 2010). This method looks for the improvement of plan reliability by protecting task execution from constraints, and by the generation of a workable backlog (what can be done). At the start of the week, the crew accepts commitment planning by selecting the workable backlog tasks (what will be done); and at the end of week, a percentage of the completed plan and

the reasons for the variance are monitored (what was done). In previous case studies, it was found, that the LPM resulted in waste reduction and an improvement in site productivity (Ballard and Howell, 1998; Ballard, 2000).

The concept of the LPM has five main integrated elements. These include a master plan, phase plan, look-ahead plan, a weekly-work plan, and the completed percentage plan (Ballard, 2000; Ballard and Howell, 2003, cited in Koskela et al, 2010). A weekly-work plan is a production task for the next day or week. This helps to plan the work that will be done in the next week, bearing in mind the work that is being done now, and in the knowledge of the work that is ready to be done. The weekly plans include safety issues, quality issues, resources planning techniques, construction methods, and any problems that occur in the field (Koskela et al, 2010).

2.3.6 Advantages and limitations of scheduling methods

The main advantages and limitations of existing CPM and LOB scheduling methods to plan the work are listed in Table 2.2 (Jongeling and Olofsson, 2007). Despite the advantages of the LSM, there are some limitations, particularly concerning the non-repetitive activities in a linear project. These activities, such as a box culvert or a bridge in a road project, need to be scheduled using network techniques and then incorporated into the linear schedule in different ways (Mattila and Park, 2003).

Table 2.2 Advantages and limitations of the existing scheduling methods

Methods	Advantages	Limitations
1. CPM and 2D drawings	<ul style="list-style-type: none"> • Common and accepted format • Relatively cheap and powerful software available 	<ul style="list-style-type: none"> • Planning work-flow is difficult and results in very detailed schedules • Spatial configuration of an activity difficult to plan and communicate
2. LOB and 2D drawings	<ul style="list-style-type: none"> • Managing activities (i.e. lines) requires little effort • Explicit support for planning of resource-flow through locations • Powerful software available 	<ul style="list-style-type: none"> • Limited support to plan and communicate the spatial configuration of an activity • Relatively unknown method
3. CPM and 4D CAD	<ul style="list-style-type: none"> • Provides spatial insight in the planning of work-flow 	<ul style="list-style-type: none"> • Inherent to limitations of CPM • Many 4DCAD models are limited to the use of 3D building components and do not include components related to work-flow • Relatively unknown and developing method

Furthermore, Mattila and Abraham (1998) recommended that location information in the LSM is vital for the planning and scheduling of linear construction projects that reduce the construction cost and interruption caused by construction at the same locations. Polat et al (2009) introduced a new approach in scheduling highway projects by combining LOB and discrete event simulation techniques to incorporate resource constraints and to reduce the interruption of workflow between off-site and on-site operations. They stated that the LCM enables the easy and effective management of activities and the required resources from location viewpoints, and found that this approach assists in solving the resource allocation problem in linear construction projects.

Previous studies (Johnston, 1981; Harris and Ioannou, 1998; Arditi et al, 2002; Mattila and Park, 2003; Kenley, 2004; Garold et al, 2005; Kenley and Seppanen, 2010) highlighted that the LSM/time-location chart, which is also known as the location-based scheduling method, assists construction managers with different aspects. These aspects include providing information of working locations; planning the work sequences of crews; allocating resources in respect to locations; identifying space conflict; and controlling progress during multiple activities working at the same location.

Since the quantities of earthwork vary from location to location along a road section, it is very important to know the weekly location-based information for producing an effective construction schedule and efficient resource planning of earthworks. In this context, it is concluded that location-based scheduling is a possible solution to overcome the issues highlighted above. Thus, a detailed review of location-based planning and scheduling is necessary to achieve the aim of this research project. The next section discusses the theory of location-based planning and scheduling in construction projects.

2.4 Location-based Planning and Scheduling

This section starts with the development history and the theory of Location-based Planning and Scheduling (LBPS). In this thesis, the term “planning” is used to include planning, scheduling and other terms related to the building of time-related

models of construction works in order to develop a logical plan of work. This section explains the activity based scheduling methods and their shortcomings, as identified by previous researchers. The next section describes the history of LBPS.

2.4.1 History of location-based planning and scheduling development

Karol Adamięcki (1896, cited in Kenley and Seppanen, 2010, p50) developed planning techniques that are believed to be the foundation of a Location-based Management System (LBMS). He developed graphical techniques, and ontology to describe the management of production and complex interactions between the production engineering and production efficiency. In 1896, he created a novel way of displaying interdependence of processes that aimed to improve the visibility of production schedules. He also developed a diagram called a “harmonogram” or “harmonogar”. Adamięcki (1896) provided earlier thinking to the development of LBMS, particularly the concepts of alignment of production speed and importance of harmonograms to communicate to a modern LBMS. The importance of creating good teamwork and team harmony is only being reinvented through the practical application of lean concept and LBMS. The earliest evidence suggests that the method emerged 100 years ago (Kenley and Seppanen, 2010, p50-54).

The development of activity-based scheduling methods has considerably improved the construction industry and these methods continue to be a method of choice for complex projects with little or no repetitive activities. However, there is a hesitation about their suitability for real construction projects. Some researchers (Selinger, 1980; Reda, 1990; Russell and Wong, 1993; Arditi et al, 2002, cited in Kenley and Seppanen, 2010, p49) pointed out that activity-based systems were inefficient, failed to identify the importance of workflow and continuity, and were unreliable in their application. These researchers noted that CPM networks methods lacked the ability to solve the planning problem in the case of a project having repetitive activities (Kenley and Seppanen, 2010, p49).

The term location-based scheduling was first proposed by Kenley (2004) to distinguish the emphasis on locations and activities in planning. Currently, location-based methods for planning are available with the support of commercial software

such as Virtual Construction (VICO) and DynaRoad software. Location-based planning is the natural planning system for the construction of linear projects. It has a long history as the earliest planning system, used on a large-scale project, and is suitable for linear construction activities. The next section now presents the theory of the location-based planning and scheduling.

2.4.2 Theory of location-based planning and scheduling

Location-based planning and scheduling is the core of the theory of LBMS. These methods use the knowledge of location as a natural element of the planning and scheduling system and focus on the connection between the location of the work and unit of work to be performed. The LBMS believes that there is value in breaking a project into smaller locations. These locations are used to plan, analyse and control the daily activities as they flow through these locations. The location attribute provides a reservoir (storage space) for project data at a scale that helps to monitor and analyse project performances (Kenley and Seppanen, 2010, p123).

The main significance of LBPS is to plan the productivity according to locations. LBPS explicitly manages work-continuity for resources and assists in optimising production in projects. It is the first planning system to be able to organise both activity sequences and sequence of work for production efficiency. It has a record of accomplishment and practical suitability associated with the repetitive nature of construction projects, including roads, railways and pipeline projects (Kenley and Seppanen, 2010, p123). In LBPS, locations in a project are defined by a location-breakdown structure similar to Work Breakdown Structure (WBS). Locations are hierarchical in order to include the logic of higher-level to lower-level locations. Location breakdown structure differentiates between activities and tasks, where a sequence of activities in different locations represents a task. A task is defined as a set of activities in a sequence of locations and a single crew or multiple crews can perform it. The planning system therefore also considers internal logic to plan the sequences of working location and crew, and to plan productivity to achieve continuous production by determining durations that is based on the available quantities (Kenley and Seppanen, 2010, p124).

LBPS is based on the extension of activity-based logic combined with location-based logic, which provides a new tool for planning and analysis of construction activities. Location-based logic can be used to calculate the impact of control actions taken to recover delay from the original schedule. The LBPS assists in the assessment of time-claim with regard to cost. Location-based flow logic assists the claim agent to show the results of any deviation graphically, while using critical path logic as a theoretical base (Kenley and Seppanen, 2010, p124). They pointed out that the most building projects should be planned and controlled using location-based methods, particularly in scheduling the required resources and work activities effectively.

Andersson and Christensen (2007) conducted three case studies of Danish residential projects aiming to identify the practical implication of location-based scheduling. They focused on the production phase, using the location-based scheduling method with three different types of building construction projects, and comparing these to CPM-based schedules. The findings were discussed and evaluated by construction managers, together with other staff involved. Andersson and Christensen (2007) found that improved schedules, establishment of workflows and enhanced project controls are the three major constructive implications of location-based scheduling.

Despite some difficulties during the implementation, the improvement in overview of a schedule helps to visualise the repetitive activities at multiple locations and to communicate amongst the involved parties, including sub-contractors. The establishment of workflows provides information on the resource flow through locations, and avoids overlapping or unused locations. The enhanced project control system provides information on locations for each resource crew, which assists them in controlling the work progress at each location. Taking into account the above observations, the author believes that for linear projects, location-based scheduling is a suitable technique for the improvement of earthworks scheduling, resource planning and the communication of scheduling information.

The past studies associated with location-based planning, which mainly focused on building construction projects, stimulate further investigation into linear construction projects. Therefore, this study focuses on developing the location-based scheduling of earthworks in linear construction projects.

2.4.3 Location-based planning in linear construction projects

A linear project is a typical project in civil engineering that involves a continuous sequence of work activities along a long route, such as roads, pipelines, tunnelling and railways. It depends on the principle of LOB techniques for both purposes of analysing and representing the scheduling information; hence, LBMS is considered more suitable for the projects having a linear nature. The LBS for linear projects is different from other types of construction projects. In contrast to other projects, locations in a linear project can be transferred to distances along a line; thus, it is called 'linear'.

A suitable method for the visualisation of scheduling information in linear projects is a Time Distance Diagram (TDD). In this diagram, location is placed on the horizontal axis and time on the vertical axis. Hence, the TDD enables easy comparison between scheduling and other charts, such as a Mass Haul Diagram (MHD) and the longitudinal section of a linear project. In the linear project, multi-skilled resources are used at different activities; for example, the same excavators can be used at different locations in a road construction project (Kenley and Seppanen, 2010, p467).

Productivity is a key factor associated with equipment size and capacity; therefore, it is used to calculate the durations of project tasks. Resources with high hourly rates and relocation times represent a much higher cost than in building projects; therefore, optimisation of production time and cost is more critical to linear projects. This is a consequence of the very high delivery costs for plant and construction equipment.

Moreover, the productivity of earthwork activities is variable according to the topography of a road section and the type of equipment sets planned for operations. It is highly influenced by several factors including topography, space constraints, soil characteristics, topographical conditions and site-working conditions; therefore, this research focuses on optimisation of resource use in such circumstances. The next section describes the earthwork planning issues, optimisation and associated factors.

2.5 Overview of Earthwork Planning Issues

This section outlines the planning issues of earthwork in a linear construction project. Earthwork in road construction has distinct characteristics including one-off projects, variable site conditions, uncertainty of soil characteristics and weather. Therefore, it is necessary to understand the factors that have an adverse effect on earthwork planning.

2.5.1 Factors affecting earthwork planning

Factors affecting earthwork operations are classified into four groups with consideration of the influence of each factor shown in Figure 2.3 (Kim and Russell, 2003). Examples of factors that influence earthwork operations include earthwork characteristics, work-type and volume, space constraint, job-site conditions, equipment characteristics, site management, and construction methods.

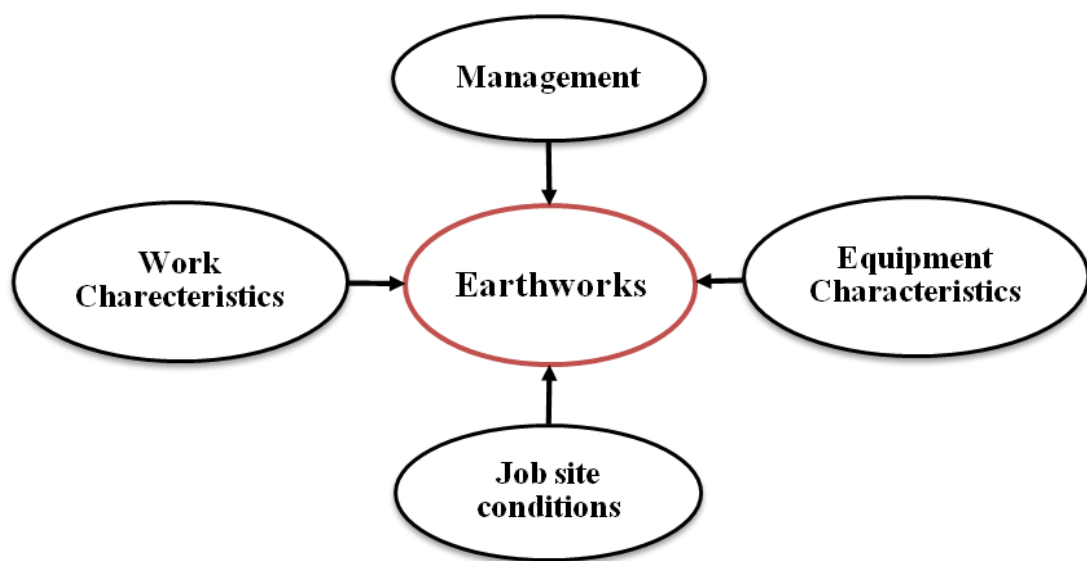


Figure 2.3 Map of four groups of factors affecting earthworks operations

- Work characteristics: work type, volume, and technical specifications
- Job-site conditions: space constraint, topography, weather, soil types, site conditions, access road conditions on-site and off-site, location of borrow pits and local resources
- Equipment characteristics: capacity, efficiency, failure rate (break down)

- Management: planning the sequences of work, resource allocation including crew and materials, selection of the correct number of equipment sets at required locations relative to time and construction methods

The performance of earthwork operations can be measured by several criteria such as time (duration), cost and safety. The evaluation of effective operations is based on multi-criteria but the focus in this study is on generating the weekly information of locations and the duration of earthwork activities. The production duration of earthwork operations is highly dependent on productivity which, in turn, is dependent on several factors as described above.

Taking into account the above factors, it is concluded that the planning and scheduling of road tasks represents an additional challenge compared to building construction projects. Hence, this study concentrates on earthwork optimisation and discusses the application of optimisation techniques in earthwork planning in the next section.

2.5.2 Existing methods in earthwork optimisation

Normally, earthwork takes place in all civil engineering projects in some form. The earthworks may be small or large in volume depending on the nature and size of the construction project. According to Warren (1996, p85), earthwork operations are classified into four major categories, as follows:

- Top excavation: stripping top soil and clearance of vegetation
- Confined excavation: excavation for trenches or pits
- Open excavation: cutting
- Embankment construction: filling

For efficient operations in earthwork, it is essential to match the correct plant to the location factors along the linear route. Therefore, it is necessary to consider a wide-range of factors that control the planning and execution of earthworks, the main factors being:

- Types of materials and availability

- Geographical factors: topography, access, size of site and weather conditions
- Plant (construction equipment) availability
- Volume of soil to be moved between cut-and-fill section
- Time and site-access constraints
- Local constraints: noise, working time, pollution and other disturbances

In larger earthworks, the effects of volume, distance and timing are identified using Mass Haul Diagrams (MHDs). They provide a graphical representation of the volume of cutting and filling sections in relation to their position on the site, and are widely used for linear construction like road and railways (Warren, 1996, p85). Several optimisation techniques in earthwork planning were developed and used in cut-fill assignments (as discussed above); however, the MHD and the linear optimisation techniques are the most commonly used in the cut-fill assignments of earthworks problems. The next section discusses these techniques.

2.5.2.1 Mass haul diagram

The MHD plays a vital role in reducing the haulage cost by minimising haul distances and the amount of temporary stockpiling during a linear construction project. Kenley and Seppanen (2010, p468) pointed out that integrating the construction schedule with a mass haul plan is an important factor for the successful completion of earthwork construction projects on time and within budgeted cost. However, the scheduling of mass haulage faces several difficulties that include the distribution of excavated quantities in reverse sequence for embankments. For example, topsoil on the proposed terrain must be removed first although this is required for covering the slope of embankments, which is last in the construction sequence.

Moreover, an additional challenge occurs when both cutting and filling operations include similar sequences of works. Therefore, working locations become a vital issue because a delay in one location of a road section can severely affect multiple locations including other activities. This has a direct impact on the procurement schedule of mass haul activities in a linear project. Linear projects, especially roads or railways, are defined by locations, not by trade, because multiple tasks use the

same resources throughout construction operations. A complex interaction of sequential cuts and sequential fills is broken by physical obstructions such as land and road profiles, intersections, and the requirements for traffic management.

Sub-contractors are separated by splitting the road section and limiting their mass haul activities within their own construction zone (a section having balanced mass volume of cut and fill sections). This helps in identifying the schedule deviation occurring in a mass haul project. Therefore, mass haul planning and the optimisation of resources become vital and challenging tasks, particularly in allocating the boundary of working sectors for sub-contractors (Kenley and Seppanen, 2010, p469).

2.5.2.2 Linear programming

Linear Programming (LP) problems are concerned with the efficient utilisation, or allocation, of limited resources to meet the desired objectives (Gass, 1984). LP has been applied in a wide range of fields, including economics, operational research and optimisation problems (Spielman and Teng, 2004). It solves a linear objective function subject to linear equality and linear inequality constraints. LP is a mathematical method, which uses a linear relationship to identify a way to find the best results (maximising profits or minimising cost) subject to satisfying the existing constraints. The Simplex method, which remains widely used today since George B. Dantzig introduced it in 1947, was the first practical approach for solving linear programmes (Hosseini, 1996). A brief development history of the linear optimisation method is outlined below.

- Italian mathematician Joseph Louis Lagrange solved a tractable optimisation problem with simple equality constraints in 1762.
- Gauss solved a linear system of equations (Gaussian Elimination) in 1820.
- A method for finding “least square” errors as a measure of goodness-of-fit was improved by Wilhelm Jordan in 1866. Currently it is popular under the name of the Gauss-Jordan method.
- The Digital computer emerged in 1945.
- The Simplex method was introduced by George B. Dantzig in 1947.

- The Interior-point method was introduced in 1984 by Narendra Karmarkar aiming at solving linear programs and with the addition of his innovative analysis (Hossein, 1996).

According to Spielman and Teng (2004), LP has been established as a powerful tool for solving linear problems by using the Simplex method, which was introduced by Dantzig in 1947. Since then, different researchers have invented several algorithms for LP. For example, Khachiyan applied the ellipsoid algorithm in 1979 to LP but, in practice, it has not been competitive with the Simplex method. In contrast, Narendra Karmarkar introduced the interior-point method in 1984, which in practice is occasionally superior to the Simplex method.

Despite the development of several alternative methods, Spielman and Teng (2004) stated that the Simplex method remains the most popular method for solving linear programmes because of its excellent performance. Moreover, an Excel solver uses the Simplex method to develop the computer programming for solving linear optimisation programmes. Therefore, the Simplex method has been selected in this study for solving the linear problem associated with cut-fill assignments in earthwork operations. The next section discusses the past studies associated with LP's use for earthwork allocation and construction planning.

2.5.3 Previous research studies in earthwork planning

Several research studies have been carried out in earthwork planning which consider the linear programming techniques, particularly in linear construction projects such as roads and railways. Stark and Nicholls (1972) suggested the first linear programming in earthwork allocations and it has been developed further by Nandgaonkar (1981) and Mayer and Stark (1981). Nandgaonkar (1981) applied the transportation technique of operation research for the allocation of earthwork between cut and fill sections including borrow pits. He found that the transportation cost of earthworks allocations could be reduced.

Mayer and Stark (1981) used linear optimisation as a technique to produce earthwork activities aiming to minimise the haul distance that ultimately reduces the movement of earthwork quantities between non-adjacent cut and fill sections. Essa (1987) used

a system known as EARTH. The system was built on an LP approach that aimed to reduce the earthmoving cost by minimising the haul distance while considering the non-constant unit cost of borrow pits and landfill sites. In 1988, he further enhanced the model with the consideration of a quadratic model of the cost coefficient of unit-cost earthmoving. The above studies exclude factors that affect the unit cost due to soil characteristics at different locations or the longitudinal slope of a roadway.

Jayewardene and Harris (1990) enhanced the existing LP further by developing the integer-programming model for earthwork optimisation, aiming to reduce the cost of earthwork allocation by incorporating the project duration and different soil strata at cutting sections. Furthermore, Jayewardene and Price (1994) developed a comprehensive model by combining computer simulation and linear programming to optimise the earthwork moving system. The model includes three parts: simulation, LP and network scheduling. The simulation model provides the realistic unit cost and productivity by balancing plant teams; the LP model provides the optimum allocation of material distribution by considering constraints such as plant availability, project duration and sequences of operations; and, finally, network scheduling provides a construction plan. They do not incorporate the location aspects for developing a construction plan of earthworks.

Ahmad (1996) designed a model to identify the optimal roadway slope to reduce the cost of earthwork activity using the linear programming. This model incorporated the roadway longitudinal slope in a linear programme. He concluded that the model is able to provide a significant level of optimality. Mawdesley et al (2002) developed a model for the automatic generation of cut and fill activities for earthworks considering the MHD. The model was developed incorporating a knowledge-based system and different types of material aiming to minimise the effective haul distance in earthwork construction projects and to reduce the earthwork allocation costs in a cut-fill assignment in road projects. The model might be more useful for effective resource planning and controlling the progress of earthwork activities from the location aspects, if the location aspects were included in the model.

From a planning aspect, Hassanein and Moselhi (2004) developed an object-oriented model that aimed to integrate the planning and scheduling stage of highways

construction projects. The model was capable of automatically generating the work breakdown structure, but it could not generate a location-breakdown structure, which is a key element in location-based planning. It gave priority to the network logic of the particular job, and used a list of stored construction operations faced in a road construction project, but failed to address location aspects for highway scheduling.

Using linear programming, Son et al (2005) developed a mathematical optimisation model for the determination of minimum haul distances and the direction of the movement of cut-fill quantities on an excavation project. The main inputs in their model are the quantities of cutting and filling activities. The location of these activities and haulage distance represent the outputs of the model, which enables construction professionals to identify the optimal solution in an earthmoving problem. Son et al (2005) did not address how to integrate the different productivity rates of earthworks in the model.

Kim et al (2007) developed a three-dimensional optimisation methodology for highway alignment that automatically determines whether bridges or tunnels are economically viable to replace high embankments or deep excavation, during the planning of road alignment across a landscape; however, Kim et al's (2007) methodology did not include linear programming for earthwork allocation between embankments or excavations.

Tam et al (2007) introduced a method to automate the planning of an earthmoving task. The method integrated several factors including path-finding, a plant selection system, compatibility, and genetic algorithms in order to optimise the best possible solution taking account of cost, productivity, safety and environmental impacts. Although the introduced method is useful, it fails to integrate the different productivity rates or consider the location aspects, which is critical for efficient resource planning and location-based scheduling in earthworks operations.

Shahram et al (2007) proposed a fuzzy-logic linear programming model for the allocation of earthwork quantities and for dealing with uncertainty parameters based on the consideration of the assumed unit cost coefficients. The borrow pits and disposal sites capacity were assumed as a fuzzy-number while minimising the total

moving cost of mass earth, this being the objective function. However, the authors did not address the importance of location viewpoints together with shrinkage and swell characteristics of soil in the earthwork allocation problems.

Moreover, some software companies have also developed earthwork allocation tools. For example, DynaRoadTM (2006) developed commercial software for producing a mass haul plan, a construction schedule, and a controlling model for the earthwork activities using linear programming techniques.

Similarly, ASTATM (2009) also developed Time-Location Planning Software (TILOS) for managing linear construction projects, aiming to produce construction schedules and to improve the visualisation of repetitive tasks in a linear construction project. The TILOS provides the flow of scheduling data in terms of time and place. This is a crucial factor for resource-planning and time-space allocation of earthwork activities.

The linear schedules produced by the TILOS and DynaRoad are, however, unable to provide daily or weekly information on working locations, particularly in earthworks. The developed schedules also fail to incorporate different productivity rates. As a result, the decision-making process associated with production schedules becomes difficult due to the limited information on weekly locations at the construction site.

Taking into account the above points, further development involving a new approach to location-based planning is justified from the viewpoints of effective resource planning at required locations, progress monitoring, and improvement in the overview of earthwork scheduling, particularly in a linear construction project. The next section describes the modelling concept in the construction industry.

2.6 Modelling background in the Construction Process

Modelling is the most important part or component of the construction planning process. It is a prerequisite of a construction system, in order to analyse the response or outputs of the system in certain working conditions. These outputs are usually expressed in terms of quantity, cost and time. Generally, these are used to select the resources, schedule the works and determine the construction budget. Therefore, the accuracy of the modelling process in the construction operation is a key factor in the quality of the overall planning process (Castro and Dawood, 2005).

In the construction planning process, a mathematical, logical or physical representation of construction operations and activities should be developed with the necessary accuracy to adequately represent the system, and to answer the behavioural questions associated with the construction system. Two approaches such as analytical and simulation modelling which are commonly used in construction modelling process are analysed and presented in the following section.

2.6.1 Analytical modelling

The analytical modelling method is difficult to apply in road construction due to the number of variables involved in the process. Road construction is a system involving complex interactions between activities and resources; therefore, the establishment of mathematical models is only possible with the introduction of a number of simplifications and assumptions in construction methods and planning techniques (Castro, 2005).

If all parameters of the model were introduced, the resulting mathematical model would become extraordinary complex and difficult to apply in practical terms. The disadvantage of mathematical modelling is its inability to deal with space requirements and its respective management. Time-consumption is another problem related to analytical modelling methods for road construction activities. Despite the limitations and difficulties associated with it, an analytical approach is the most commonly used modelling method for planning purposes in road construction activities (Castro, 2005).

2.6.2 Simulation modelling

Halpin (1998) defined simulation as a modelling technique showing the graphical representation of events occurring in construction processes that also involve deterministic or stochastic variables. Simulations allow the analysis of the construction processes in detail, relating to the behaviour of the whole system in different circumstances or in relation to the performance of a certain construction resource. Shi and AbouRizk (1998) developed the Resource-based Modelling (RBM) methodology with the aim of automating the modelling process of construction simulation, whilst capturing the properties of construction operations.

Two main categories of a simulation system can be encountered in construction: systems using virtual reality with visualisation in 2D, 3D and 4D, as well as systems making predictions in terms of productivity but without visualisation. Virtual Reality (VR) is a modelling technique enabling interactive real-time viewing of three- and four-dimensional data. This technique is included in architectural tools and proved its excellence in designing complex construction objects especially related to physical feasibility. This is probably the reason for the use of this technique, primarily as a design tool (Kurmann et al, 1997), but VR has limited applications as a planning tool (Bouchaghem and Liyanage, 1996). Due to the complexity of construction operations, it is analytically difficult to validate models to ensure that they represent “real-world” systems. This limitation can be overcome by the use of a computer to evaluate the model numerically and collect information referring to the behaviour of the model in different circumstances (Law and Kelton, 2000).

The other group of simulation systems include tools conceived for the automation of the planning process, and are used for decision making processes based on the expected outcomes (productivity) of the considered construction systems (Castro and Dawood, 2005). Simulation has proved to be very helpful in designing complex construction operations when combined with visualisation and for assisting in making improved decisions when planning construction operations (Kamat and Martinez, 2001).

2.7 Simulation in the Road Construction Process

Simulation is defined as the act of replicating various actual objects, states of affairs or processes. The work of simulating something generally involves the representation of behaviours of a particular physical event. Simulation can also be defined as the representation of a certain system in a computer to allow the analysis of the behaviour of the system in different scenarios; for example, the Monte Carlo-based models Micro Cyclone, Stroboscope, and Coops. Simulation is a common tool, used to simulate construction activities and to represent the key characteristics or behaviours of construction processes that affect the planning and scheduling process of a road construction project (Castro, 2005).

Dawood and Castro (2009) introduced a knowledge-driven site simulation system called “RoadSim”. It is a simulation-based planning tool conceived for road construction projects using a knowledge-based approach. The key concept of the “RoadSim” depends on the atomic models theory, which was identified by Ziegler (1987) and implemented by AbouRizk and Mather (2002). In “RoadSim”, every operation is associated with an atomic model and the whole construction activity is modelled by coupling the atomic models that participate in the respective construction operations (Castro, 2005).

Each construction operation is broken down successively into elements of lesser complexity until a final and indivisible element is found similar to an atomic model. Therefore, every construction operation can be seen as a molecule resulting from the coupling of a given number of atoms. The forces influencing the coupling and the type of “molecule” are exactly the same elements that control productivity in real life; for example, volume of work, resource constraints, haulage distance, types and conditions of site access roads, access point, soil characteristics, working conditions, weather conditions, and other relevant factors (Castro, 2005).

The “RoadSim” simulation system has integrated productivity equations, considering the factors affecting the productivity data of an activity in a road construction project. It determines the duration of activities for scheduling purposes by

identifying the productivity of activities and functionality needed to produce a schedule bar chart (duration produced by the productivity model).

Moreover, Marzouk and Moselhi (2003) developed a simulation model for earthmoving operations. They focused on process simulation using distinct event simulation. In a consistent way, an object-oriented model accounted for the uncertainty at the construction stage of the earthmoving activities.

Mohamed and AbouRizk (2005) proposed a framework which provided the structure for integrating intelligence into simulation objects, to allow a further reduction in the required knowledge in experimenting with a simulation model and to assist in decision-making processes. However, the proposed framework neglected the visual simulation of earthwork construction processes from spatial aspects in respect to time dimension. To overcome the issue, 4D modelling was suggested for visual simulation of the earthwork processes. Therefore, a detailed discussion of 4D modelling as a part of visual simulation is given in the following section.

2.8 4D modelling of Construction Process

2.8.1 Definition of 4D modelling

A 4D model is defined as a 3D model plus time (3D+time) (Koo and Fisher, 2000; Dawood et al, 2002). The viewing and rehearsal aspect of 4D models in projects assists project stakeholders to understand the process of a planned construction facility on a computer screen, in a virtual environment. It also assists in reviewing the planned and actual status of a project in the context of a 3DCAD model for a particular day, week or month throughout the project period. The benefits of 4D CAD models have been confirmed through numerous case studies and published research papers (such as (Fisher and Kunz, 2004; Ragip, 2005; Dawood et al, 2005). Previous research studies on 4D modelling are discussed in the following section.

2.8.2 4D modelling in building projects

A 4D model enables different team members to understand and visualise the project scope, including the corresponding construction schedules, in a proactive and timely

style. Past studies assist in the exploration and enhancement of project execution methodology and constructability together with improving site productivity. They also assist in identifying time-space conflicts, and in planning how to resolve them, before they occur in reality on a construction site.

4DCAD models have been proven to be helpful in those construction and renovation projects that involve a large number of stakeholders and where there is limited space at construction sites, particularly in urban areas (Chau et al, 2004; Dawood et al, 2002; Fisher and Kunz, 2004). The 4D visualisation tools provide a critical workspace analysis to identify space congestion at the site workforce through the visualisation tools incorporated within them. They also enable the identification of the workspace as a factor and can potentially increase the productivity at the workforce by 30% (Dawood and Mallasi, 2006).

Retik et al (1990) identified the potential use of computer graphics in construction scheduling by representing the construction activities in the form of graphical images, at a particular time during the construction period. Zhang (1996) reported on a 3D graphical construction model. Williams (1996) designed demand-driven 4D models for the generation of a graphical construction plan based on simulation, visualisation and communication.

Collier and Fischer (1996) demonstrated visually-based 4D modelling and scheduling in a case study of the San Mateo County Hospital. McKinney et al (1996) proposed a Four-Dimensional Computer-Aided Design (4DCAD) tool with visual and communicative functions to facilitate the design process. Adjei-Kumi and Retik (1997) applied the concept of virtual reality to visualise the construction plan using a library-based 4D model.

McKinney et al (1998) demonstrated the capability of 4DCAD models to identify construction problems prior to their actual occurrence. Zhang et al (2000) developed a 3D visualisation model with schedule data at construction component level. Kamat and Martinez (2001) presented a 3D visualisation model depicting the entire process of a typical construction activity. Kamat and Martinez (2003) described a visualisation system, which is a CAD-independent simulation system for general

purpose use. This system has the functionality to visualise 3D models of construction operations and the resulting products more accurately, in relation to spatial and sequential aspects.

Taking into account the above research studies, previously developed 4D models were utilised at the design and construction stages mainly in building projects, but their application in construction planning and scheduling processes is still limited to infrastructure projects; for example, roads, railways, and oil and gas pipeline projects. The following section describes the previous research studies related to 4D modelling in road construction projects.

2.8.3 4D modelling in road construction projects

The literature review revealed that there are few published research studies on the topic of 4D models for road construction projects. Liapi (2003) discussed how 4DCAD visualisation models can be used in the construction phase of a highway project, and suggested a framework by developing and applying 4D modelling in such a project. He focused on the benefits of 4DCAD for traffic planning. He also highlighted that transportation projects often involve complex geometric configurations, which provide the communication of project information between interested parties. Liapi (2003) recommended that 4D visualisation models can provide a better understanding of the communication aspects and spatial constraints in a project compared with traditional 2D data.

Kang et al (2006) indicated that currently available 4D tools have outstanding functionality in simulating building projects, but that these tools are not easy to implement in civil engineering projects; for example, roads and railways projects, in which the progress of earthwork activities takes place in horizontal zones because the earthwork aspects depend on the natural ground conditions. He also suggested a new method to improve the limitations of the 4D system for a civil engineering project. The suggested approach included the use of a morphing technique to simulate 4D objects in earthwork operations. The operation included cutting and filling activities where they are progressed on natural ground conditions. Kang et al (2007) suggested an advanced methodology to organise 4D objects for construction

schedule management and progress control, including WBS to visualise 4D objects that consist of horizontal work areas in road construction projects.

Additionally, Makanae and Dawood (2008) developed a Tangible Terrain Representation System (TTRS). A tangible interface is one that recognises the terrain in 3D and provides a more efficient approach for highway route planning and design. The developed system was evaluated by comparing its usability to an alternative system using a group of evaluators at Miyagi University, Japan, and it was concluded that the system was an effective tool for terrain representation and highways planning. The system did not, however, consider the balancing of the earthwork quantities between cut and fill sections or between borrows/landfill sites for the road alignment planning processes.

Similarly, Kang et al (2008) also developed a 4DCAD system for earthwork simulation in selecting a road alignment to support road design, alternative to the route simulation, and structural simulation. The developed 4DCAD system failed to integrate different productivity rates for simulating earthwork operations and selecting a road alignment. Furthermore, Platt (2007) highlighted that the earthwork operations which did not work within a finite object were difficult to simulate with 4DCAD technologies. He recommended that a new approach was necessary to overcome this problem to assist the modelling of earthwork operations. Although the previous studies in 4D modelling of earthwork operations used and suggested different approaches, the key issue faced at the construction site is “variation in productivity value”, and this was not addressed. Site productivity of earthwork varies from one day to another because of the unique characteristics of the road construction industry, including deviations in topography, soil characteristics along the road, daily weather conditions, working conditions at the construction site, resource constraints, and other unpredictable factors.

Therefore, the research study is intended to overcome the above problems by developing an innovative approach for earthwork modelling that can produce the visual representation of terrain progress profiles (3D+time) by incorporating, partially or fully, all of the factors that affect the productivity of earthwork activities during the development of the tool.

2.9 Visualisation of Planning and Scheduling Information

The use of visualisation as an emerging technology in the construction industry means it is necessary to understand the potential benefits and concepts associated with its development in the construction field. The visual approach of understanding construction methods help construction managers to improve the effectiveness of project planning, and to enhance the communication of scheduling information amongst projects (Koo and Fischer, 2000; Dawood et al, 2002; Sriprasert, 2004).

Since the mid 1990s, space congestion was considered by construction researchers who have engaged in the innovation of visualisation technologies aimed at enhancing the capability of scheduling information, communications and resources planning. Visual representations are an important approach for the effective evaluation and communication of construction plans and schedules to construction teams. The visual representation of construction plans was divided into four categories: 2D, 3D, 4D and VR (Sriprasert, 2004; Chau et al, 2004; Fisher and Kunz, 2004; and Dawood et al, 2005).

1. Two dimensional representations include:
 - a. Worksheet – it is easy to prepare and is generally used for work-face instruction or method statement;
 - b. Bar chart or Gantt chart – it is used at operation-level planning or as a representation of CPM network;
 - c. 2D (two dimensional) drawings – these are normally used for site layout and space planning;
2. 3D (Three-dimensional) CAD – it is generally used for product conflict detection or clarification of detailed connections;
3. 4DCAD (3D+time) – it presents temporal and spatial aspects of visual construction plans in respect to time, and therefore it is useful for planning, evaluation and the communication of scheduling information.
4. VR – it is a technology that allows users to navigate and interact with virtual objects in 3D space with a computer-simulated environment. Therefore, it has a huge potential for application in construction planning

and in the graphical simulation of construction operations and traffic planning.

Two major approaches (4DCAD and VR) have been applied to aid the evaluation of physical constraints such as technology, space and safety with spatial aspects. For example, technological dependency constraint (McKinney and Fischer, 1998; Koo and Fischer, 2000), space constraint (Akinci et al, 2002; Dawood et al, 2002) and safety constraint (Hadikusumo and Rowlinson, 2002) are studies conducted using both 4DCAD and VR approaches.

Taking into account the above observations, the author thought that the above two approaches were mainly used to identify information on space and activities' conflicts and resource constraints. Therefore, visualisation technology would be useful for analysing space congestion and to communicate scheduling information from the location aspects in earthwork components amongst stakeholders in a road construction project. The next section discusses the past research associated with space congestion analysis.

2.10 Previous studies in Space Congestion Analysis

In earthwork, workspace is defined as the available space at construction sites for work activity. Several research studies (Kunz, 1994; Oglesby et al, 1989; Sander et al, 1989) revealed that space congestion is a major cause of productivity loss. Sander et al (1989) found a 65% loss in work efficiency because of space congestion at the workplace and a 58% loss in efficiency due to restricted site access in a construction project.

Moreover, VR technologies have been partially adopted in order to identify space conflicts in building construction works (Akinci et al, 2002; Dawood and Mallasi, 2006). Further innovation is added to this research study by introducing a numerical approach for identifying space congestion on a construction site at an early stage of earthwork operations. This approach depends on the principle of comparing the available and required space (area) for a selected set of construction equipment to perform a cutting or a filling operation in a road construction project.

Construction managers are under pressure to deliver construction projects on time and within budget. To overcome these issues, planners and contractors are planning and scheduling additional work activities simultaneously by reinforcing additional equipment required by the activities. As a result, space congestion can occur due to the limited space at a construction site or because of management pressure to perform concurrent activities in the same areas. Moreover, additional demand for work space by different sets of equipment can also lead to space congestion or activities conflicts on a construction project.

Similarly, time-space congestion also occurs when the space requirements of one activity interfere with another activity's space requirement. Therefore, this decisive factor affects the productivity of any construction activities and the overall delivery schedule of the project. Space congestion causes several problems such as delays in work progress, reduction in productivity, and incremental increases in safety hazards (Dawood and Mallasi, 2006).

Earthwork operations, in particular, can cause issues due to the movement of construction equipment in a limited space at the beginning of the construction stage. Since the working activity progression takes place in the horizontal direction on existing terrain surfaces, the correct planning of working space is vital.

Planning and scheduling of the equipment sets and relocation of material can be managed effectively and efficiently within the available working space at a construction site, if a suitable equipment set is planned according to the space availability. Therefore, the study intends to develop new methodology that can assist in identifying the space-congested activities at the early stage of earthwork construction sites and can help to manage them by selecting a suitable set of construction equipment within those sets available.

2.11 Review of Existing Software and Tools in Construction

This section describes the key features, functionalities and limitations of existing commercial and research software currently used in the construction industry. The software review assists in analysing the development of a tool for the generation of location-based earthwork scheduling in linear construction projects.

The software review highlights the main functionalities of the software which includes: Autodesk Civil 3D; CAICE Visual Constructor; VICO Constructor; Construction SIM; Naviswork Solution; Inroad; DynaRoad; TILOS; V-CPM; 5D-CCIR and UC/Win Road, used for real time 3D VR modelling of urban planning, traffic and disaster simulation.

The VIRMEEC tool, which is used for the automatic generation of location-based schedules and weekly progress profiles of earthworks, weekly quantities and costs at each chainage/stations along a road section, considering different productivity rate throughout the construction process, is developed and outlined in this study. A comparative study of the functionalities, limitations and features of the commercially available and researched software is presented in Table 2.3.

2.12 Summary

This chapter provided an overview of the existing construction planning and scheduling techniques used in construction projects. The main focus was on the existing planning and scheduling techniques and tools useful for analysing earthwork components in road construction projects. The theory of the location-based planning was analysed and discussed. The limitations of these techniques and tools in solving time-location scheduling and space congestion identification in earthworks construction projects were explained. The discussion and review of the literature suggests that there is a requirement for better visualisation methodology to communicate construction scheduling information for the allocation of a suitable set of equipment at correct locations along linear road construction projects.

The following are the key conclusions from the literature review:

- The review of the literature found that a gap existed in earthwork modelling approaches because the systems developed to date fail to integrate different productivity rates into the processes associated with earthwork scheduling in road construction.
- The study of the literature also revealed that existing LSMs of linear projects do not provide exact information on the working locations of earthwork activities in a particular period on a daily or weekly basis.
- The visualisation of scheduling information of earthworks with location aspects on a weekly basis is missing.
- The key issues faced at road construction sites are the variations in the productivity rates of earthworks from day-to-day and location-to-location along a road section.
- Earthwork activities significantly affect other road activities and the overall performance of construction site operations due to the unique characteristics of earthwork in linear construction projects.
- The literature review also showed that location-based planning is a valuable technique for planning and monitoring the progress of linear construction projects. It also helps in time-extension claims in case of variation in earthwork quantities at a particular location at the construction stage.
- The past research studies related to location-based planning show that the improved schedule overview, establishment of workflows and enhanced project control from location aspects are the major three constructive implications of location-based scheduling.

Taking into account the above points, the research explored a new methodology for the development of a computerised model for earthwork scheduling and the visualisation of the scheduling information from the location aspects. The next chapter presents a construction industry survey that was aimed at identifying the existing practices and problems in construction planning, scheduling, simulation, and the visualisation processes of earthwork operations, particularly in infrastructure construction projects.

Table 2.3 Features and functionalities matrix of commercial and research software utilised in construction applications

	Software Features	Visual Construction	VICO Constructor	Autodesk Civil 3D	Nova point Constructor	Terramodel	12d Model	Autodesk Nevis work	Bentley schedule Simulator	Construct-Sim	GeoNet V-CPM	Inroad	DynaRoad	5DCCIR	RoadSim	VIRMEEC Tools
Application	Area of Implementation	Construction oriented	Construction oriented	Design oriented	Construction oriented	Construction oriented	Design oriented	Construction oriented	Construction oriented	Construction oriented	Construction oriented	Design oriented	Construction oriented	Construction oriented	Construction oriented	Construction oriented
	Area of compliance in Road Project	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Data Exchange	Support of LandXML: Input/output	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Partially
	DWG/DXF Input/output	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No
	API flexibility	Yes	Yes	Yes	Yes	Yes	Yes	Don't Know	Don't Know	Don't Know	Don't Know	Yes	No	Don't Know	Yes	Yes
TIN Modelling	3D Terrain Modelling (TIN)	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	No	No	No	Yes
	Volume Calculation of TIN layers	Yes	No	Yes	Yes	Yes	Yes	No	Don't Know	No	No	Yes	No	No	No	No
4D & 3D visualisation	3D model Visualisation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes
	4D modelling	Yes	Yes	No	No	No	No	Yes	No	No	Yes	No	No	Yes	No	Yes
Analysis	Optimisation/ Simulation	No	No	No	No	No	No	No	No	No	No	No	Yes	No	Yes	Partially

Note: Yes No/partially Don't Know

Chapter – 3

Construction Industry Survey

3.1 Introduction

The need for the development of a new methodology and a prototype model for earthworks scheduling and visualisation considering location aspects, particularly in road construction, was discussed in the previous chapter. Chapter Two presented the earthwork characteristics and established that there was a knowledge gap associated with modelling issues in earthworks scheduling. This chapter presents a construction industry survey that aimed to identify the existing practices, limitations and tools utilised in earthwork scheduling. The problems associated with planning, scheduling, simulation, and visualisation processes of earthwork operations in linear construction projects are also discussed in this chapter.

This chapter also describes the questionnaire design, data collection and analysis, and summarises the findings of the survey. A review of the construction processes was also carried out to identify the stages where a prototype model could be relevant in construction projects. A map of construction processes was developed, showing the possible stages where a developed prototype model would be valuable in construction projects. The knowledge gained from the survey is used to justify and inform the research study.

Finally, this chapter outlines the critical issues and factors that need to be incorporated in the development of the model for earthwork scheduling and visualisation. The next section reviews the pre-construction and post- construction processes of an example construction company.

3.2 Review of Construction Processes of a Company

An important step in this research is the understanding of the details of pre- and post-construction stages in a road project. For this reason, the construction processes of a construction company, which was mainly involved in road construction projects,

were analysed. Firstly, site information and production methods were established for the survey of construction processes by interviewing the Production Director of a Portugal-based international construction company, Mota-Engil. The findings from the review of the construction processes were documented in a process-mapping diagram as shown in Figure 3.1 with four classification levels: project bidding/tendering; preparation of tender document; detailed planning stage for execution; and control process for progress monitoring. These processes are explained in the following sections.

3.2.1 Project bidding/tendering process

Project bidding or tendering is the first stage of the construction process. In this process, bid information of a construction project is obtained first from public or private organisations by the commercial department of a company. The management board of the bid purchasing company makes the decision normally to continue or reject the bid for projects based on a feasibility study and the information provided in the tender documents. Once a decision is made to start the bidding process, the preparation of bid proposals (bidding/tender documents including both technical and financial bids) are prepared, taking into consideration the company's preliminary cost estimate, limited site information, and the initially proposed construction methods within the limited resources. The details of the proposal preparation are explained in the next section.

3.2.2 Preparation of proposal (tender/bidding documents)

The bidding or tender documents normally consist of contract documents including detailed design drawings, specifications and the Bill of Quantity (BoQ). Depending on the nature and complexity of the projects, site visits and surveys are then carried out to collect the most reliable information regarding the locally available resources, site location, topography, site access points, and local rules and regulations. Such knowledge has a direct impact on the site productivity calculation, developing project scheduling, resource planning, costing the project tasks and selecting the construction methods.

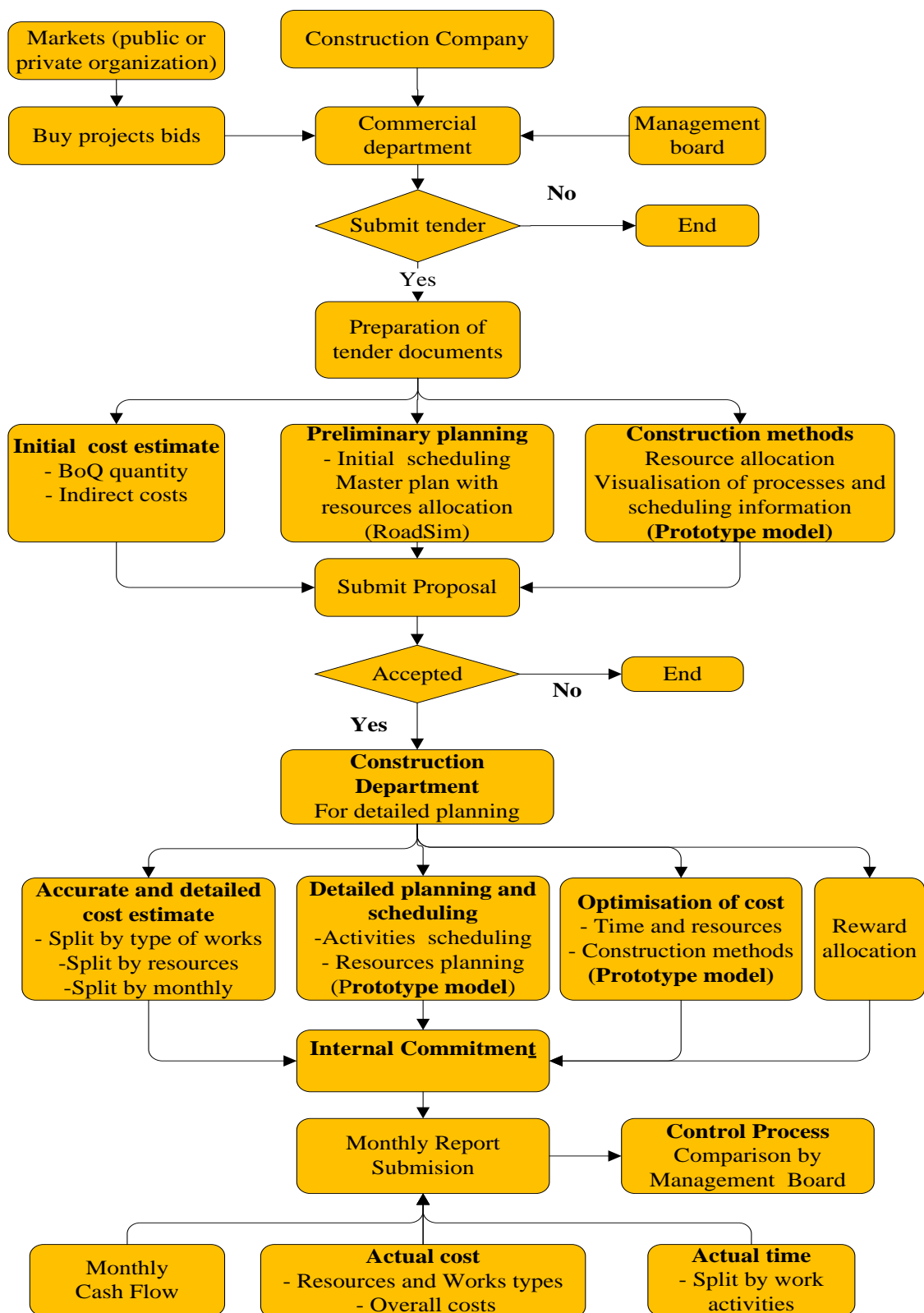


Figure 3.1 Map of construction business processes and sequences in a company

The preliminary cost estimates are based on the tender BoQ, design drawings and the specifications of works and materials provided in the contract document. Preliminary scheduling of work activities is prepared and resources are planned considering the limited site information. The preliminary construction methods are outlined to justify the bidding cost of the project and to demonstrate the construction processes. Then, the developed proposals are submitted by the bidding company to clients after completing all essential documents. Depending upon the nature of the projects, construction methods are prepared in text or graphic representation, sometimes with visualisation tools by the bidding company to show the company's expertise and technical capability of delivering the project. The visualisation tool also assists the company to persuade clients by showing the virtual construction methods and sequences of construction operations that provide additional support to the bidding company to win the bid proposal of a project.

After receiving the confirmation of the proposal, the commercial department of the bidding company forwards all essential documents to the construction/production department for the preparation of detailed plans and estimates of the project cost. The next stage is the planning and scheduling processes of a construction project. Detailed cost estimates and schedules are prepared based on available resources and the previous experience of the bidding company.

3.2.3 Detailed planning and scheduling processes

After winning the project bid, the bidding company starts the preparation of accurate and detailed project estimates for different categories such as type of works and type of resources on a monthly basis. Similarly, a detailed construction schedule is prepared considering work activities and project duration using available resources. Resource planning is a crucial process that affects the overall project performance. At this stage, focus is concentrated on resource scheduling using available tools to deliver the project on time and within the budgeted cost. Additionally, more accurate and efficient construction methods are prepared to execute the construction tasks. Depending on the company's experience and other constraints, a few months may be required to prepare the detailed execution plan and schedule before starting the construction project. An internal commitment is made and milestones are fixed by

considering necessary support and resources. The construction responsibility is transferred to a project manager for execution of the project according to the agreed detailed schedule and assigned site budgeted cost. The next section describes the control process of the construction progress

3.2.4 Control processes in construction operations

At this stage, a monthly progress report is prepared and submitted to the control department of the company for a comparison between planned progress and actual progress in terms of time and cost. The monthly report basically consists of a monthly cash flow plan; a breakdown of the actual cost in terms of utilised resources and works activities; and the actual time consumed by each activity.

The progress report is compared and discussed by the company management team in order to implement the possible corrective actions so that the construction progress can be maintained on schedule and budget. Sometimes, additional resources are allocated to complete the project within an agreed time frame and to avoid additional penalty charges (liquidated damages). The control process is normally continued every month until completion and handover to the clients as per the designed drawings and work specifications.

The next section discusses the details of the construction industry survey, data collection, analysis and results. The discussion and recommendation from the survey findings are also presented in the following section for the development of a framework and specifications of a computerised model of earthworks.

3.3 Construction Industry Survey

3.3.1 Introduction

The main objectives of the construction industry survey were to identify the existing practices, techniques and software being used; to understand the problems faced in construction planning and scheduling tasks; and to note any existing use of visual modelling and simulation practice that are used in the construction planning tasks.

UK-based road, railway and civil engineering construction companies were included in the construction industry survey.

3.3.2 Questionnaire design and data collection

A semi-structured interview questionnaire was designed by interviewing construction managers and was aimed at identifying the current practices and techniques, limitations, construction methods, critical factors affecting site productivity, and possible applications of 4D visualisation technologies in earthwork operations. Random sampling methods were used to select the construction companies, mainly involved in civil engineering and infrastructure projects, for the purpose of collecting the responses of a questionnaire. The survey was conducted through the post, by email and in person. A sample of the responses is shown in Appendix-B. A total of 30 responses out of 50 (60%) questionnaires were received from construction companies in the UK. The data analysis and results of the industry survey are presented in the following section.

3.3.3 Data analysis and results presentation

The responses from questionnaires were included in the data analysis. After analysing the survey data using frequency analysis techniques, the survey results are presented in tables and graphs (see Figures 3.2 to 3.12 and Tables 3.1 to 3.7). The companies that participated in the survey were involved with projects valued between £5 million and £50 million, mostly road/highway projects. Considering their past experience, it was assumed that such companies would have a good track record and be reputable construction organisations. Such companies' responses were expected to provide crucial information regarding the existing practices and techniques in construction projects. The questionnaire was categorised into four sub-sections as below:

1. Background information of participating company
2. Existing practices at tender/bidding stage
3. Existing practices at detailed planning and execution stage
4. Practical applications of visualisation tools in the construction industry

Each section was designed with the aim of understanding any relationships that may exist in the earthwork planning, scheduling and visualisation of road construction processes. The responses from questions 3, 6-7 and 17-19 of the questionnaire were excluded from the analysis due to the omission of satisfactory answers; these responses were, in any event, less relevant to earthwork scheduling and visualisation modelling aspects. The findings from the survey analysis are presented and discussed in the following sections.

3.4 Background Information of Participating Companies

The survey results related to the company backgrounds are displayed in Figure 3.2. The types of construction projects and project values involved are shown below.

Types of construction projects involved:

- Roads/highways 54%
- Railways 9%
- Pipelines 13%
- Tunnels 2%
- Other 22%

Project value involved:

- Equal or less than £10 million 37%
- Between £10-25 million 27%
- Between £26-50 million 13%
- More than £50 million 23%

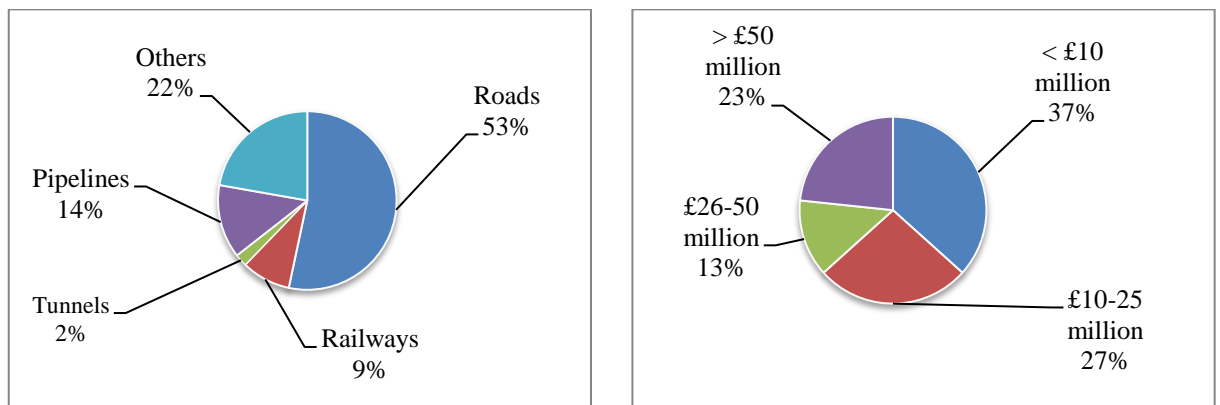


Figure 3.2 Participating company market segments

Participants were asked for information in relation to existing practices and software being used in construction planning, and existing problems and critical factors that they faced in their planning and scheduling process of earthwork operations at construction sites. The survey data collected from participants were analysed and presented in the survey results. The following section discusses the survey results related to the existing practices and issues at the tender/bidding stage.

3.5 Existing Practices and Issues at Tender/Bidding Stage

3.5.1 Basis of priority considered for a schedule development

Question 4 asked about the basis for the development of a construction schedule, and the respondents expressed their view that schedules were developed based on the priority factors of the project requirements such as project duration; project cost; complexity of projects; type of contract, like cost plus time (A+B) contract; and others. Figure 3.3 shows their responses.

The findings from the survey suggest that project duration is still the major priority factor being considered during the development of construction schedules.

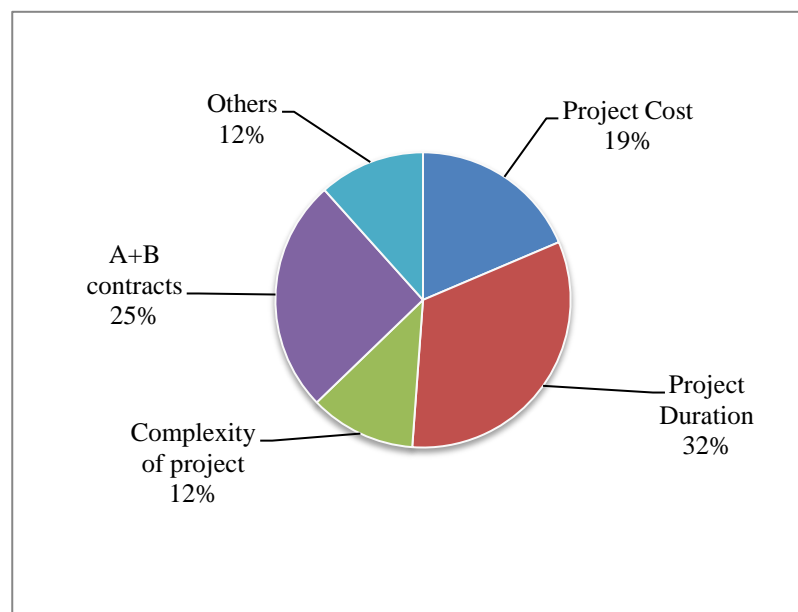


Figure 3.3 Prioritisation of the construction schedule development

3.5.2 Responsibilities for project planning and scheduling

Question 5 asked about the responsibility for developing a construction plan and schedule. Most respondents answered that their construction companies assigned one planner for the planning job, whilst others advised that normally a team of planners (two or more) and construction managers were engaged to develop a construction schedule according to the project value and size. Few companies appointed a specialist consultant or consulting company, though this depended on the complexity of projects. The survey identified the responsible organisations for planning and scheduling, which are shown in Figure 3.4 below.

The survey findings about organisation charts revealed that, generally, one planner is involved in the planning and scheduling process in construction projects. Planning and scheduling can, however, be improved more effectively by involving experienced team members, project planners and construction managers, or by appointing a specialist consultant, considering the value and complexity of the construction projects.

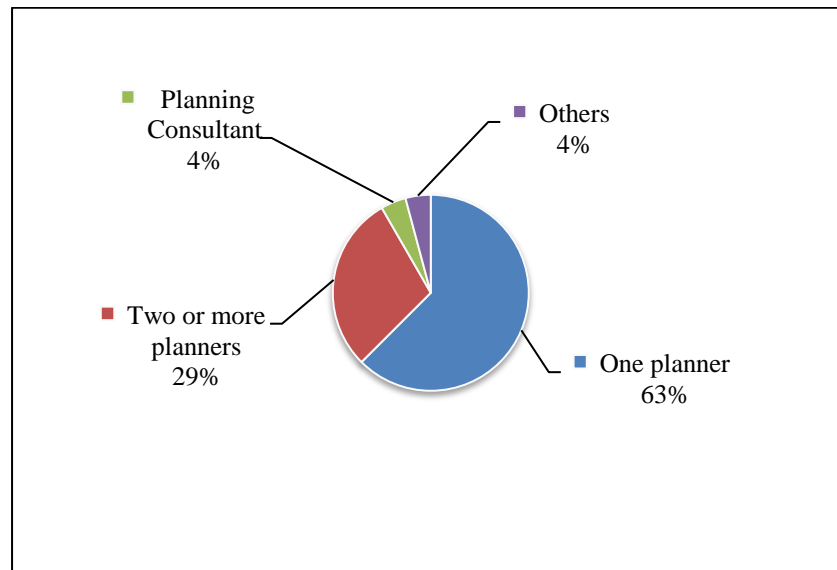


Figure 3.4 Responsibility shared in the planning and scheduling of tasks.

3.5.3 Identification of delay factors in earthwork operations

The respondents were asked to rank the major problems facing companies in earthwork operations. The result identified that the factors such as poor construction

planning (incorrect resource plan, activities sequences and assigned duration); relocation to utilities; and change orders by clients, contributing to the delay of earthwork construction projects. Incorrect design and equipment breakdown contributed minor delays to projects. The results obtained are shown in Figure 3.5.

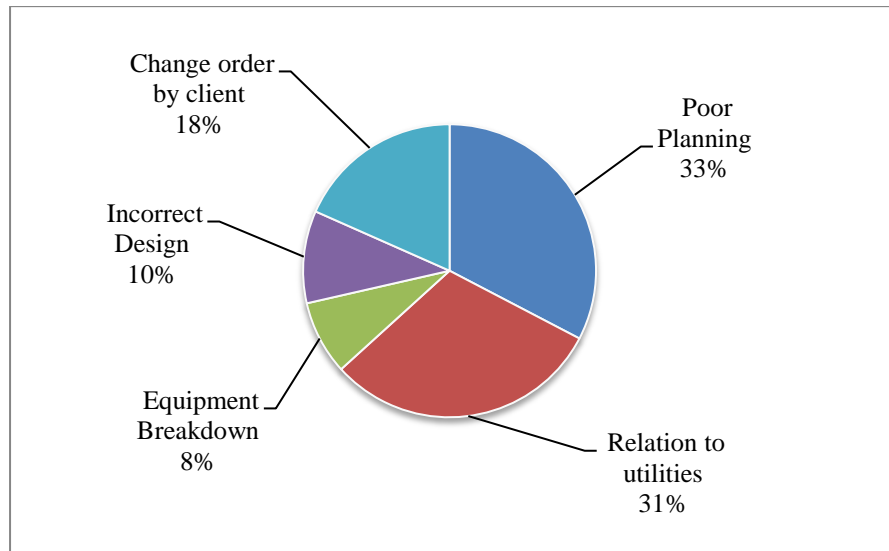


Figure 3.5 Delay factors affecting earthwork operations

From the analysis of the findings, it was concluded that planners need to focus more carefully on the impacts of possible change orders and the relocation of utilities, and to prepare effective resource planning of the earthwork operations. The following sub-sections describe practices, software and techniques used for earthwork planning and the list of critical factors that affect the planning of earthwork operations.

3.6 Existing Practices and Software used at Execution Stage

3.6.1 Existing practices in planning and scheduling

The following categories were utilised:

- A - Always
- B - Sometimes
- C - When necessary
- D - Control Impaired
- NE - No Experience
- Mean - Average Value
- SD - Standard Deviation

The survey results showed that the majority of companies still highlight previous experience as the key influencing factor in the development of construction plans and schedules; however, a few companies use intuitive methods and ‘rules of thumb’ for project planning and scheduling. Amongst the participating construction companies, the responses in the survey identified the planning and scheduling source for earthworks, particularly considering the type-A category of responses as follows:

- 73% of construction companies are still using past experience
- 20% intuitive methods
- 7% rule of thumb

The survey results of different planning and scheduling approaches for type A, B, C, D and NE cases gave a different value of mean and SD, presented in Figure 3.6 and Table 3.1.

Table 3.1 Frequency of participants in existing practices of planning and scheduling

Planning/scheduling Approach	A	B	C	D	NE	Mean	SD
Past Experience	22	3	0	0	0	5	9.6
Intuitive Methods	6	11	4	0	3	4.8	4.1
Rule of thumb	2	8	5	3	2	4	2.5

The survey results also discovered that “rule of thumb” was always used by 10% of contractors, 40% sometimes, 25% when necessary and 15% under impaired control, and that 10% of contractors had no knowledge, with the mean value of 4 and standard deviation of 2.5. However, intuitive methods were always used by 25% of contractors, sometimes by 46% of contractors, and by 13% of contractors when necessary, while 10% had no experience. The mean value is 4.8 and the standard deviation 4.1.

Similarly, the survey results also revealed that 88% of contractors always used past experience and 12% used it sometimes, with a mean value of 5 and a standard deviation of 9.6. Past experience is the most critical factor used to determine the duration of tasks and their sequential relationship amongst other tasks in producing a construction schedule, but none of those surveyed used a ‘what-if’ scenario analysis or visual simulation models for earthwork planning and scheduling processes.

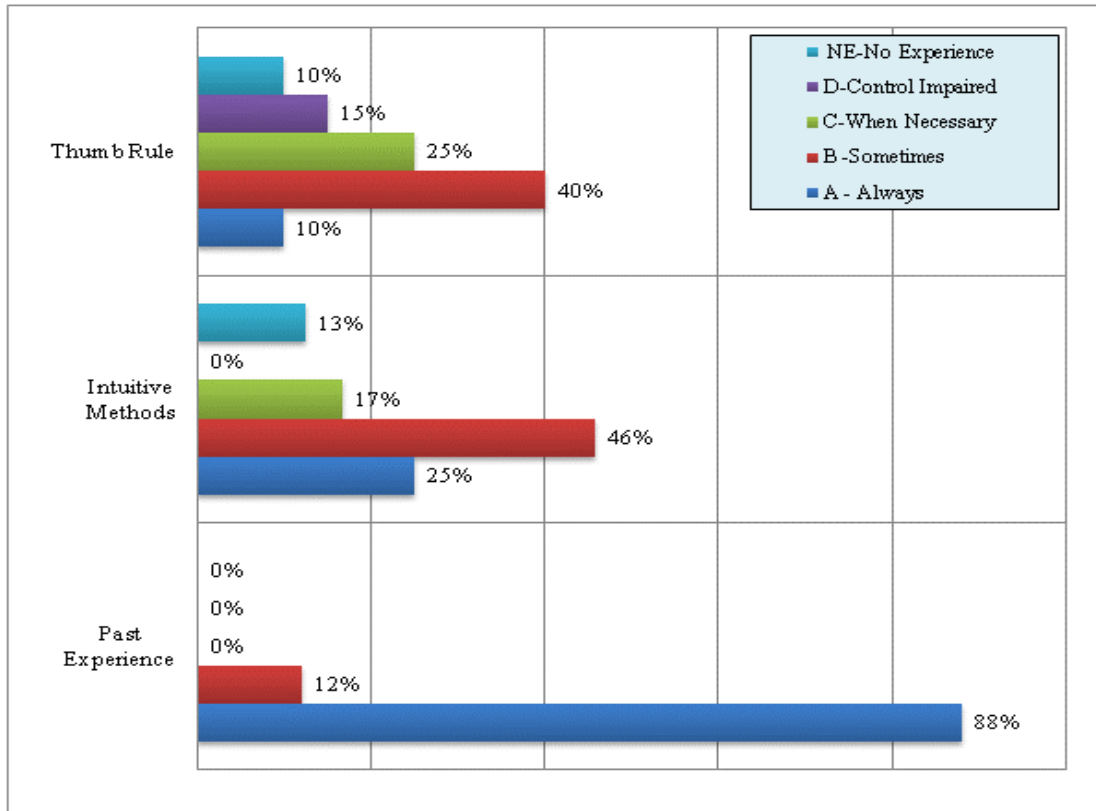


Figure 3.6 Existing practices used in construction planning and scheduling

3.6.2 Software currently used for construction planning and scheduling

The findings from the survey suggested that different construction companies use different types of planning and scheduling software based on available expertise and the contract requirements. The survey results of different types of planning and scheduling software for the case of A, B, C, D and NE are shown in Figure 3.7 and Table 3.2 below

Table 3.2 Frequency of planning software used by construction companies

Planning and Scheduling Software	A	B	C	D	NE	Mean	SD
Power Project	6	1	1	0	8	3.2	3.6
MS Project	7	8	2	0	4	4.2	3.3
Primavera	6	7	4	0	4	4.2	2.7
Sure-Track	7	6	0	0	6	3.8	3.5
TILOS	1	0	2	0	12	3.0	5.1
Others	0	2	2	0	0	0.8	1.1

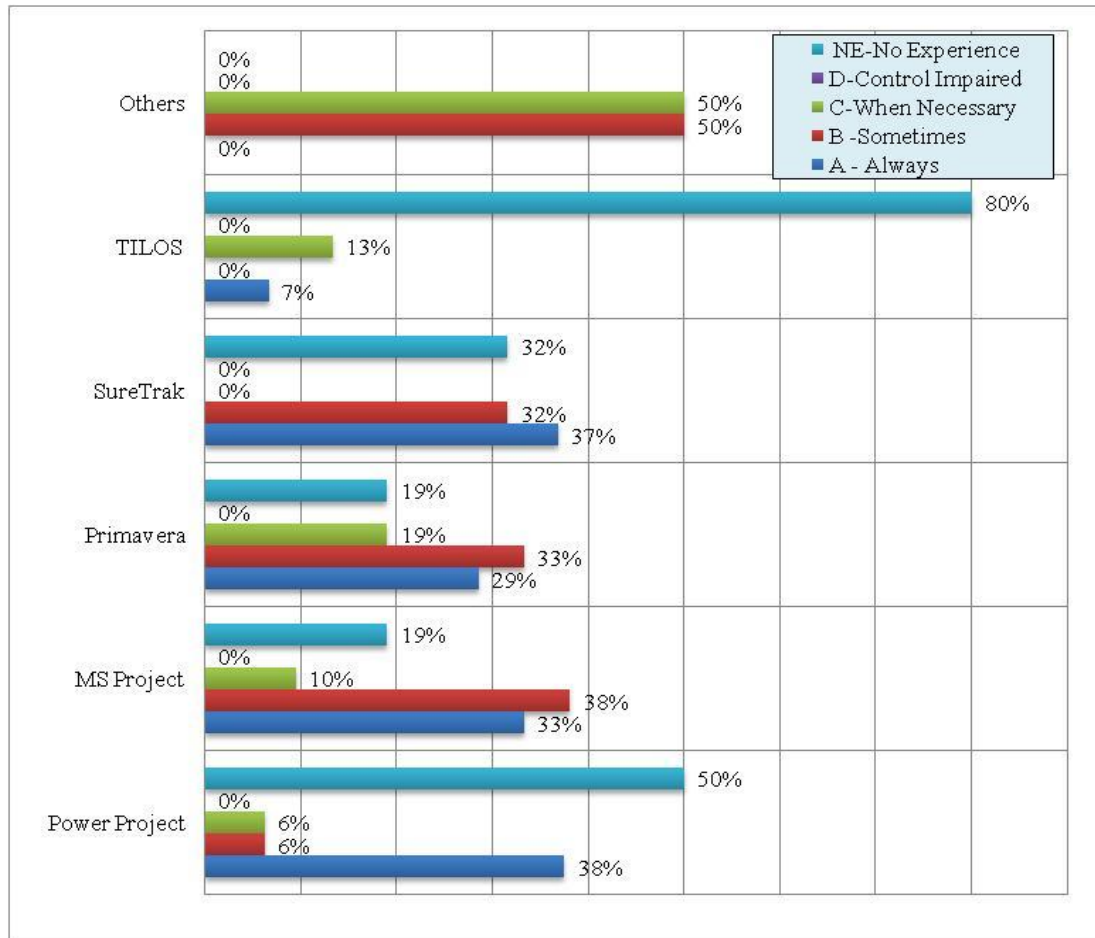


Figure 3.7 Types of software used in construction companies

The survey results revealed that ‘Power Project’ was always used by 38% of contractors, sometimes by 6%, and by 6% when necessary, having a mean value of 3.2 and SD of 3.6. In contrast, 33% of contractors always used MS Project, sometimes 38%, 10% when necessary, and 19% had no experience, with a mean value of 4.2 and SD of 3.2. The survey results for Sure Trak, Primavera, TILOS and ‘Others’ are shown in Figure 3.7. It is clear from these results that visual simulation or modelling tools are not used for earthwork planning and scheduling processes.

3.6.3 Existing practice of producing project schedules

Responses to Question 12, regarding the types of detailed scheduling used at the construction stage, indicated that different companies have different sequences and scheduling frequencies according to the contract requirements and the complexity of construction projects. For type-A responses, the results are given below:

- 49% of companies develop the schedule on a monthly basis
- 32% on a weekly basis
- 16% on a bi-weekly basis
- 3% on another time scale

The responses also revealed the differences for the A, B, C, D and NE categories, which are presented in Figure 3.8 and Table 3.3 below.

Table 3.3 Frequency of responses by participant for scheduling types

Types of Scheduling	A	B	C	D	NE	Mean	SD
Weekly	12	8	2	0	1	4.6	5.2
Bi-weekly	6	8	1	0	1	3.2	3.6
Monthly	18	3	0	0	0	4.2	7.8
Others	1	1	0	0	0	0.4	0.5

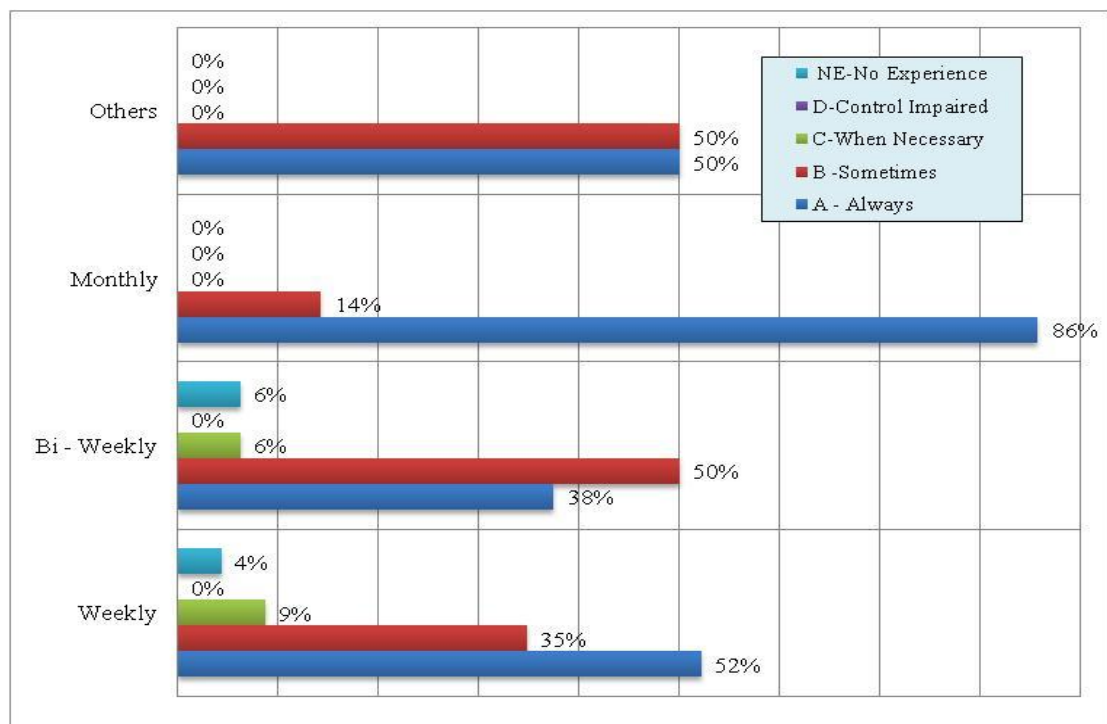


Figure 3.8 Schedule development levels used in construction projects

The survey results revealed that the weekly schedule was always used by 52% of companies, 35% sometimes, and 9% when necessary, while 4% had no experience, with a mean value of 4.6 and SD of 5.2; whereas 38% of companies always produced bi-weekly schedules for planning and monitoring construction projects,

50% sometimes, and 6% when necessary, while 6% had no experience, giving the mean value of responses as 3.2 and SD as 3.6.

The conclusion to the findings from the survey was that the majority of construction companies (86%) of category-A still use monthly construction plans and schedules, whilst (52%) of category-A also used both weekly and monthly plans for progress monitoring purposes when they believed these were necessary. However, daily schedules were also used to monitor the day-to-day progress of activities within the weekly assigned activities.

3.6.4 Existing practices used in earthwork planning techniques

For the existing practices of earthwork planning, the findings from the survey exposed the following tendencies when considering only the case of ‘always’ (type-A) responses:

- 57% construction companies are using Mass Haul Diagram
- 33% use Past Experience
- 7% use commercial software
- 3% use ‘What-If’ Scenario

The survey results of responses for type A, B, C, D and NE cases are shown in Table 3.4 and in Figure 3.9 below.

Table 3.4 Responses from companies used in earthwork planning techniques

Earthwork Planning Techniques	A	B	C	D	NE	Mean	SD
Mass Haul Diagram	17	7	0	0	3	5.4	7.1
What-If Scenario	1	8	1	1	7	3.6	3.6
Past Experience	10	6	5	0	3	4.8	3.7
Commercial Software	2	1	0	0	12	3	5.1

The survey results discovered that 63% of construction companies always used and 26% sometimes used a Mass Haul Diagram, and that 11% have no experience, with a mean value of 5.4 and SD of 7.1; the other results can be seen in Table 3.4 and Figure 3.9. The survey results showed that there is no existing practice in the use of software for visual simulation or modelling of earthwork planning using a ‘What-

If Scenario for different site conditions and soil types. The analysis of the survey findings identified that the majority of companies still use the previous experience of their professionals and intuitive methods for scheduling and planning processes.

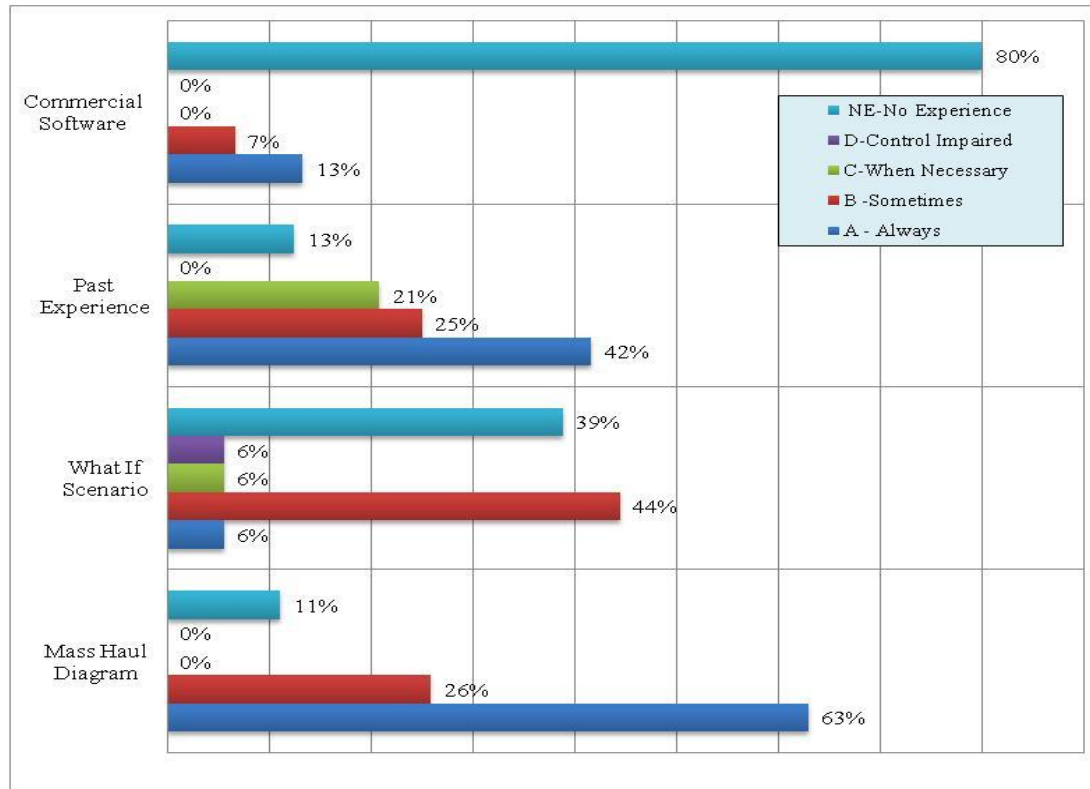


Figure 3.9 Types of earthwork planning methods used in construction projects

3.6.5 Critical factors affecting earthwork planning and operations

The respondents were asked to rank the critical factors considered in earthwork planning operations. The ranking results are presented in Figure 3.10 and Table 3.5. According to the survey results, the critical factors were ranked in the following order:

- Soil characteristics
- Method of construction
- Access road conditions
- Number of access points
- Location of borrow pits
- The availability of equipment was

Table 3.5 Ranking responses of critical factors in earthwork planning

Types of critical factors	1	2	3	4	5	Mean	SD
Number of site access points	5	5	8	5	7	6.00	1.41
Soil characteristics	1	2	4	5	18	6.00	6.89
Method of construction	1	4	6	9	10	6.00	3.67
Availability of equipment	4	8	7	6	5	6.00	1.58
Location of borrow pit	0	4	10	10	6	6.00	4.24
Access road condition	3	6	7	6	8	6.00	1.87

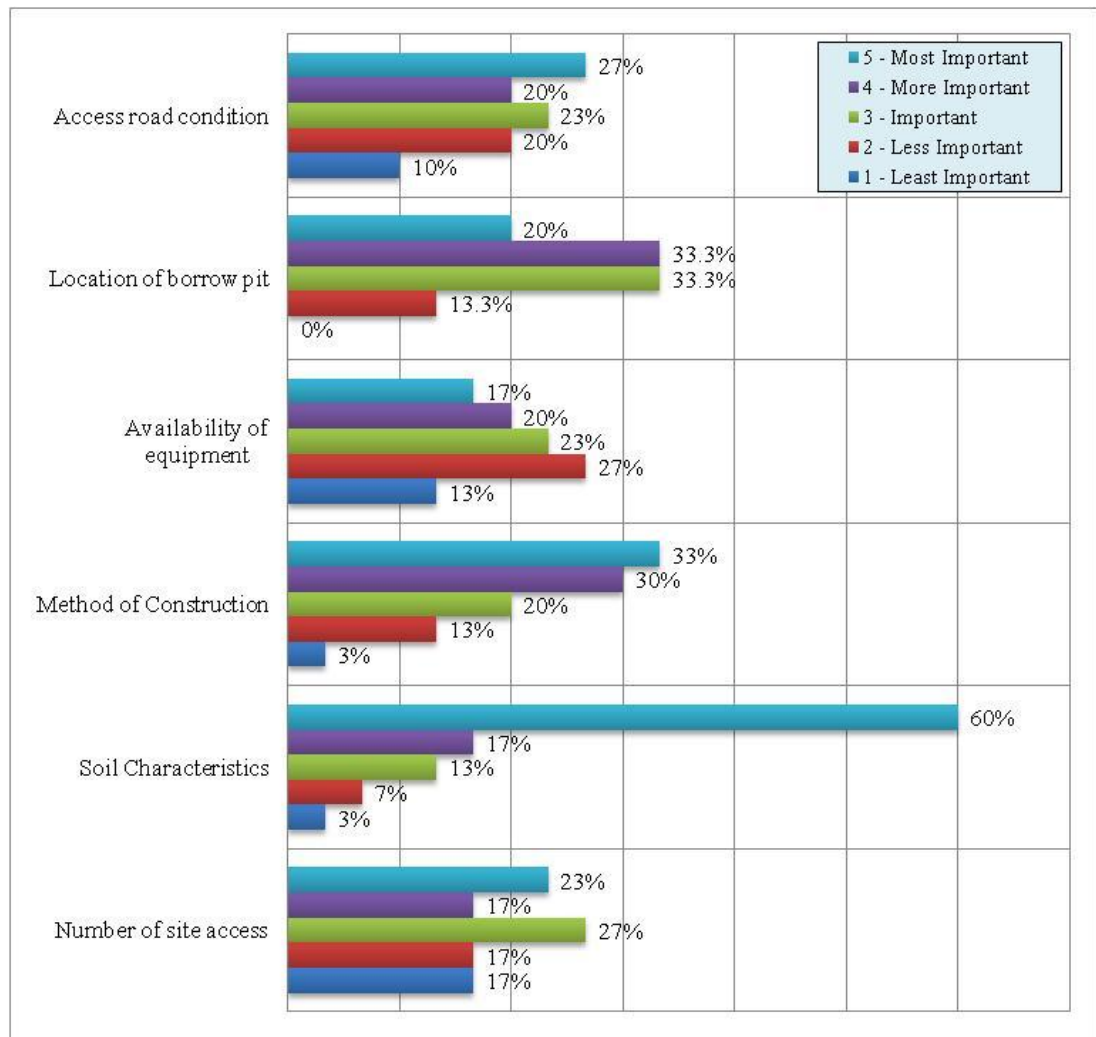


Figure 3.10 Critical factors affecting earthwork planning and operations

The survey results showed that access road condition was ranked by 27% of contractors as the most important factor, 20% as more important, 23% as important, 20% as less important and 10% as least important, with a mean value of 6.0 and a standard deviation of 1.41. The ranking results of the rest of the critical factors are presented in Table 3.5 and Figure 3.9. The respondents were experienced planning and construction professionals and the author believes that the information and

opinion provided by them was reliable and valid in relation to the construction planning and scheduling of earthwork operations. The analysis of the survey revealed that ‘soil characteristics’ is the most critical factor that affects earthwork planning.

3.7 Future Applications of Visualisation Tools

3.7.1 Anticipated application of visualisation tools at different stages

The respondents agreed that visualisation tools are applicable and beneficial at different stages of construction projects. When considering only a type-A category, the application stages of visualisation tools cited by interviewees were found as follows:

- 46% at detailed planning stage
- 27% at tender/bidding stage
- 24% at execution stage
- 3% at other stages

The survey results of responses for type A, B, C, D and NE cases are presented in Figure 3.11 and Table 3.6 below.

Table 3.6 Responses for application stages of visualisation tools

Application stages of visualisation tools	A	B	C	D	NE	Mean	SD
Tender/bidding stage	9	10	4	0	4	5.4	4.1
Detail planning stage	15	6	0	0	5	5.2	6.1
Execution stage	8	8	2	0	6	4.8	3.6
other stage	1	0	0	0	3	0.8	1.3

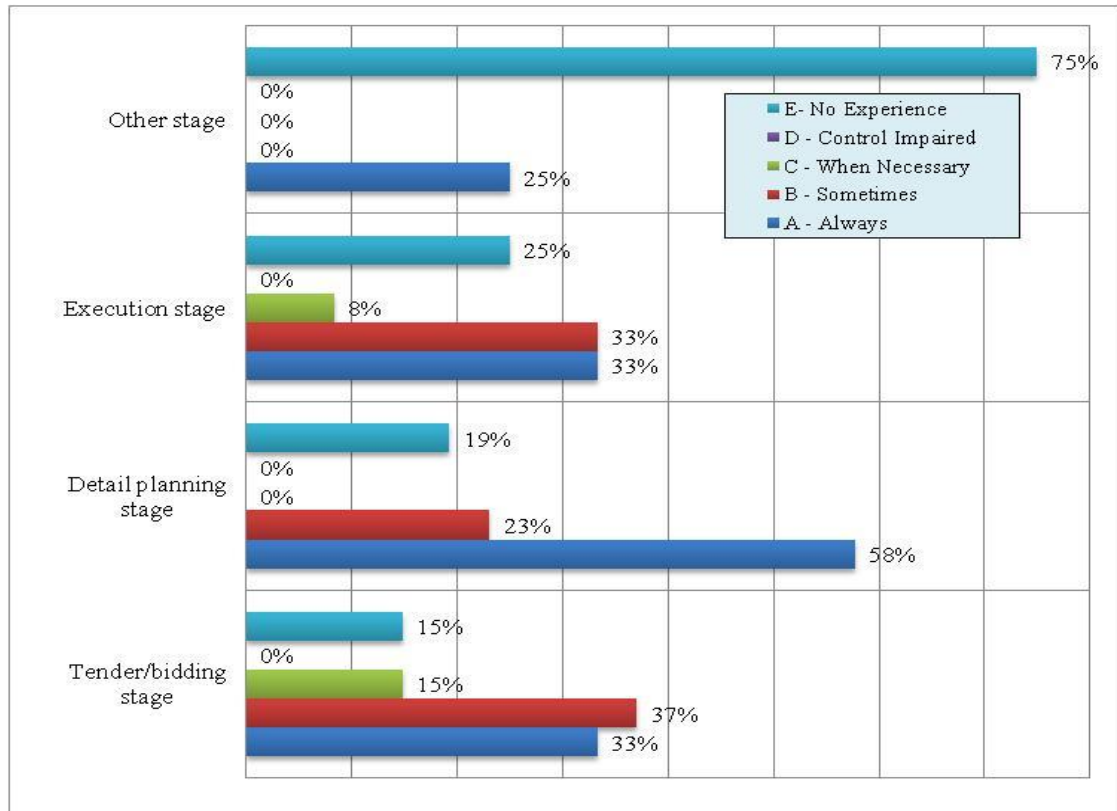


Figure 3.11 Application stages of visualisation tools in construction projects

The survey results revealed that a visualisation tool is most valuable at the detailed planning stage; however, the tool is also useful at the tender and site operation stage. The survey result showed that 33% of contractors always used visualisation tools at the tender/bidding stage, 37% sometimes, and 15% when necessary, but that 15% have no experience, with a mean value of 5.4 and SD of 4.1. The respondents agreed that the tender stage is more valuable in comparison to the detail planning stage. The analysis of the survey concludes that visualisation tools are beneficial in developing effective construction scheduling and efficient resource planning by the visual simulation of the construction process using a ‘what-if’ scenario for different site conditions

3.7.2 Importance of visualisation tools in earthwork operations

The respondents were asked to rank the application areas/influencing factors such as improvement in communication of scheduling information; pre-information of activity sequences; and crew/equipment conflicts that assist in updating in a schedule production and identification of idle time. The aim of ranking these factors is to

determine the site application areas for the existing visualisation tools in earthwork operations.

The results of the industry survey responses are shown in Table 3.7 below, on a scale of more important, important, less important and least important cases, aimed at identifying the application areas of visualisation tools. The results of the survey are presented in Figure 3.12 below.

Table 3.7 Responses in the scale of importance of visualisation tool

Application areas of the tools	1	2	3	4	5	Mean	SD
Communications improvement	3	7	2	7	8	5.4	2.7
Sequences of activities	0	1	5	8	13	5.4	5.32
Crew/equipment conflict	5	6	7	5	4	5.4	1.14
Assist in scheduling	4	8	7	5	3	5.4	2.07
Identifying idle time	4	3	10	7	3	5.4	3.05

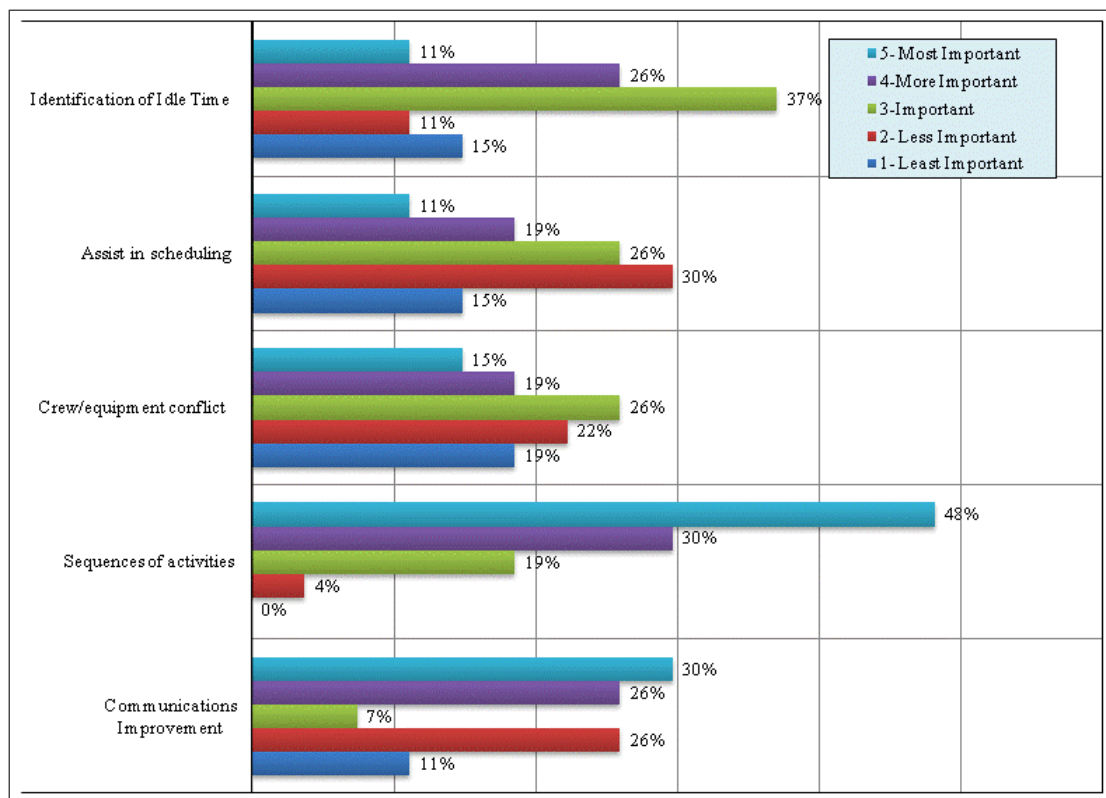


Figure 3.12 Site applications of visualisation tools in earthwork operations

The survey results showed that visualisation tools enable the improvement of the communication of scheduling information, and was ranked by 30% of contractors as the most important factor, 26% as more important, 7% as important, 26% as less

important, and 11% as least important, with a mean value of 5.4 and standard deviation of 2.7.

The respondents ranked from the most important to least important factors which have high impact on visualisation systems in earthwork planning. For the most important case, the responses provided by the participants showed that visualisation tools assist in the influencing factors, according to a descending order of impact in earthwork planning as shown below:

- 48% - providing advanced information of activity sequences
- 30% - improving the communication of scheduling information
- 15% - assisting in updating the construction schedule
- 11% - identifying the idle time of the equipment
- 11% - crew/equipment conflict identification

Considering the survey results above, it was concluded that visualisation tools for earthwork operations are beneficial for resource planning and in producing effective construction schedules. They enable proactive actions to be taken before embarking on the execution stage by virtually rehearsing the construction process of earthwork, which is the “major operation” in road construction projects and plays a great role in project delivery on time and within cost. This is because of high uncertainty factors affecting earthwork activity, i.e. different site conditions in the open air, weather uncertainty and resource constraints.

3.8 Discussion and Findings from Construction Industry Survey

After analysing the survey data, the results of the survey were presented in tables, graphs, pie charts and histograms. Simulation of the different variables that affect earthwork schedules before starting the project execution can play a valuable role in improving project execution and control. Earthwork activity plays a substantial role in the final cost and delivery parameters because of the unique characteristics and the uncertainty involved. Any improvements in this area will therefore contribute

significantly to the success of a project. The findings which are drawn from the survey data analysis are listed below:

1. Lack of scheduling information regarding the activities sequences, changes in soil characteristics and variation of equipment productivity are the key factors to be considered for the development of an effective and efficient construction plan of earthwork operations.
2. From the findings of the survey, most of the construction companies argued that the major causes for project delay are change orders, relocation of utilities and poor construction planning.
3. The majority of respondents planned their schedules weekly and monitored the work progress at a construction site on a weekly basis to control time and cost more effectively throughout the earthwork construction operations.
4. Most of the companies are still using existing techniques such as mass haul diagrams to plan the earthwork operation in road projects. This provides less information in relation to accurate earthwork quantity distribution between cut and fill sections, particularly in the cross direction. There are also shortcomings associated with the traditional mass haul diagram for planning and scheduling of earthwork operations.
5. In the company survey, it is found that visualisation technology for the simulation of earthwork activities –including spatial aspects and analysis of activity sequence – does not exist and has not been applied.
6. Factors such as soil characteristics and methods of construction are the most critical factors that affect earthwork planning. Similarly, factors such as access road conditions, the number of access points, and the location of borrow pits also affect the planning processes. The type of equipment sets and equipment breakdown time need to be carefully considered to enable high levels of process efficiency.
7. Forty-eight percent of the companies agreed that a visualisation tool would be beneficial to provide information on schedule activity sequences before implementation in the earthwork construction process, while thirty percent agreed that the tool would assist in improving the communication of scheduling information at a construction site.

3.9 Summary

This chapter explained the design of the questionnaire, data collection and analysis, and has presented the findings drawn from a construction industry survey. The survey was targeted at construction companies, particularly involved in roads, railways and civil engineering linear construction projects with earthwork operations. The survey was conducted using semi-structured interviews and questionnaires and was well received by the industry with a 60% response rate.

The following are the key findings concluded from the industry survey:

- Mass haul diagrams and past experiences were commonly used in earthwork planning despite the development of commercial software and tools. The reason given was that existing tools were too complex in application and costly.
- The majority of the companies used weekly schedules for the execution and monitoring of the work progress of earthworks; however, some companies still used monthly schedules for execution and monitoring purposes.
- Availability of different sets of construction equipment, selection of construction methods, soil characteristics and site access points were found to be the key factors affecting earthwork planning and construction operations.
- Visualisation of earthwork progress profiles provides information on construction sequences and space/location allocation. This helps to analyse space/location and crew congestion, and assists in communicating the scheduling information more effectively amongst project stakeholders.
- A map of construction processes presented in this chapter showed that the visualisation of construction sequences would be valuable in the bidding and detailed planning stages of earthworks' components in road construction projects.

The findings listed above were incorporated into the development of the specification for the prototype model. The details of model specification development are presented in Chapter 4.

Chapter 4

Development of Model Specifications

4.1 Introduction

The objective of this chapter is to introduce and present the basic specifications of the prototype model and its components. The specification considers the features required for the computer modelling of earthwork scheduling and the visualisation of construction processes in linear construction projects. Specification of the prototype model was developed with three components: inputs, processes and outputs.

The chapter explains the research methodology used in this study and outlines a theoretical framework of computer modelling of earthwork operations. The prototype model was designed with two key objectives: 1) automatic generation of location-based scheduling (a time-location plan); and 2) visualisation of progress profiles including scheduling information of earthwork operations. The model was developed for resource scheduling and visualising of the scheduling information on a weekly or daily basis throughout the construction phase of earthworks. The model includes a visualisation capability to imagine the construction processes from a location aspect. This facility was designed to assist construction managers to improve the way of communicating the scheduling information amongst construction teams throughout the earthwork operations in road construction projects.

The specification of the prototype model was developed by incorporating the findings which have been summarised from a literature review and construction industry survey (see Chapters 2 and 3). This chapter explains and derives the mathematical equations and the design of the arithmetical algorithms for different functions of the model. These include the automatic generation of weekly progress profiles, location-based schedules, space congestion plans and location-based costing information in addition to a cut-fill optimisation module of earthwork allocation in a road construction project.

The ‘cut-fill optimisation module’ deals with the optimisation of the earthwork allocation quantities and the direction of movement along cutting to filling sections, borrow pits to filling sections or cutting to landfill sites using a linear programming technique. The unit cost of the earthwork allocation was used as a decision coefficient for minimising the haulage cost associated with earthwork operations. The next section gives an overview of the prototyping.

4.2 Overview of prototyping

The prototyping approach is popular in the development of computer-based modelling because of the rapid delivery of the systems and the precise determination of system requirements (Dennis et al, 2008). Fitzgerald et al (2002, p50) stated that prototyping is a technique and a philosophy for system development. Bowen et al (1994, p116) stressed the importance of building a prototype. They outlined the benefit of a prototype assisting project teams in solving problems faster at strategic junctures, thereby allowing developers to generate possible solutions, demonstrate expected functionality, and build required alterations before producing the final model. Therefore, a prototyping approach was selected in this research for building a model for earthworks scheduling and visualisation of scheduling information in road construction projects. A conceptual map of the data processing prototype model is shown in Figure 4.1.

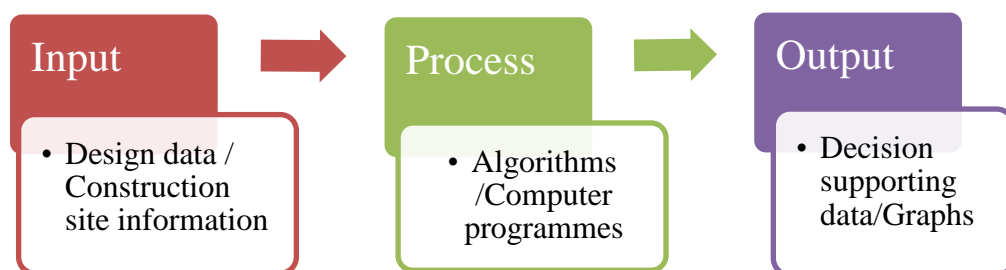


Figure 4.1 Conceptual map of data processing prototype model

In the model, the design data or construction site information is processed to obtain the model outputs in terms of tabular data and graphs using algorithms and computer programmes. The outputs are decision supporting tools that aid construction managers and projects planners in producing effective construction schedules and

accurate resource planning at required locations and when necessary. Hence, construction equipment idle time and resource wastage can be reduced using the location-based schedules developed by the model.

The data processing prototype model was developed using a new approach. This is focusing on the automatic generation of data by integrating different productivity values associated with earthworks. The productivity is known as a production rate of work activity. The values of productivity vary according to the site conditions and other factors including soil types, weather, working conditions and equipment characteristics. In this study, earthwork productivity was calculated using the “RoadSim” simulator, which was developed by Dawood and Castro (2009) and aimed to determine the productivity and unit cost of road activities. The simulator incorporates characteristics of the construction equipment, site access conditions, soil characteristics and working efficiency at an earthwork construction site. The productivity and unit cost calculation sub-module of the “RoadSim” simulator was tailored, and it was also integrated into the prototype model to analyse and visualise the impact of these factors in the earthwork modelling.

In the prototype model, a trapezoidal rule was utilised for the calculation of sectional quantities of earthwork and the automatic generation of weekly or daily progress profiles of earthwork throughout the construction phase of a road section. Furthermore, the mass haul diagram was used for the identification of economical haulage distance and generation of cut and fill activities along a road section. The theory of location-based planning was used to generate location-based schedules of earthwork activities. The improvement of the planning process and productivity of each activity in a road project from location aspects was the most important purpose of Location-based Planning (LBP). Kenley and Seppanen (2010) highlighted that location-based planning is applied to both a planning and scheduling technique simultaneously. It has the capability to organise both activities and work sequences to improve the site productivity in construction projects.

The LBP depends on the extension of activity-based logic combined with location-based logic, which provides a new tool for the planning and analysis of work activities in a linear construction project. It has a superior record of accomplishment

about practical appropriateness in the repetitive nature of construction projects, including roads, railways, canals and pipelines projects (Kenley and Seppanen, 2010, p123). The next section explains the framework design and specification of the prototype model with detailed specifications.

4.3 Framework of a Prototype Model

A framework of a prototype model was designed for earthwork scheduling using the findings obtained from the literature review and the construction industry survey. This was utilised as the basis for the analysis and visualisation of scheduling information of earthwork operations in road construction projects. The framework of the prototype is presented in Figure 4.2 below.

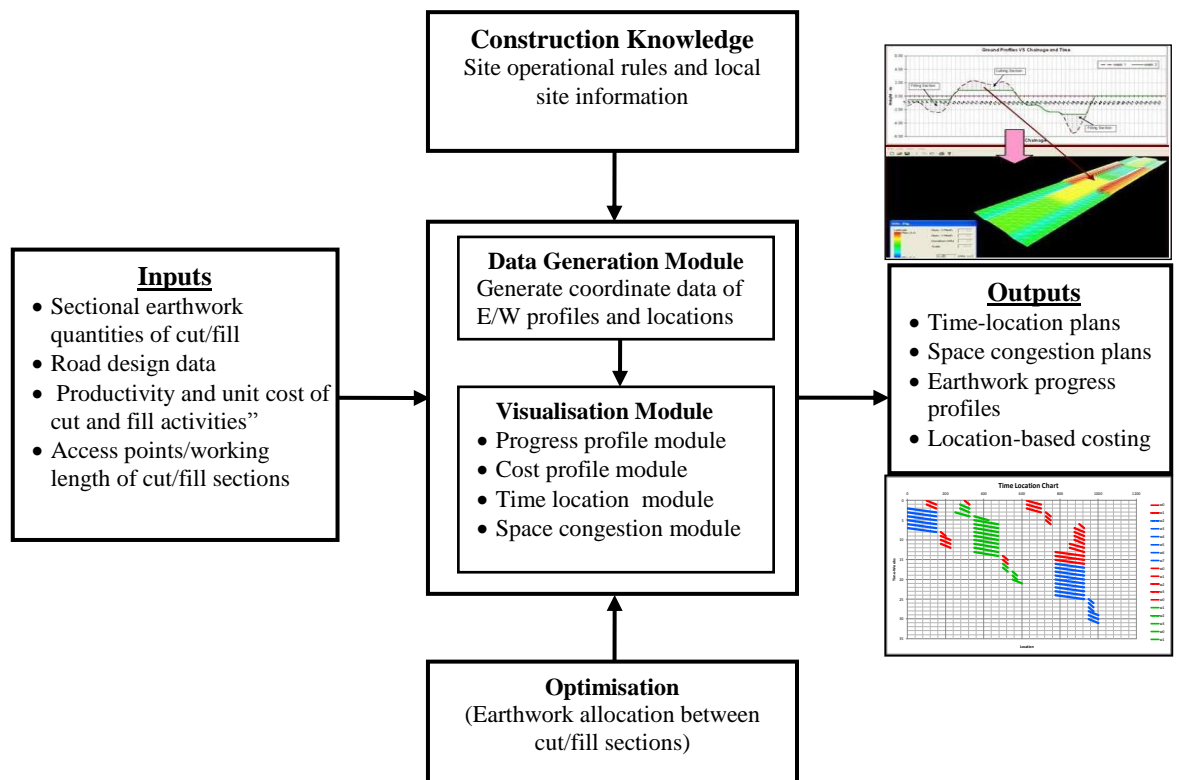


Figure 4.2 Framework of a prototype model for earthwork scheduling

The key inputs of the model are:

- Sectional quantities of earthwork activity of a road section
- Productivity and unit cost data

- Site access points and working lengths
- Construction site knowledge and algorithms

The outputs were obtained by processing the input data. The model was integrated with the construction site knowledge embedded within algorithms and the utilisation of visualisation technology. The key outputs are:

- Weekly progress profiles
- Location-based schedules/time-location plans
- Space congestion plans
- Cost profiles/S-curves

The two key processes of the prototype model were “Data Generation Module” (DGM) and “Visualisation Module” (VM). The DGM was designed to generate coordinate data and it was sub-divided into four sub-modules, with different functionalities: automatic generation of earthwork progress profiles; location-based cost profiles; time-location plans; and space congestion plans for earthwork operations. The VM that processes the coordinate data produced by the DGM for each function transforms the coordinate data into outputs in tabular and graphical form.

The graphical form of the model outputs communicates the scheduling information including activity sequences and resource allocation plans more precisely with location aspects on a weekly or daily basis. The model assists analysis of the impacts of different factors associated with productivity on the resource scheduling using a “what-if scenario” analysis throughout the construction operations in linear repetitive projects. The next section explains the development of the model specifications and functionalities.

4.4 Development of Prototype Model Specification

The detailed data flow diagram of the whole prototype model is presented in Figure 4.3. The diagram outlines the model functionalities. Graphical images of inputs and

outputs are also included in the diagram to aid understanding of the expected model deliverables.

The prototype model key functionalities include:

- Generation of earthwork progress profiles and cost profiles
- Automatic generation of location-based schedules and space congestion plans
- Optimisation of earthwork allocation quantities of a cut-fill assignment

The technique used to develop the prototype model was focused on integration processes of “variable” factors associated with productivity data of earthwork activities. The findings from the construction industry survey presented in Chapter 3 revealed that types of construction equipment sets, soil characteristics and site access points were the key factors affecting project duration and cost of earthwork components in road construction projects.

The model was designed by incorporating user-defined site access points (locations) or working lengths of cutting and filling sections in a road section. Site access points and working lengths between two access points were integrated as a key input of the model. The working lengths are equivalent to the economical haulage distances between cutting and filling sections identified by the module, considering site constraints along a road section and the mass haul diagram. The next section explains the details of the model inputs.

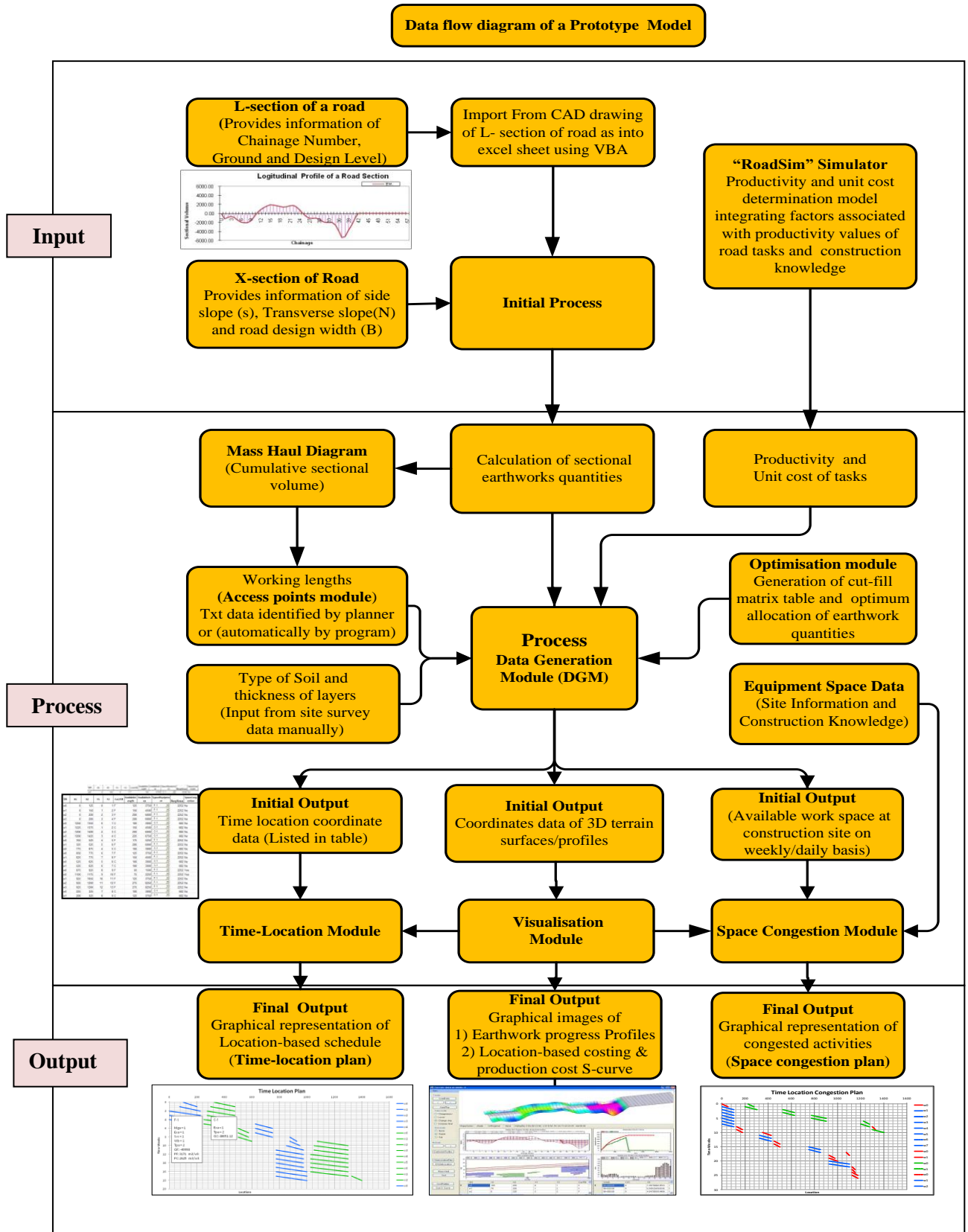


Figure 4.3 Data flow diagram with different modules of the prototype model

4.5 Inputs of the Prototype Model

The geometrical design data of a road section including longitudinal sections and cross sections were collected. Other contract documents providing site information were used to determine the sectional quantities of earthworks at the required chainage interval. The L-section provides information of existing ground level and road design level at each chainage point/station and soil characteristics along the cutting section of the road, whereas the X-section provides the road width, side slopes and dimensions of geometrical parameters at every chainage, including ground level and road design level. The inputs of the model are:

- Sectional quantities of cutting and filling activities
- Geometrical design data including L-sections and X-sections
- Productivity and unit cost data of earthworks
- Locations of access points and haulage distance/working length

The sectional quantities of a road section at the cutting and filling sections were calculated using the trapezoidal rule with the information provided in longitudinal and cross-section profiles of the road section. The site survey provided the following information: the site access points; the location of borrow pits; and the landfill sites. The productivity data of earthwork activity was integrated into the model in order to analyse the effects of influencing factors associated with the productivity data and to identify the duration of earthwork activity throughout the construction process.

The findings from the construction industry survey showed that earthwork is normally planned and progress is measured on a weekly basis. Therefore, a weekly unit was automatically used as an input of the model to generate progress profiles and location-based schedules of earthworks.

According to road practitioners, the limit of an economical hauling distance is 50m for bulldozers; 100-500m for motor scrapers; 500-1500m for dumpers; and greater than 1000m for dump trucks or tippers (Mota-Engil). Using this knowledge, a new algorithm was developed to identify the possible site access points /working lengths

between the cutting and filling sections, considering site conditions and resource constraints. The development of the algorithm for identifying access points is explained in Chapter 5. This is a key feature of the model and it takes into account physical obstructions or resource constraints at a particular point or section of the working lengths, a variable according to topographical constraints for earthwork construction projects.

The soil characteristics of the road section, type and number of equipment sets, haulage distance, site access road and working conditions at the site were integrated into the prototype model by tailoring the productivity determination module of “RoadSim”. This enabled the impact of these factors, on the earthwork progress profiles and location-based schedules, to be analysed and visualised, dynamically.

Moreover, construction knowledge was encapsulated from the literature review of construction processes, from construction professionals from “Mota-Engil”, and from the construction industry survey in the UK. This assisted in establishing the sequences of the earthwork activities and in selecting possible construction methods of earthwork operations. The next section explains the processing components of the prototype model in detail.

4.6 Processes of the Prototype Model

This section contains the detailed design and development of two major components of the prototype model: DGM and VM as shown in Figure 4.2 above. The DGM processes the input data and generates numerical data for all four component modules:

- Time-location module
- Space congestion module
- Progress profiles module
- Cost profiles module

These modules were designed using arithmetical algorithms and VBA programming language with functionalities as follows:

- Location-based schedules/time-location plans
- Location-based space congestion plans
- Earthwork progress profiles
- Location-based cost profiles

The generated data incorporates the productivity data for earthworks operations, which generates the earthwork progress profiles and location-based schedules on a weekly basis (or daily, if required). Therefore, the impact of different factors associated with the earthwork productivity was analysed and visualised.

Similarly, the VM processes the data generated by DGM, and transforms it into graphical images as the model outputs, including progress profiles and location-based schedules of earthworks. The weekly progress profiles represent the terrain surfaces at each week throughout the earthwork operations. The progress profiles of earthwork are represented on a regular triangulation grid. The detailed development of VM, including algorithms and processes, is explained in Chapter 6.

A conceptual model for the development of the DGM for automatic generation of the required data of all modules is discussed in the next section.

4.6.1 Concept diagram for data generation module

The aim of the DGM is to generate the required data for different functions of the prototype model. A conceptual map of different construction layers of a typical road section, which has both cutting and filling sections, is presented in Figure 4.4 below. The concept originated from the reviews of earthwork operations as mentioned previously, and from what the author has experienced in road construction projects. The DGM was developed using layer logic and volumetric analysis at each construction layer of earthwork operations as shown in Figure 4.4. The integration of productivity data associated with cutting and filling activities is a key feature of the

prototype model. The explanation of integrating processes of different productivity rates (p) and assumptions made for the development of a mathematical equation is given in the following section.

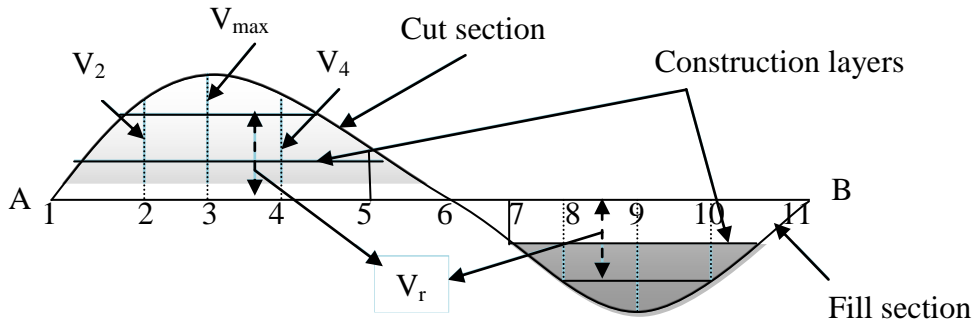


Figure 4.4 Typical mass profile with construction layers of cut-fill sections in earthworks

Figure 4.4 represents a typical mass profile of a road section which includes different construction layers at each station. In this figure, a line AB represents a road section having cutting and filling sections, with a total of 11 stations at equal intervals of 20 or 25m considered as normal. The stations from 1 to 6 represent a cutting section, whilst the stations from 6 to 11 represent a filling section. The sectional volume of earthwork was calculated using the 'Average end-area' method. In Figure 4.4, above, V_2 represents the volume of earthwork between stations 1 and 2, whereas V_4 represents the volume of earthwork between stations 3 and 2. Similarly, V_3 represents the volume of earthworks between stations 2 and 3, which shows the maximum volume (V_{max}) in the cut section.

4.6.2 Derivation of mathematical equation

This section discusses the derivation of a basic mathematical equation, which underpins the prototype model for automatic generation of location-based scheduling and the visualisation of earthwork progress profiles. The assumptions made during the development of the model are presented below.

- Earthwork operations are normally scheduled in suitable weather periods to avoid extreme wet or adverse weather because it has a high impact on earthwork productivity and overall progress. Furthermore, Castro (2005) also

pointed out that weather factors cannot be simulated in a model for measuring the impact on productivity due to their complexity and uncertain nature; however, the impact of the weather can be considered by incorporating a few days in the construction scheduling, according to locations and weather patterns of an earthwork construction site. Therefore, weather was not incorporated into the prototype model.

- Earthworks are performed as a layer-by-layer approach at both cutting and filling sections, which is normal practice in earthwork operations, particularly in a linear construction project. Rock excavation is excluded in the prototype model since it is performed by blasting and is planned separately.
- Each station represents the average volume of earthwork between station intervals of 25m or 20m since the cross-sectional information of the road design is normally available at that interval. However, the model can be adjusted for a shorter station interval.
- It is assumed that the selected road section is between two major obstructions such as rivers, railway/road crossings or bridges. The road project can be divided into smaller sections (1 to 1.5 km) for producing a weekly location-based schedule of earthworks. However, the model is flexible enough to incorporate a longer road section according to site conditions.
- Additional cutting quantities will be spoiled if unsuitable for backfilling; alternatively, if suitable, these will be deposited at a temporary place for other purposes. The shortage quantities are borrowed from nearby borrow pits or temporary deposited places. The optimisation module (Chapter 5) provides information on the cutting and filling quantities of the earthwork allocation and the movement direction between the cut and fill sections.

Considering the assumptions made above, and referring to Figure 4.4, a basic mathematical equation for the generation of location-based earthwork scheduling and weekly progress profiles is derived as follows.

It is considered that earthwork productivity (P) is equal to the volume of earthwork performed at a particular period of time. The unit of time has been considered as a week. Considering a road section AB as shown in Figure 4.4, the total volume of earthworks (a cutting or a filling section) in a road section can be represented by equation 1 below:

$$V = V_1 + V_2 + V_3 + \dots + V_n \quad (1)$$

Whereas,

V = total volume of a cutting or a filling section of a selected road section.

Total volume of the cutting section is equal to (V₁+ V₂+.....+V₆).

Total volume of the filling section is equal to (V₇+V₈+.....+V₁₁).

The numbers of stations in cut or fill section can be represented by 1, 2, 3,....., n

Hence, Equation 1 can be expressed by equation 2 as follow:

$$V = \sum_{i=1}^{i=n} V_i \quad (2)$$

In case of station number 2 of the selected road section AB (see Figure 4.4); the station includes multi-layers and represents the sectional volume of earthwork between stations 1 and 2. The sum of volume of all layers represented at the station can be expressed by equation 3 below.

$$V_2 = V_{21} + V_{22} + V_{23} + V_{24} + \dots + V_{2t} \quad (3)$$

Equation 3 can be expressed as $\sum_{j=1}^{j=t} V_{2j}$ (4)

Whereas, t = number of layers during earthwork operations, j = 1, 2, 3,....., t

Combining the equations 2 and 4, the total volume of earthwork at all layers along a selected cut/fill section is represented by equation 5 as follows:

$$V = \sum_{i=1}^{i=n} \sum_{j=1}^{j=t} V_{ij} \quad (5)$$

After performing earthwork operations, the remaining volume (V_r) of earthwork at a layer and at each station is represented by equation 6 below:

$$V_r = (V - P)/n \quad (6)$$

The V_r shown in equation 6 represents the remaining volume of earthwork at a construction layer and at each station along a cutting or a filling section. Substituting the value of V from equation 2, equation 7 can be found as below:

$$V_r = [\{ \sum_{i=1}^{i=n} (V_i) - P \} / n] \quad (7)$$

Whereas;

n = number of stations selected by algorithm at a layer section

V_i = sectional volume of earthwork at each station, $i = 1, 2, 3, \dots, n$

V_r = the remaining volume after progress at a layer and each station

r = number of construction layer at a station of a cut/fill section, $r = 1, 2, 3, \dots, t$

$p = (p_c/p_f)$ productivity of earthwork activity according to a cut/fill section.

The formula shown in equation 7 was used to identify the starting and the ending location information at a construction layer of earthwork. This is used to automatically generate a location-based schedule and visualise the weekly progress profiles of cut/fill sections in earthwork.

For the verification of equation 7, an illustration is presented by selecting a road section. The illustration results are presented in tables and figures which provide the information on weekly quantities of cut and fill sections compared with the total sectional quantities of earthworks separately (see Appendix-G). The next section discusses the processes of earthwork progress profile generation.

4.7 Earthwork Progress Profiles

The development of earthwork progress profiles is a major function of the prototype model. The DGM is a central part of the prototype model which processes the inputs

and produces the progress profiles of earthworks of a road section. The data flow diagram for generation of earthwork progress profiles and corresponding terrain surface is shown in Figure 4.5a below.

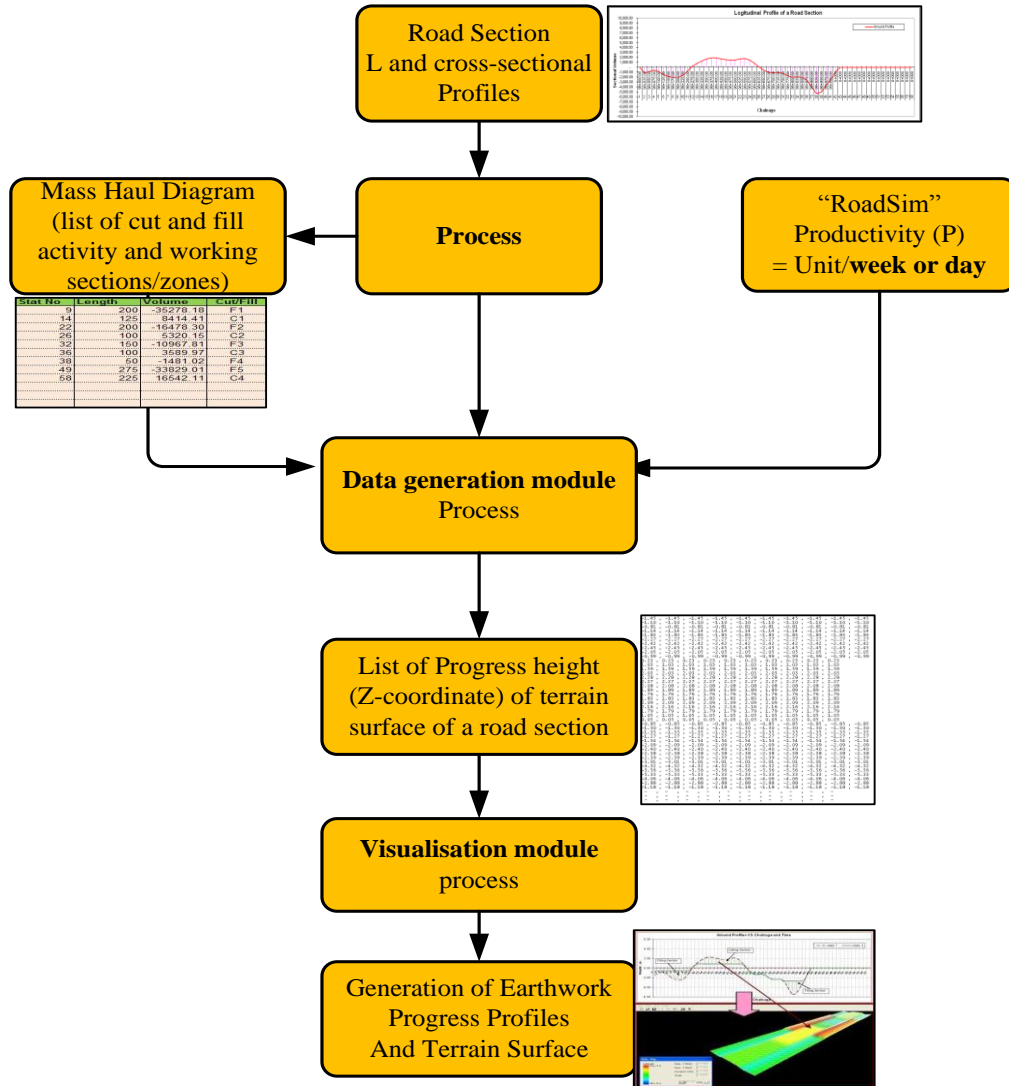


Figure 4.5a Data flow diagram for generation of earthwork progress profiles

4.7.1 Generation of coordinate data of progress profiles

The input of the visualisation module is the weekly coordinate data of progress height produced by the DGM. The derivation of the mathematical equations and algorithms are discussed in the following sections.

4.7.2 Derivation of mathematical equations for progress height

This section explains the development of mathematical equations. The equations were used in the algorithm for the calculation of progress height of earthworks at each station. Mathematical equations were derived assuming the trapezoid shape of road cross-section for two cases: flat terrain and terrain with transverse slope. These cases are widely utilised in earthwork operations. These two cases (a) and (b) were considered in order to derive mathematical equations 8 and 9, aiming to calculate the progress height of cutting and filling sections (see Appendix-C).

Case (a) represents a typical road cross-section which was used regularly in road projects, particularly in a flat terrain. It was selected to derive a mathematical equation for the calculation of earthwork progress height as shown in equation 8 below.

$$h_i = \frac{-B \pm \sqrt{(B^2 + 4SV_i/L)}}{2S} \quad (8)$$

Case (b) represents a typical cross-section which was used in road projects, particularly in a terrain having transverse slopes. It was selected to derive a mathematical equation for the calculation of earthwork progress height as shown in equation 9 below.

$$h_i = -\left(\frac{b}{S}\right) \pm \left[\left(\frac{1}{S}\right) \sqrt{\left(\frac{V_i S}{L} + b^2\right) \times \left(1 - \frac{S^2}{N^2}\right)}\right] \quad (9)$$

The detailed derivations of mathematical equations for both cases (a) and (b) are presented in Appendix-C.

4.7.3 Algorithm for data generation of progress profiles

The algorithm was designed to generate the progress height as the Z- coordinate data of terrain surface during earthwork construction. The trapezoidal rules were utilised for the calculation of the progress height at each chainage (station) in a road section.

Another algorithm was developed using volumetric analysis for the identification of stations having earthwork quantities equivalent to the weekly (or daily) productivity value at each construction layer at earthworks. The coordinate data was integrated with a 4th dimension (time), which was derived from productivity data (production rate of earthwork activity) in road construction projects.

According to the existing practice, the excavations are progressed on a layer by layer basis in a horizontal direction for both cutting and filling activities in the earthwork operations in road construction. This practice was assumed as a basic principle in order to design an algorithm and calculation of the progress height of earthworks. The progress of the earthworks is commonly monitored on a weekly basis; therefore, a weekly schedule is considered for the calculation of the progress height of earthworks in this study.

The algorithm was designed to identify the starting location during earthwork operation, which is a station (chainage point) representing the highest point of mass volume at a cutting section and the lowest point of mass volume at a filling section. In this algorithm, the remaining quantities of earthwork are identified after reducing excavated quantity (equivalent to weekly performed quantity) at each location. The height of the remaining section is calculated using equation 8 or 9 depending upon the types of road cross-section used in road construction. This process is repeated to achieve the final design level as shown in a longitudinal profile of a road section. The production rates determine the duration of earthworks in a road section.

The details of the algorithm, including inputs, processes and output of the earthwork progress profiles module, are shown in Figure 4.5b.

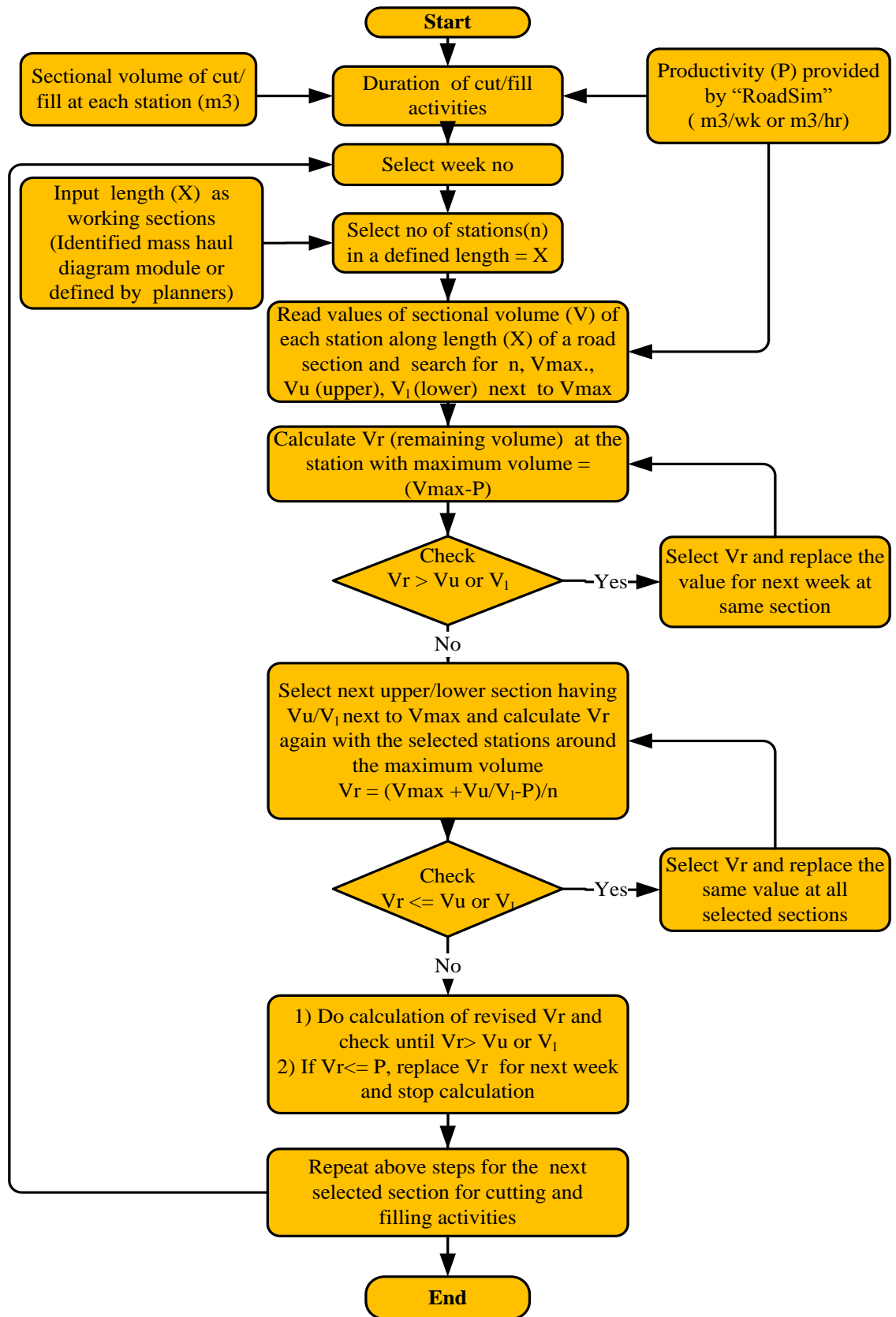


Figure 4.5b Coordinate data generation algorithm for earthwork profiles

Similarly, the remaining sections of cutting and filling are repeated to achieve the final design level of the selected road section for construction. The above processes are repeated to complete the earthwork operations in a road section. A road project is broken down into smaller sections or a practical length to satisfy the prototype model because earthworks are performed in smaller sections in road projects according to site conditions and resource constraints. In this way, the module generates the coordinate of the progress height of earthworks on a weekly basis. The module creates a 2D graph of progress profiles of earthworks and shows the number of weeks required to complete the cutting and filling operations separately.

The VM transforms the coordinate data into visual images of terrain surfaces of earthwork progress profiles. The DGM, which also produces the coordinate data for the location-based schedules and space congestion plans, is discussed in Chapter 5. The detailed development processes of the VM of earthwork progress profiles and generation of terrain surfaces throughout the construction operations are discussed in Chapter 6. The next section outlines the concept and algorithm for the automatic generation of a location-base schedule (time-location plan) for the earthwork components in road projects. This is the key output of the prototype model.

4.8 Location-based Scheduling/Time-location Plan

The section presents the concepts for the development of a location-based schedule/time-location plan for earthwork components in road construction projects, representing a key objective of this research study. A prototype model was developed to automate the generation of a location-based schedule and space congestion plan by integrating the factors associated with the productivity data of earthworks.

4.8.1 Overview of obstructions in time-location plan

The time-location module has been advanced by integrating different obstructions along a road section; for example, bridges, rivers, intersections, railways crossings and tunnels. These obstructions divide the whole road section into two or more

sections for the purpose of earthwork planning and scheduling. Hence, each road section was considered separately in this study with a separate set of crews, including construction equipment, which is selected by considering the site conditions and expected obstructions for the earthwork operations. This was considered by Hassanein and Moselhi (2004) for the development of a planning and scheduling tool for highway construction projects.

According to Hassanein and Moselhi (2004), road obstructions are defined into two types: 1) surmountable, where access is possible across the obstruction at an overhead of cost and time, such as an intersection or a railway crossing; and 2) insurmountable, where no access is possible, such as rivers. Therefore, work zones (areas) were defined based on insurmountable obstructions, while working segments/sections were divided according to surmountable obstructions as shown in Figure 4.6 below:

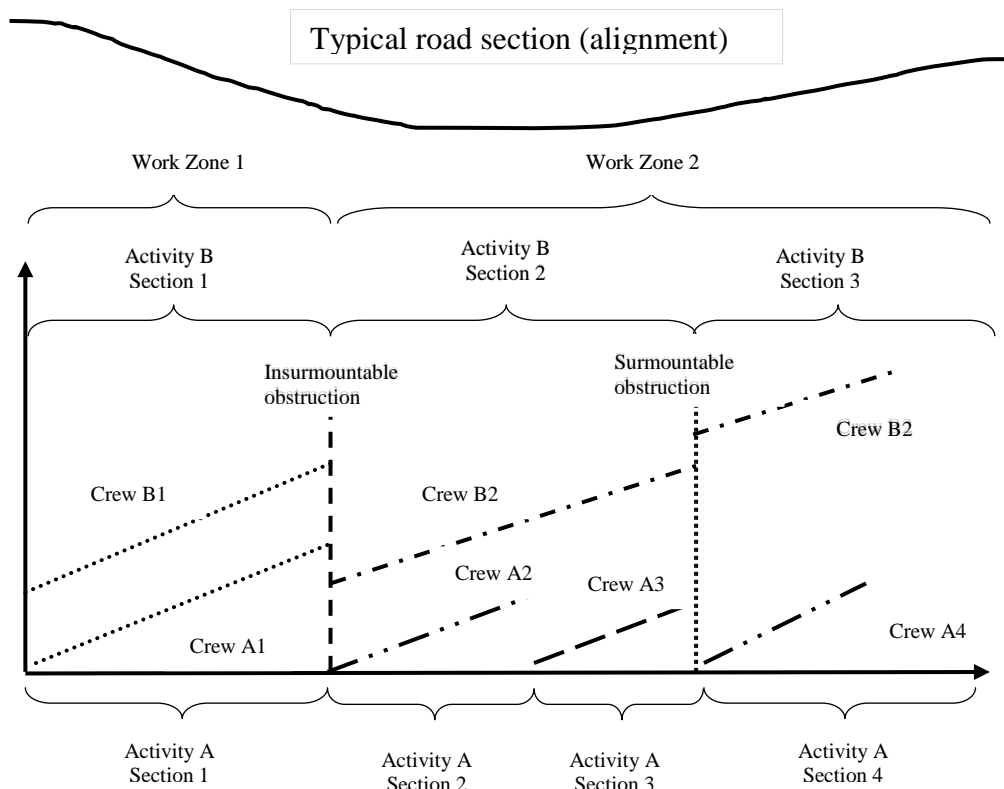


Figure 4.6 Typical divisions of road activities and sections for a highway scheduling (Hassanein and Moselhi, 2004)

Referring to Figure 4.6, a road section is divided into different sections and working zones considering the available obstructions and resource constraints for earthwork operations. An additional input of obstruction points across segment lengths was created within the data generation algorithms in the time-location module. This input breaks the different working sections according to the number of obstructions and generates the time and location coordinates for a time-location plan. The demonstration of the time-location plan with the integration of obstructions is presented in Chapter 6.

The DGM is a vital part of the prototype model since it was designed to generate the coordinate data automatically for producing a location-based schedule and a space congestion plan for earthworks. To achieve this, a new methodology was developed which is focused on the automatic generation of coordinate data of time and location. The coordinate data was used to generate a location-based schedule for earthworks considering location aspects of the schedule.

4.8.2 Data flow diagram of location-based scheduling

This section outlines the details of the data flow diagram for the automatic generation of location based schedules / time-location plans as shown in Figure 4.7 below. The longitudinal profile and cross-sectional profiles of a road section is the main input in this module. The mass haul diagram was developed using longitudinal profiles information. The characteristics of a mass haul curve and the knowledge of construction equipment utilisation were used to identify the working sections (construction zones) together with working access points. The user's defined locations, obstruction points, and the sequences of cut and fill activities were incorporated in the algorithm. This was considered as an additional input in this module.

The productivity values determined by "RoadSim" were used to determine the project duration. The algorithm was designed by integrating the inputs and mathematical equation 7 discussed in the above section. The algorithm was used to generate automatically the coordinate data of weekly locations associated with earthwork activities. Then the coordinate data was used to produce a location-based

schedule with the information of the starting and ending locations of earthwork activities on a weekly (or daily) basis).

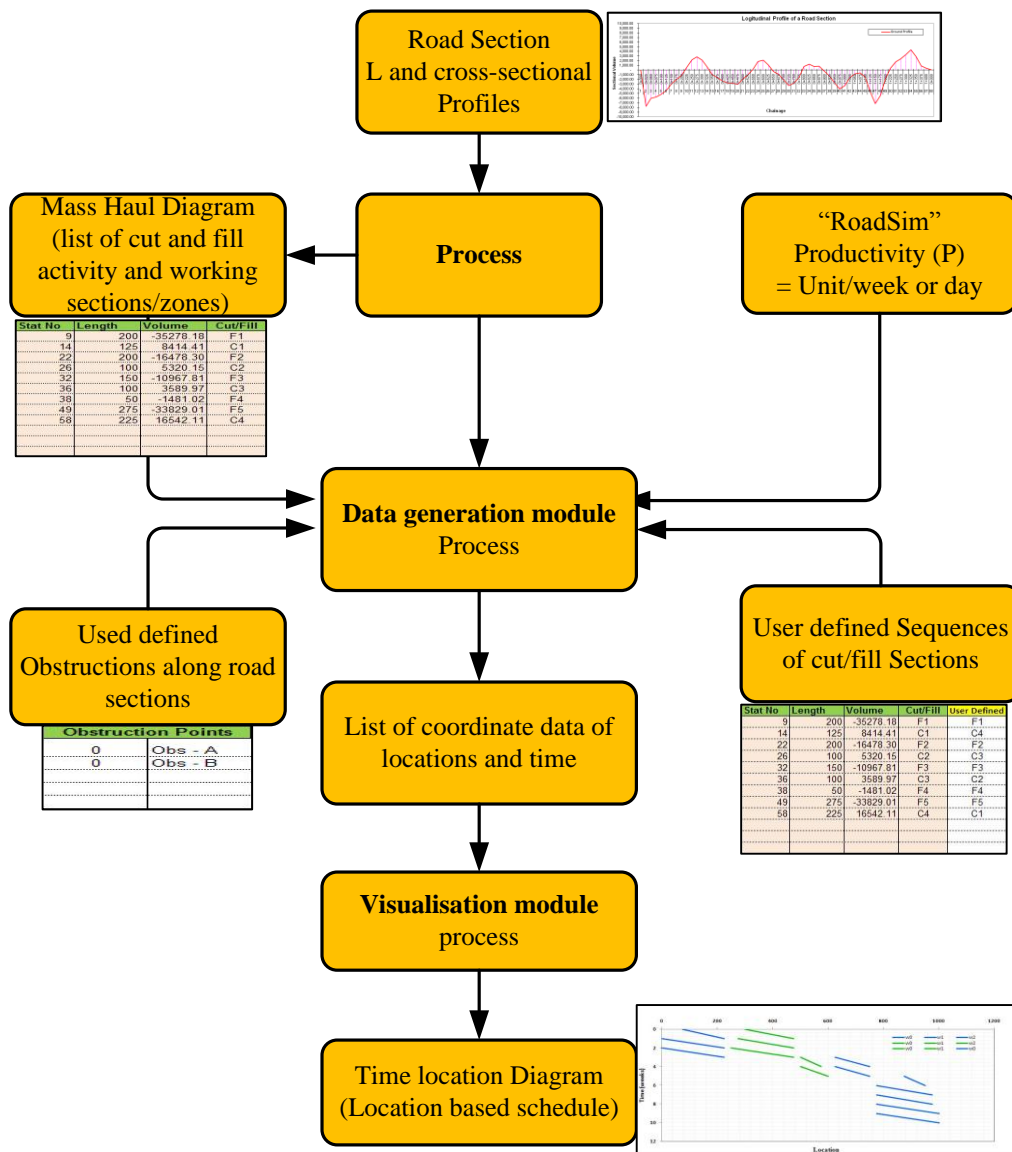


Figure 4.7 Data flow diagram for generation of location-based scheduling

The module generates location-based schedules and presents them in a two dimensional graph. In the graph, the time dimension is represented by the Y axis with the location dimension in the X axis. The slope of a line represents the rate of production of the activity. The graph represents a time-location plan.

The time-location plan provides the accurate information of an earthwork schedule and planned production rate of activity on a weekly (or daily) basis from the location

aspects throughout earthwork operations. The plan provides a decision support tool that assists project planners and construction managers to identify the weekly (or daily) working locations and to allocate resources including equipment mobilisation correctly at each location. It also assists in improving the communications of scheduling information and analysing the impact on production time of earthwork activities from a location aspect along a road section. The detailed development of algorithms and a demonstration of the location-based schedules are presented in Chapter 5. The next section explains the concepts used for the development of a location-based space congestion plan.

4.9 Location-based Space Congestion Plan

Space congestion in earthworks operations occurs due to the lack of sufficient workspace at a construction site. The aim of the space congestion module is to identify suitable sets of construction equipment for the required earthworks to avoid space congestion at the construction site and to improve the productivity of site operations and personnel.

4.9.1 Overview of space congestion in earthwork

In earthworks, the workspace is limited at the early stage of construction and there is a change of workspace congestion if suitable sets of construction equipment are not mobilised for earthworks operations. Therefore, it is necessary to identify the available workspace at the construction site and to mobilise the sets of equipment accordingly, so that earthwork operations can be performed safely and without loss of productivity throughout the construction operations.

Several research studies (Kunz, 1994; Oglesby et al, 1989 and Sander et al, 1989) revealed that space congestion is a major cause of loss in productivity. Sander et al (1989) found that a 65% loss in work efficiency was caused due to space congestion at the workplace and 58% loss in efficiency could be attributed to the restricted site access. Their observations justify the development of the Space Congestion Module (SCM) for identifying the congested locations.

4.9.2 Conceptual diagram of earthwork operations

The SCM automates the identification of space-congested locations in earthwork operations by incorporating the key contributing factors, including equipment sets, site access conditions and soil characteristics. A conceptual diagram of earthwork operations is presented in Figure 4.8 below.

Figure 4.8 represents a typical road section with a set of construction equipment for both cutting and filling operations. The figure shows the multi-construction layers having different working lengths at both cutting and filling sections throughout earthwork operations. In practice, the length of each layer is proportional to the productivity of construction equipment sets, terrain conditions, and site constraints, including the availability of working space at the construction site. Working space reduces as earthwork progression continues but the working length at each construction layer of cutting and filling activities increases as shown in Figure 4.8.

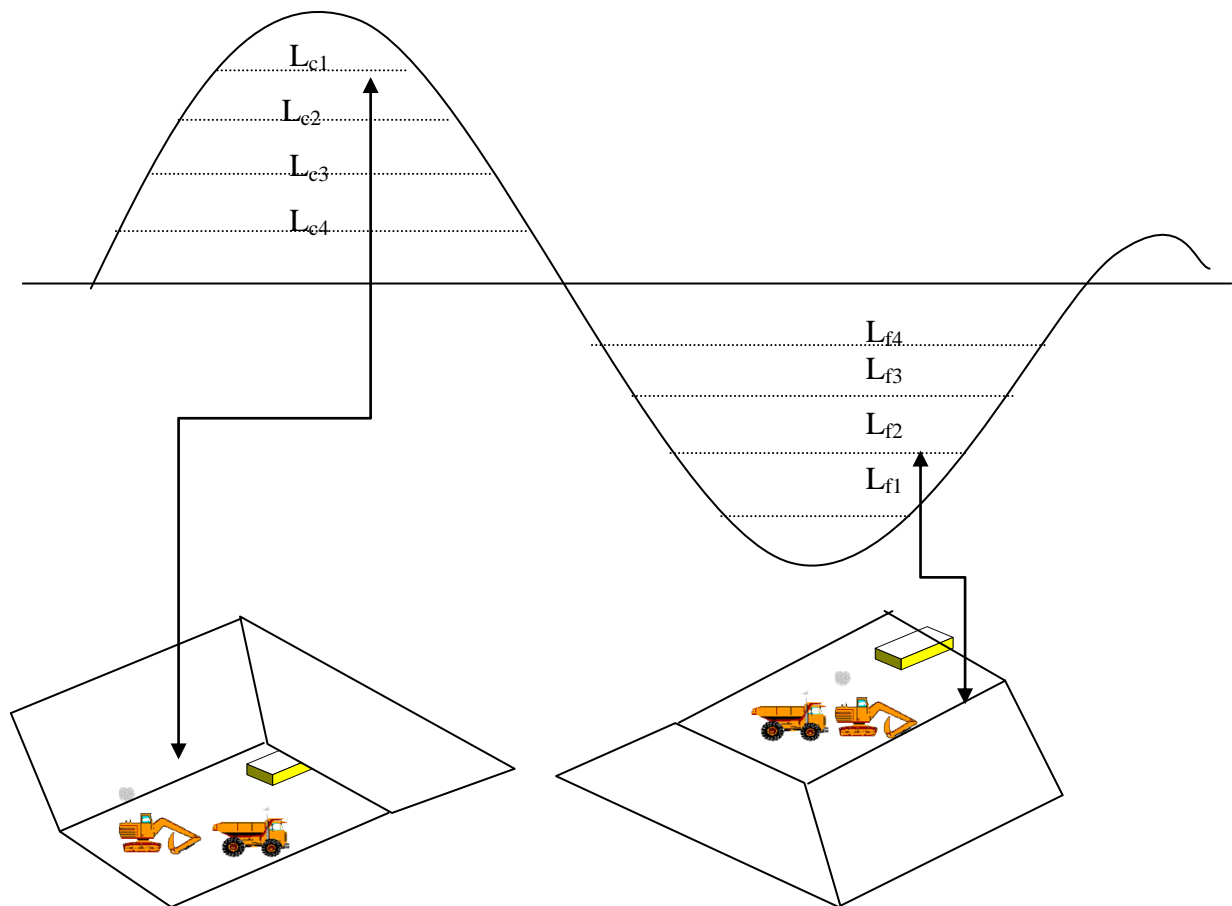


Figure 4.8 Conceptual diagram of a space congestion plan for earthworks

For example, the length of each layer at a cutting section is represented by L_{c1} , L_{c2} , L_{c3} , L_{c4} ,, L_{cn} , whereas the length of each layer at a filling section is represented by L_{f1} , L_{f2} , L_{f3} , L_{f4} ,, L_{fn} .

Since these lengths are proportional to the productivity data associated with earthwork activities, an algorithm was introduced to identify the length of each construction layer for both cutting and filling sections incorporating “variable” productivity data that depends directly on the set of construction selected, the type of soil characteristics, and the site working conditions in earthwork operations.

The time-space module is divided into two sub-modules:

- 1) Required area calculation sub-module
- 2) Available space determination sub-module

The required area calculation sub-module was developed to calculate the required working space for a selected set of construction equipment to perform cutting or filling operations during earthwork operations. The available space determination sub-module focuses on the calculation of available working space. This depends on terrain conditions and the location of the starting space for cutting or filling operations.

The detailed development of the space congestion module is outlined in Chapter 6. This includes the algorithms and development processes of the space congestion plan for earthwork operations, including a demonstration of the functionality. The next section explains the concept and methodology for the development of the earthworks optimisation components of the prototype model.

4.10 Earthwork Optimisation Module

This section explains the development of the earthwork optimisation module for the allocation of optimum haulage quantities and the directions of movement between the cut and fill sections in a road section. The optimisation module was designed by integrating mass haul parameters and the unit cost of the earthwork allocation

identified by “RoadSim” and Excel solver. The Excel solver is a function within MS Excel developed using a Simplex algorithm for solving linear optimisation problems. A data flow diagram of a cut-fill optimisation module of earthwork is shown in Figure 4.9 below.

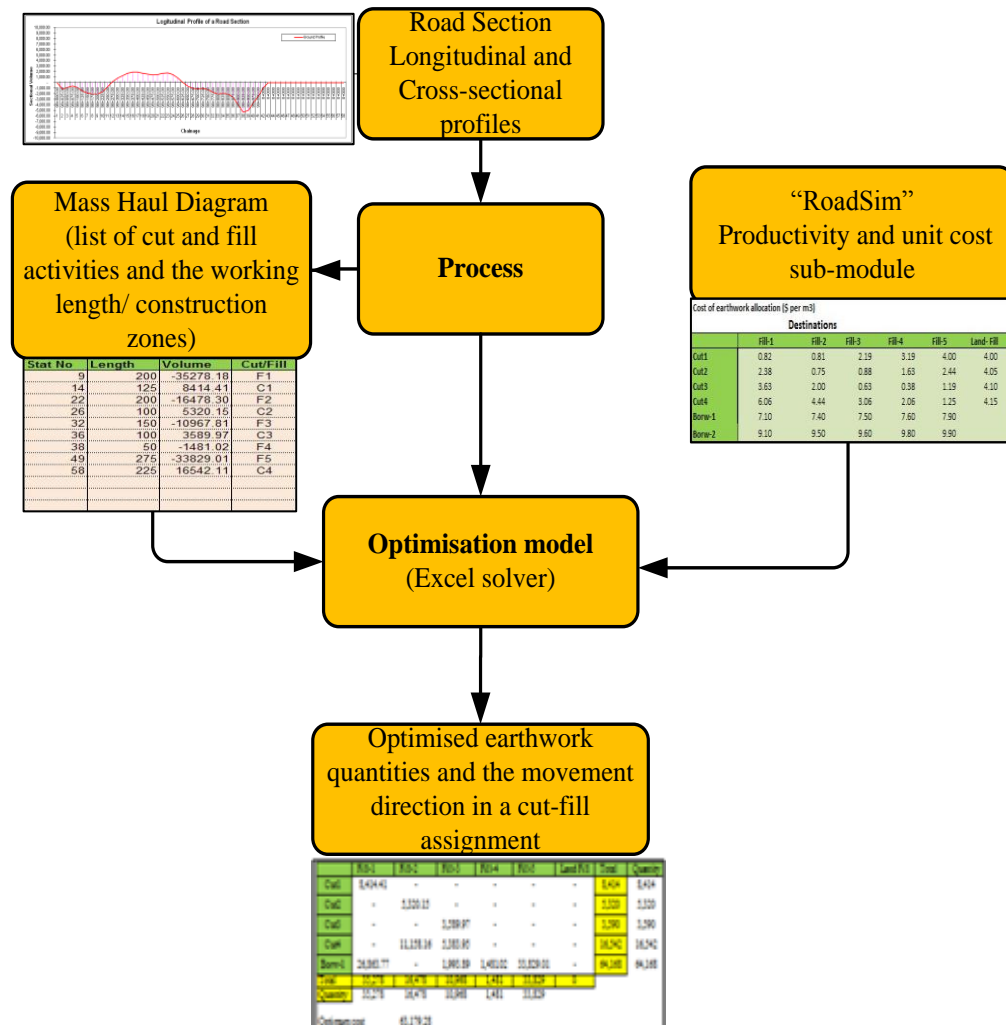


Figure 4.9 Data flow diagram of earthwork optimisation module

The optimisation module was integrated with the prototype for earthwork planning. The inputs of the optimisation module include sectional quantities with the working length of the cut and fill operations and the unit cost table of earthworks. The “RoadSim” identified the unit cost within the model and further processed the cost data using Excel solver to obtain the optimised quantities of earthworks and direction of movement. In the optimisation module, a list of cut and fill sections with available quantities was identified and listed in a table (for details see Appendix-D).

The next section explains the concept and algorithms for the development of location-based cost profiles and the cost S-curve for earthwork operations in a road construction project.

4.11 Location-based Costing of Earthworks

4.11.1 Overview of cost profiles

This section indicates the functionality of the prototype model that deals with methods and algorithms for automatic generation of location-based costing and the production S-curve. The availability of cost profiles assists project planners and construction managers by giving an indication of the production cost of the earthworks at each location. The unit cost of the earthworks production is used to generate weekly cost profiles at each station. The components of the production cost associated with soil characteristics, available equipment sets and site conditions are incorporated within the model.

Furthermore, the module was integrated with the prototype model to analyse and visualise the impact on earthwork progress profiles, project duration, and the comparison status between planned and actual production cost of earthwork operations. The details of the algorithms for the development of weekly cost profiles and the cost S-curve of earthwork operations are discussed in the next section.

4.11.2 Algorithms for generation of cost profiles

In this section, the research focuses on exploring and developing an additional module (cost-profile module) which is integrated with the prototype model. The module aims to generate and analyse weekly production costs at each chainage point along a road section throughout earthwork operations. The module is also valuable for the monitoring of production costs for earthwork operations by comparing with the actual and the planned production cost of earthworks using the cost S-curve at any intermediate stage throughout the construction process.

The data flow diagram is similar to the earthworks progress profiles generation except for the addition of the unit cost of earthworks. In the cost-profiles module, the unit cost calculation sub-module of “RoadSim” was tailored and integrated with the cost profile module to generate weekly cost information of earthworks at each location on a weekly (or daily) basis in road construction projects. The data flow diagram of the cost profile module is shown in Figure 4.10 below.

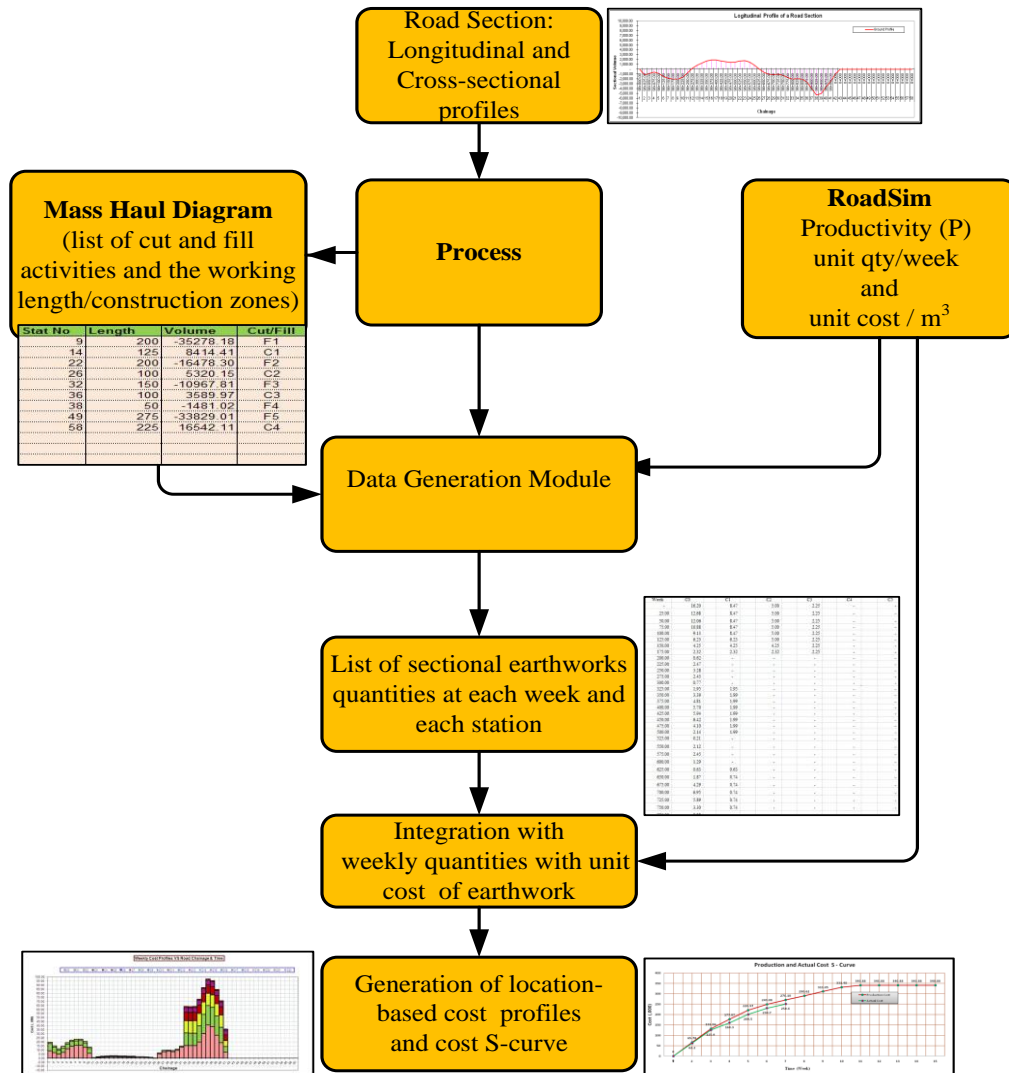


Figure 4.10 Data flow diagram for generation of location-based costing

The cost-profile module provides weekly cost information to project planners and construction managers in analysing the production cost of earthwork operations according to soil characteristics at each layer in cutting sections along a road project. As a result, action can be taken to plan and schedule the resources efficiently, including the allocation of construction equipment, thereby reducing cost. The

detailed processes and algorithm of the cost-profiles module and cost S-curve of earthworks in a road section are presented in Chapter 7.

4.12 Summary

A theoretical framework of the prototype was developed and presented in this chapter. The chapter also explained the model specifications with respect to computer modelling for earthwork progress profiles and location-based scheduling. The specifications of the model were arranged under input, process and output. The sources and collecting methods of model inputs were also explained to gain an understanding of the required input information by users so that location-based earthwork scheduling can be generated.

The influencing factors associated with earthwork productivity data were integrated with the prototype model by tailoring the “RoadSim” simulator. The aim of integrating the simulator was to analyse the impacts of different factors influencing the productivity data. The process of the model was divided into two parts: the data generation module and the visualisation module. The key outputs of the model were earthwork progress profiles; location-based cost profiles; location-based schedules / time-location plans; and space congestion plans.

This chapter outlined a conceptual framework for a cut-fill optimisation module. This is also a key functionality of the model in the earthwork planning processes that helps to optimise the haulage quantity and to minimise haulage cost. The model was designed by integrating Excel solver within the model. Further detailed development of the modules is presented in Chapter 6. The chapter also discussed the concepts and algorithms for the development of a prototype model for earthwork planning intended to produce weekly progress profiles and location-based schedules.

The next chapter discusses the development of the prototype model for automatically generating location-based schedules and space congestion plans of earthworks in road construction projects.

Chapter - 5

Location-based Scheduling

5.1 Introduction

The previous chapter discussed the conceptual design and the detailed specifications for a prototype model of earthwork scheduling. This chapter presents the development processes for the prototype model. This includes the automatic generation of the Location-based Scheduling (LBS), the Space Congestion Plan (SCP) and a cut-fill optimisation module for the earthwork component of road construction projects. The model helps construction managers in resource planning at the correct locations and assists in visualising the scheduling information of earthworks from a location viewpoint. The LBS of earthworks provides precise information on where and when the required resources need to be allocated on a weekly (or daily) basis throughout the earthwork operations.

For the development of a location-based schedule (time-location plan), it is necessary to identify the economical source and the destination for a cut-fill assignment of earthwork in road construction projects. Therefore, a cut-fill optimisation module was developed, aiming to identify the optimum allocation of earthwork quantities and movement direction (see Appendix-D). The module provides information on optimised quantities and the directions of earthwork movement between cut and fill sections, fill from borrows, or cut to landfill sites.

Moreover, this chapter also presents a detailed process and the algorithm for the generation of the location data for the LBS.

The LBS explains the integration processes of variable productivity data and its associated factors, including equipment types, soil characteristics and site access points affecting the productivity values. The integration of different productivity values helps in analysing the impact of critical factors on LBS and resource planning. Furthermore, this chapter also outlines other functions of the prototype model which deals with the development of an SCP to avoid space congestion issues at an early stage of earthwork operations, thereby reducing productivity losses and

improving equipment allocation at correct locations and when necessary. The design of an algorithm for the identification of space-congested locations is developed, and a demonstration of the SCP with a typical road section is presented.

5.2 Development of Location-based Scheduling

This section explains the development processes and an algorithm for the automatic generation of the required data for producing LBS. The LBS is also known as a time-distance planning or a time-chainage chart, a time-location plan, or a linear scheduling method (Kenley and Seppanen, 2009).

As discussed in Chapter 4, where the detailed development of the model specification was given, sectional quantities of earthwork in road sections, working lengths with access points, planned productivity data and mathematical algorithms were integrated by developing different VBA macros to automatically generate the coordinate data (location and time) for the cutting and filling activities of the earthwork component.

In a time-location plan, a line represents a work activity whereas the slope of the line represents the production rate of the activity. The line is defined by the coordinates of location and time, similar to the X and Y axis in 2D graphs. The locations of the working activities are plotted on the X-axis and time on the Y-axis or sometimes vice versa. The time dimension was derived from the earthwork productivity data. Therefore, the time-location plan is directly dependent on the units of the productivity data. The unit of productivity data was assumed as one week for the generation of a weekly time-location plan.

The time-location module was also integrated with the productivity data to analyse the impact of the factors associated with the productivity data. The survey results found that the type of equipment sets, the soil characteristics and the site access points were the major factors that influenced the productivity data (see Chapter 3). In this study, these factors were used in the sensitivity analysis process to examine the effects on a time-location plan and the allocation of resources from a location viewpoint. The next section explains the detailed inputs and algorithms in the data generation processes.

5.3 Input Data for Location-based Scheduling

As discussed in Chapter 4, the data generation module processes the inputs and produces the required data of location and time for the automatic generation of a location-based earthwork schedule. The following are the key inputs of the data generation module:

- Calculation of sectional quantities of earthworks
- Calculation of productivity data of earthwork activities
- Identification of working lengths and site access points
- Mathematical algorithms and construction knowledge

5.3.1 Calculation of earthwork sectional quantities

This section explains the detailed process of the sectional quantities calculation methodology for the earthwork in a road section. Longitudinal and cross-sectional profiles of a road section are required for the calculation of the sectional quantities. A typical longitudinal profile of a road section is shown in Figure 6.1.

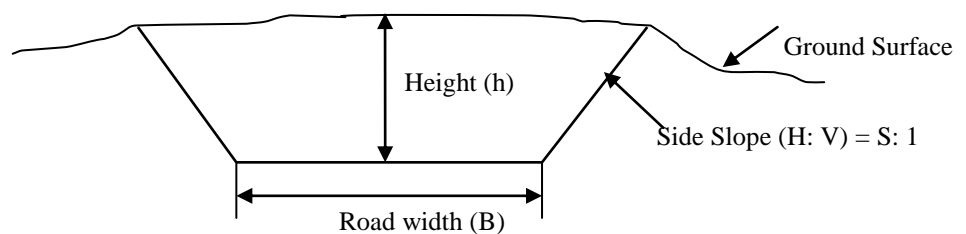
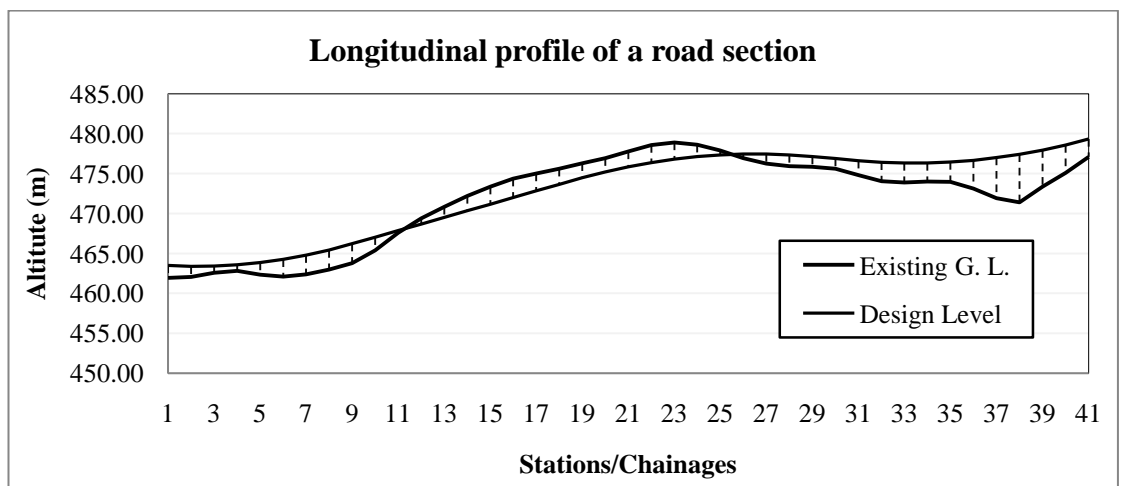


Figure 5.1 A typical longitudinal and a cross-sectional profile of a road section

The longitudinal profile provides the information on the sectional depth or the height of each station at the cutting or filling sections, and the distance between two chainage points or a station interval. The cross-sectional profile provides the information on a road's width, the side slopes, the transverse slope and the depth or the height of the section from the existing ground level. A trapezoidal formula was used to calculate the sectional area, and an average end area technique was used to calculate the sectional quantities of a road section.

In the prototype model, a VBA macro was developed to capture the text data of the design level, the ground level and the number of chainage points (stations) from a CAD file, where the longitudinal profiles of a road section are normally drawn. This data is exported to an Excel file and is used to determine the sectional quantities of the earthwork. The sectional quantities at each station and the station intervals of a road section are then exported to the data generation module, which is a key input in the prototype model. Since the sectional length and the quantities of the cut-fill activities are different, according to the topography of a road section, it is necessary to determine the economical haul distance in a cut-fill assignment of a road section. The next section presents the calculation processes of the productivity data that determine the time dimension of the earthwork scheduling.

5.3.2 Calculation of the productivity data of earthwork activities

This section presents the detailed process of determining the productivity data of earthworks. The productivity data was determined by using the "RoadSim" simulator developed by Dawood and Castro (2009). The time dimension for the location-based schedule was derived from the productivity data, which is represented as m^3/day or m^3/week . It was integrated into the model to generate the daily or weekly coordinate data for producing LBS.

Earthworks are usually performed with the utilisation of heavy construction equipment units. According to Castro (2005), the earthworks in a road construction are an aggregation of the following activities:

Cut+ Hauling/Dump + Levelling + Watering + Compaction

These activities are performed by the different sets of construction equipment and different execution methods as shown in Table 5.1.

Table 5.1 Earthwork activities, options and sets of equipment (Castro, 2005)

Activity	Execution methods (Options)	Combination of Equipment sets for different earthwork operations
Cut to spoil or deposit to temporary sites	C-1	<ul style="list-style-type: none"> • Excavator + tipper truck
	C-2	<ul style="list-style-type: none"> • Bulldozer + motor scraper
	C-3	<ul style="list-style-type: none"> • Bulldozer + pay loader + tipper truck
Fill from borrow pit or fill from cut	F-1	<ul style="list-style-type: none"> • Excavator + tipper truck + motor grader + water tanker + roller
	F-2	<ul style="list-style-type: none"> • Bulldozer + motor scraper+ motor grader + water tanker + roller
	F-3	<ul style="list-style-type: none"> • Bulldozer + pay loader + tipper truck + motor grader + water tanker + roller

The productivity calculation module in the “RoadSim” was developed by combining three options for the cutting and filling operations of the earthwork as mentioned in the above Table 5.1. The productivity values for different sets of equipment were determined by considering the equipment capacity, the number of cycles performed for each set of equipment, the soil characteristics, the compaction degree, the haulage distance, the nature of the works, and the site working conditions.

The productivity values of each set of equipment were determined and stored in a database according to the characteristics of the construction equipment. The site productivity values for the earthwork were calculated by integrating the site working efficiency coefficient (empirical) within the model. The coefficient of the site working efficiency was determined from the extensive site experience in construction projects over many years and was incorporated into the determination of the earthwork productivity.

Four levels of working efficiency coefficient – good (0.83), medium (0.75), rather poor (0.67) and poor (0.58) – were incorporated, to determine the productivity

values for different types of operations associated with earthworks (Mota-Engil). The productivity values of the cutting and filling operations were determined by simulating different factors according to the earthwork site conditions and the soil characteristics along the cutting sections, using the “RoadSim” simulator. The simulated productivity values were incorporated in the prototype model to calculate the tasks’ duration and to produce a location-based earthwork schedule.

5.3.3 Identification of the working lengths and the site access points

The identification of the working length and the access points are the main inputs of the prototype model that generates location-based schedules and progress profiles of earthworks. The detailed development processes, including an algorithm for the identification of the working length and the access points, were discussed in this section.

Warren (1996) stated that a mass haul diagram (MHD) provides important information to manage the earthmoving task, including the number of cut-fill balance sections and the length of the cut-fill section. The location and size of each earthmoving operation can also be identified with the aid of an MHD (Curgenvan, 2005). The construction industry survey results, discussed in Chapter 3, showed that the majority of construction companies still use MHDs for the identification of the economical haulage distance (EHD) and possible access points for the selection of suitable equipment, particularly for earthwork operations, so that the earthwork quantities between the cut-fill sections can be optimised within minimum cost. The next section presents the detailed development processes and the algorithm for identification of the haulage distance and the access points.

5.3.3.1 Algorithm for the identification of working length/access points

This section explains the concepts and the development process of the algorithm. The construction industry survey found that practitioners used their expertise and experience for identifying the EHD. In this study, an algorithm was designed using the characteristics of a mass haul diagram to identify the optimum haulage points and the distance between cut and fill sections in a road section.

In earthwork operations, different types of equipment have different economical haulage distances for earthwork movement, considering the nature of the work and site conditions. For example, the EHD for a bulldozer is 100m; for a motor scraper it is 100m to 500m; and dumpers are used for 500m to 1500 m, with more than 1000 m associated with tipper trucks when used for hauling in the earthwork process (Mota-Engil). However, Harris (1981, p51-57) pointed out that motor-scrapers are economical up to a 300m haul distance and bulldozers are suitable up to 100m for moving earth; taking into account the above points, an EHD of 300 m was selected, and it was incorporated into the algorithm as a variable to identify the working lengths and the access points of a construction zone between cut and fill sections.

Additionally, the algorithm was developed with the aim of incorporating the user's defined haulage distance, if the haulage distance and the points identified by MHD were not suitable because of site conditions and other resource constraints.

According to the design information provided in the longitudinal and cross-sectional profiles of a road section, sectional quantities of earthwork at each station were determined. In practice, this was obtained from contract documents or sometimes calculated using the road design information provided in the contract drawings. An MHD was generated by determining the algebraic sum of the cross-sectional earthwork quantities of each station in a road section. The next section discusses an algorithm for calculation of the economical haulage points and distances using MHD characteristics.

A data flow diagram for the development of an algorithm is shown in Figure 5.2.

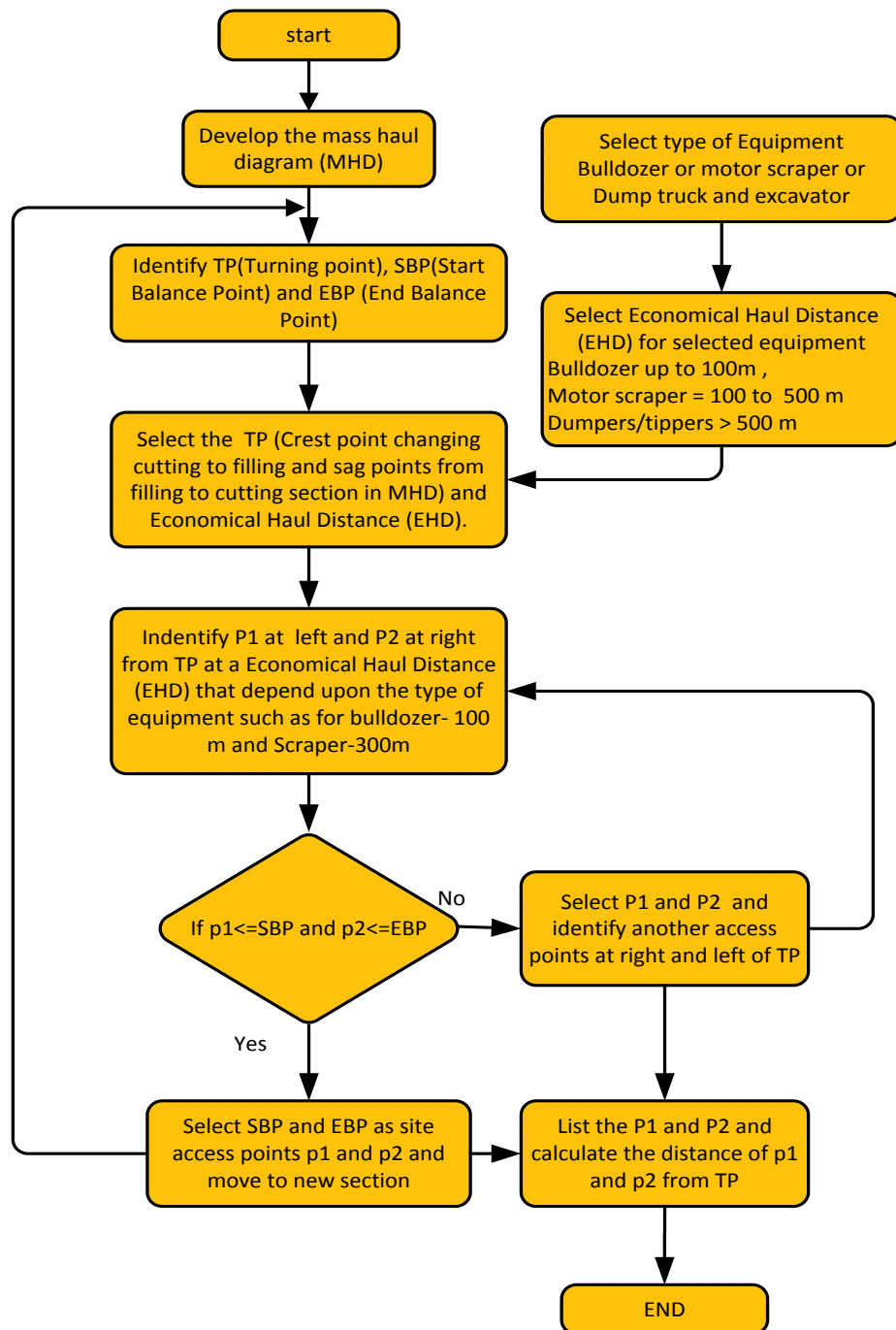


Figure 5.2 Data flow diagram for identification of economical haulage points and distances

Referring to Figure 5.2, a searching algorithm was designed to identify the Turning Point (TP) on a mass haul curve where the accumulated volume of the earthwork changes in direction from max to min or vice versa. Two types of turning points occur in a mass haul curve: the first one called a crest “TP”, where the cumulative

values of earthwork changes from cut to fill section; and a second one called sag “TP”, where the earthwork changes from fill to cut section.

After identifying the crest TP and the sag TP, a Start Balance Point (SBP) and an End Balance Point (EBP) were selected at the left side of the TP and at the right side of the TP respectively. These points were identified using a search algorithm at a defined haulage distance (input variables in the algorithm) according to the type of hauling equipment selected for the earthwork operations. For example, the haulage distance used in the algorithm is 300m. This is an economical haulage distance when using a motor scraper for hauling the earthwork from cut to fill sections (Harris, 1981, p57).

The EHD is determined according to the construction equipment types which are selected for the earthwork hauling operation and the specific equipment suitability for a given site. The developed algorithm identifies the start and the end points for EHD from the TP between cut and fill sections. Similarly, the second set of points were identified for a road section with a longer haulage distance, considering the double distance involved compared with the initial haul distance.

5.3.3.2 Demonstration of access points identification

A road section was selected to demonstrate the algorithm capability of identifying access points and working length. A snapshot of the interface is shown in Figure 5.3 below. The figure shows the information of identified working length and access points (station number), including sectional quantities of cut-fill sections of the selected road section. The road section was divided into multiple sections of both cutting and filling for the minimisation of the earthwork operation cost in a cut-fill assignment of a road section. The project planners or construction managers have two options from which to select these points, either based on the points identified by the algorithm, or on the planner’s personal judgement according to their experience and site constraints.

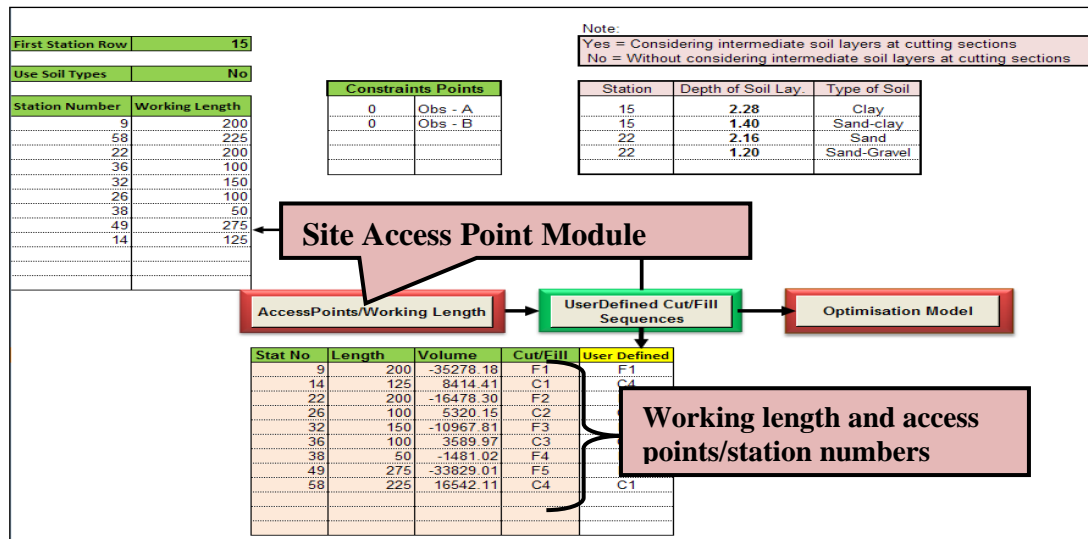


Figure 5.3 Snapshot of access point module for working length and access points

The information provided by the algorithm of the access point module is also a key input for the earthwork optimisation module (see Appendix-D). The list of cut-fill sections with working length/access points are utilised for the generation of a location-based schedule and a time-space congestion plan.

5.3.4 Mathematical algorithms and construction method

The mathematical algorithms and construction method are other inputs of the time-location module. An algorithm was designed by integrating within the model appropriate mathematical equations to generate the coordinate data linked to location and the time, to achieve a location-based schedule of the earthwork component (Section 4.6.2 of Chapter 4). The detailed processes of generating coordinate data for a time-location plan are discussed in Section 5.5 below. The next section discusses the development of an algorithm of soil layer identification.

5.4 Development of Soil Layer Identification

This section outlines the development of a new algorithm that assists in identifying different soil layers at cutting (excavation) sections, and in updating the productivity of earthwork activities, according to the soil characteristics of each layer in a longitudinal direction.

In such circumstances, the productivity of the earthwork excavation varies according to the soil characteristics. Therefore, there is a direct impact on progress profiles and the duration of the earthwork operations. The impact on the progress profiles and productivity due to the soil types can be analysed by simulation using “what-if” scenarios, during the planning and execution stages of a road construction project.

The possible preventive measures can be taken in advance, to avoid further delays at the construction site by improved resource planning at the affected locations. Therefore, the module has several benefits, such as identifying the soil characteristic at different construction layers; analysing the impact of soil characteristics on the visual aspect of the progress profiles; and updating the earthwork productivity of the cutting operation, according to the soil characteristic at each layer of the cutting section.

5.4.1 Algorithm for the development of soil layer

In this algorithm, the total height of the different types of soil layers is determined by using a borehole survey along a road section and the data is then stored in the input of the module. The detail of the algorithm for the calculation of the progress height of earthwork was discussed in Chapter 4. The algorithm first calculates the height of earthwork progress on a weekly basis at a selected section, and then compares it with the actual height of the soil layers. The actual height is identified by the borehole survey. A data flow diagram with an algorithm of the soil layer module is shown in Figure 5.4.

The algorithm was designed to discover the types of soil layers by comparing the height calculated by the module with the existing height of the different layers of soil profiles at a cutting section. If the calculated height (h_c) is greater than, or equal to, the height of an existing soil layer (h_s), then productivity is determined by considering the same layer of soil. Otherwise, productivity is determined according to the next layer of soil at a selected cutting section. The process was repeated to achieve the final design level of a road at all cutting sections.

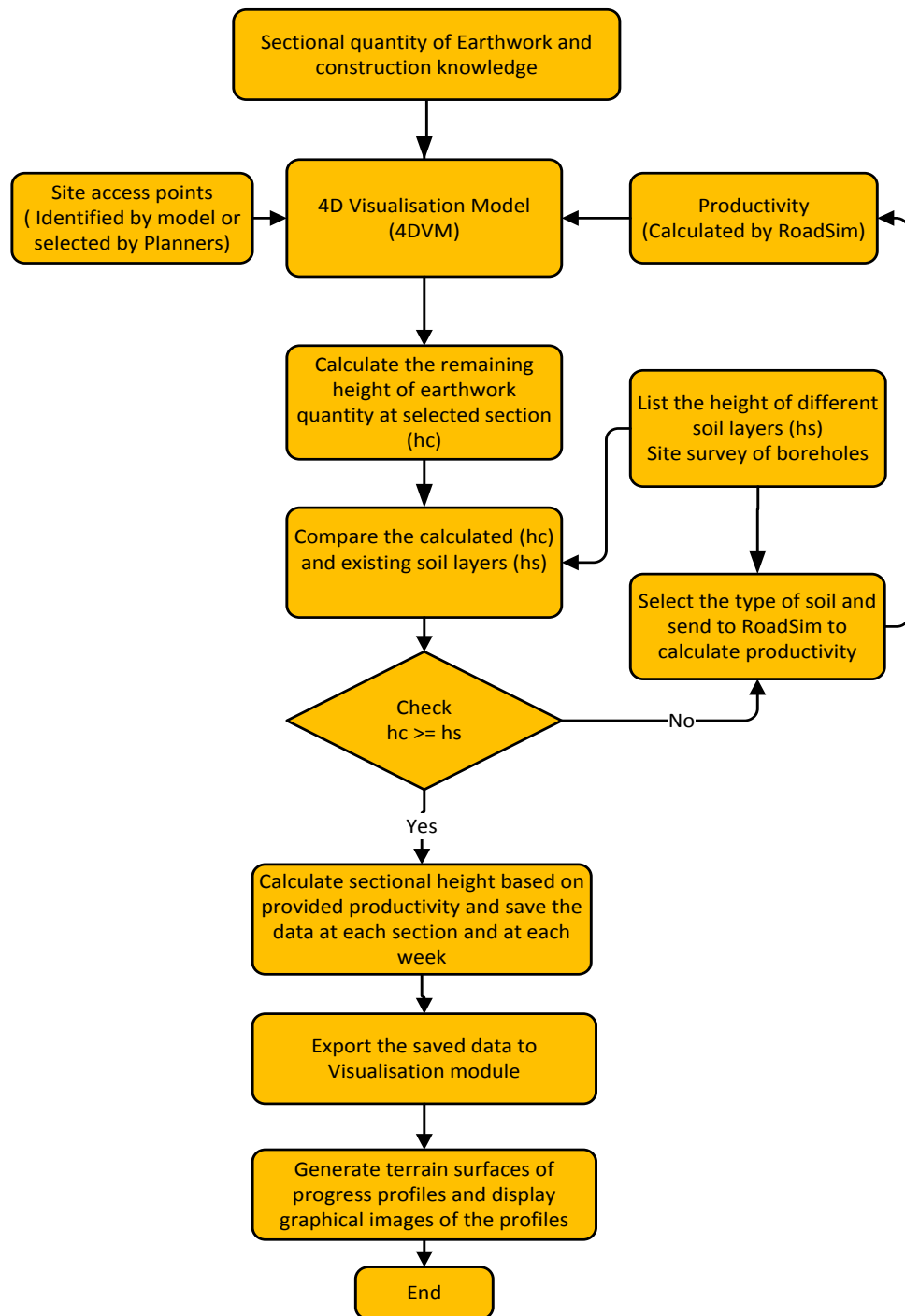


Figure 5.4 Data flow diagram of an algorithm for identification of soil layers

The function allows construction managers to optimise the different alternative access points considering the soil characteristics at all cutting sections in a road section. The site access points, normally identified and selected by planners, depends upon the “rules of thumb” and personnel judgement according to construction site conditions and construction rules. The height of the earthwork progress at each

station between two access points is determined considering the variable productivity data provided by “RoadSim” along the selected road section and saving the height as coordinate data. The coordinate data is then exported to the visualisation module, where data are processed to generate the terrain surfaces of the progress profiles, as well as assisting in visualising the impact on the locations and the progress profiles due to the variation in the soil characteristics at different layers of a cutting section.

The algorithm enables an analysis of the impact on the values of the site productivity of the cutting operations, according to the variation in soil characteristics and the position of the site access points. The next section discusses the features of the model that search for and identify the changes in the soil layers affecting the productivity model, so that the new productivity rates can be calculated, according to the identified layers of the soil characteristics at the cutting sections.

5.4.2 Demonstration of the soil layer identification

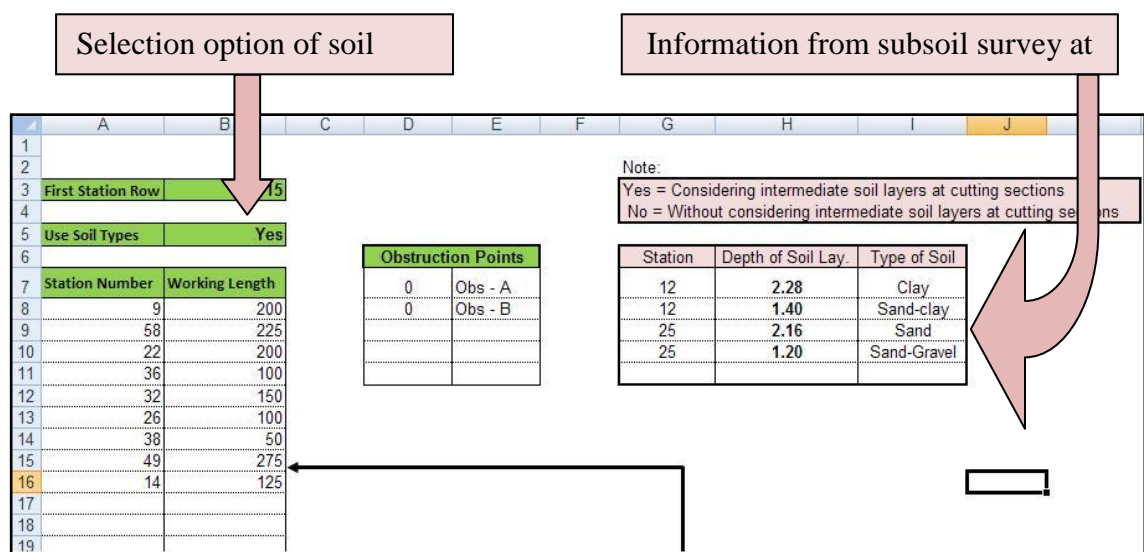


Figure 5.5 Snapshot of input sheet for selection of soil layer information

Figure 5.5 is a snapshot of the input information of the prototype model, where major inputs, such as sectional quantity, productivity value, working length, access points and characteristics of the soil at a cutting section are entered. In the input sheet, there are two options: “Yes to indicate the consideration of the intermediates layers having different types of soil characteristics”; and “No to indicate that the

intermediate layers have the same soil characteristics”. The sub-soil survey provides information on the soil characteristics at each layer of the cutting sections. The height and type of the soil at each layer is identified by the bore-hole survey at the required interval, and is entered in the input sheet as shown in Figure 5.5.

The algorithm of the model was designed in such a way that the calculated heights of all stations of a cutting section are compared with the existing height of the intermediate layers. The process is repetitive. Once the intermediate layer is identified, the module displays a message box showing the type of soil and the layer height (see Figure 5.6).

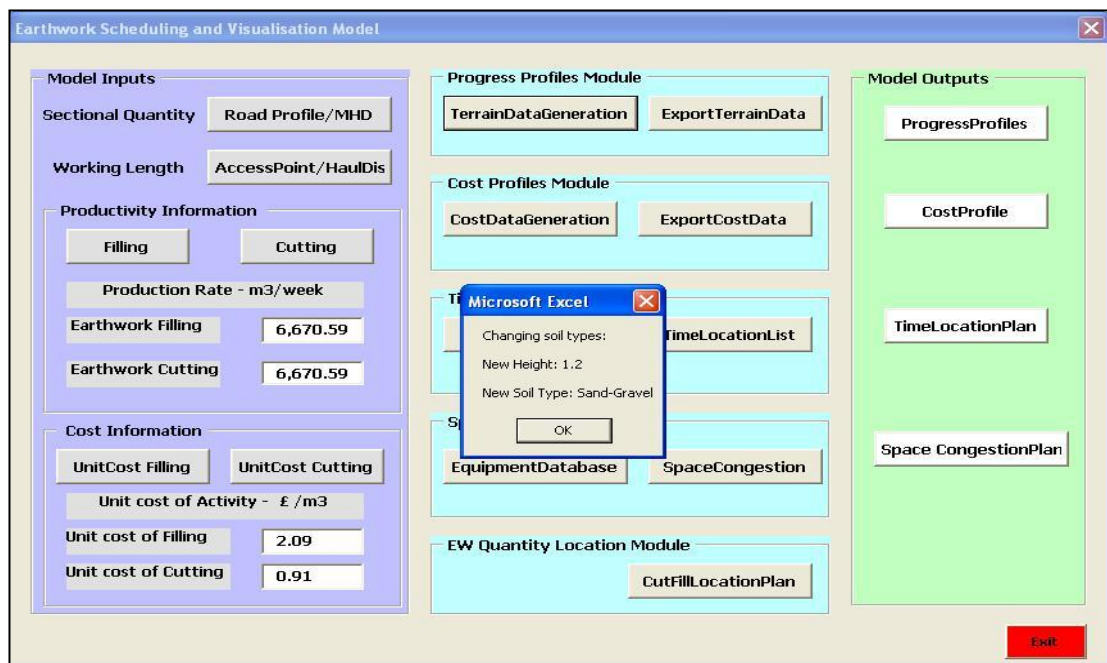


Figure 5.6 Snapshot of message showing changing of soil layers

After clicking “OK” in the message box, the productivity sub-module (Figure 5.6) appears when the soil types are changed; according to the identified soil type, the process is continued to achieve the final design level of the road. In this way, the productivity value at different layers of a cutting section is determined for the earthwork scheduling and visualisation of the scheduling information. The next section presents the algorithm of the data generation for a time-location plan or LBS.

5.5 Algorithm for Generation of Location-based Scheduling

A data flow diagram is shown in Figure 5.7 to enable the understanding of the coordinate data generation process. The data generation algorithms and the data flow diagram are explained as follows: the unit of time was considered as a day or week (see above) for developing a location-based schedule. The algorithm, developed in this module, deals with the identification of a station, where the earthwork cutting or filling operation starts. According to the author's personal knowledge in construction, the highest station in a cutting and the lowest station in a filling section are identified at first.

After identifying the maximum or the minimum station, representing the highest quantities of cutting or the lowest quantities of filling, the algorithm starts to search the nearby stations forward (upper limit station) and backward (lower limit station) from the first station to satisfy the earthwork quantity equivalent to the planned production quantity, using equation 7 (explained in Chapter 4). The quantity is equivalent to the sum of the volume of all the selected stations along a road section. The number of working stations is selected in such a way so that the remaining volume of the selected stations at a unit time remains the same.

Equation 7 was used for the identification of station numbers at each layer during earthwork operations by incorporating the productivity data. This process is repeated at each layer for both cutting and filling sections to achieve the remaining volume at each station within a selected road section equivalent to zero (at the design level of the road) longitudinally.

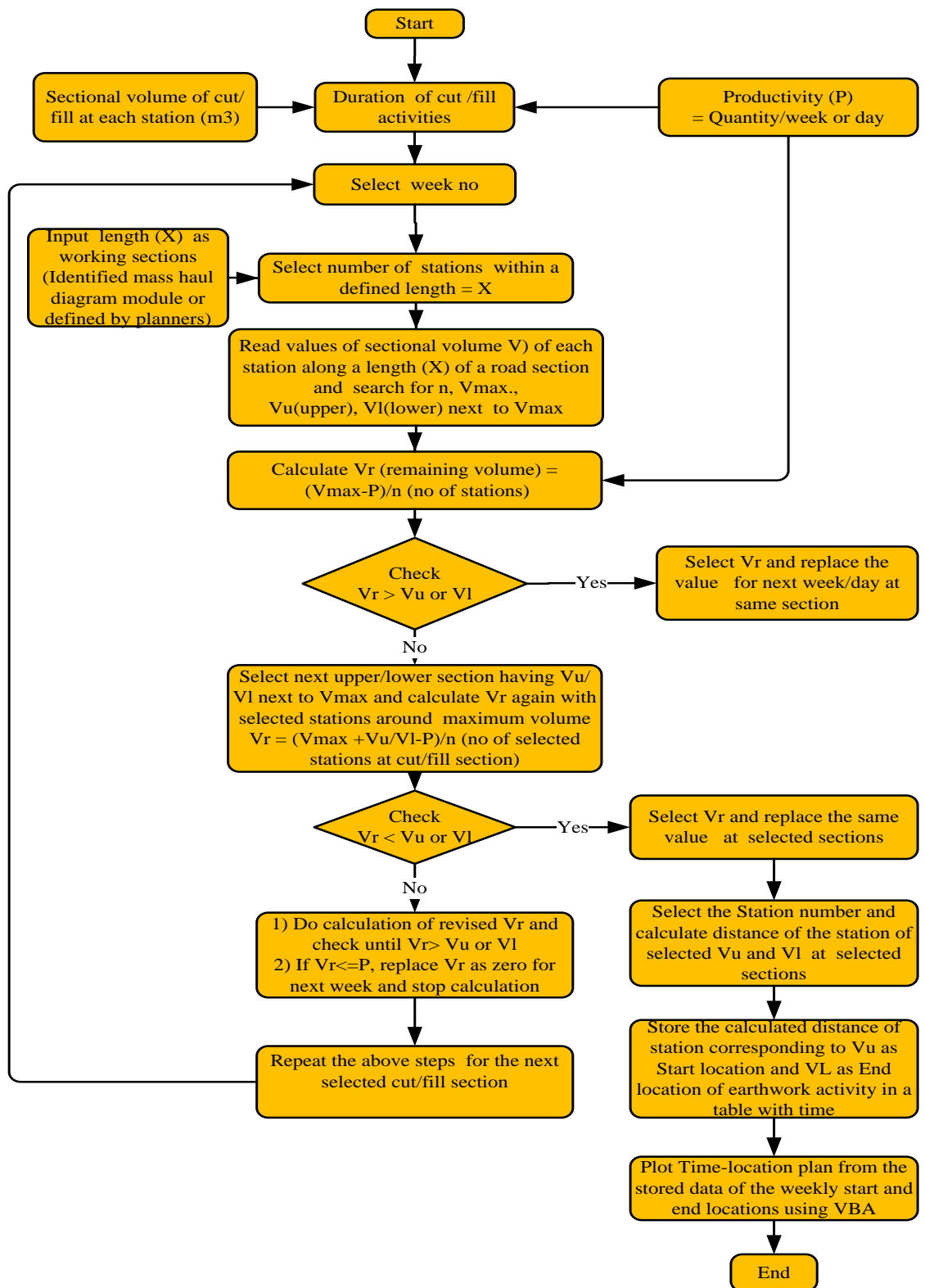


Figure 5.7 Algorithm for automatic generation of location-based scheduling

At each layer, the starting and ending stations are identified and their working lengths between two stations are determined, using the algorithm. This was developed by designing and integrating VBA macros within MS Excel. The working length at each layer between working stations increases from the first to the last layer at both cutting and filling sections. Similarly, the cutting and filling sections are selected according to the priority in a schedule to complete the earthwork operations of a road section. If the cutting or filling sections are too long, such sections are divided into manageable sections/smaller lengths, and the above processes are repeated to achieve the design level of the road.

Referring to Figure 5.7 above, this module has two key input variables:

- Productivity (P) of earthwork activities produced by “RoadSim”
- Working length (X) determined using the mass haul diagram

The two variables (P and X as shown above) were integrated within the model to search for the start and the end location of a working section at each construction layer, the location coordinates being dependent on the unit of productivity data, i.e. daily or weekly. In the model, the unit of productivity was set at a week, with standard working hours (40 hrs per week and 8 hrs per day) used for the generation of a weekly schedule.

The model also provides flexibility to enable users to select a unit in days if required. The generated coordinate data of locations and time were stored in a tabular format as shown in Table 5.2 below as initial outputs of the prototype model, and were exported to the visualisation module by developing VBA macros embedded within MS Excel to produce the graphical view of the LBS.

5.6 Demonstration of Location-based Scheduling

The prototype model produces the LBS automatically for earthwork operations. A typical list of coordinates of starting and ending locations, as well as the start and the end dates, for the earthwork activity is shown in Table 5.2.

The coordinate data of the working locations produced by a time-location module are used to produce the LBS. The data table was used for producing a time-location plan using arithmetic algorithms and VBA programming. This graphical output of the model provides a convenient and effective way of communicating the scheduling information.

Table 5.2: Automatic generated coordinates data of locations and time

S.N.	X1 (Start Station)	X2 (End Station)	Y1 (Start Date)	Y2 (End Date)	Cut/Fill
w0	75	225	0	1	F
w1	0	250	1	2	F
w2	0	250	2	3	F
w0	300	500	0	1	C
w1	275	500	1	2	C
w2	275	500	2	3	C
w3	250	500	3	4	C
w0	500	600	4	5	C
w1	500	625	5	6	C
w0	625	775	0	1	F
w1	625	775	1	2	F
w0	875	975	2	3	F
w1	850	1000	3	4	F
w2	775	1000	4	5	F
w3	775	1000	5	6	F
w4	775	1025	6	7	F
w5	775	1025	7	8	F
w6	775	1025	8	9	F

The LBS was integrated with the different productivity rates to produce the earthwork schedules under the different rate of production due to the site and the resources constraints. The LBS incorporates the site access point, the type of equipment and the soil characteristics throughout the construction operations. A snapshot of the weekly progress profiles of earthwork operations for a selected road section is shown in Figure 5.8. The different layers of the progress profiles are represented by a different colour.

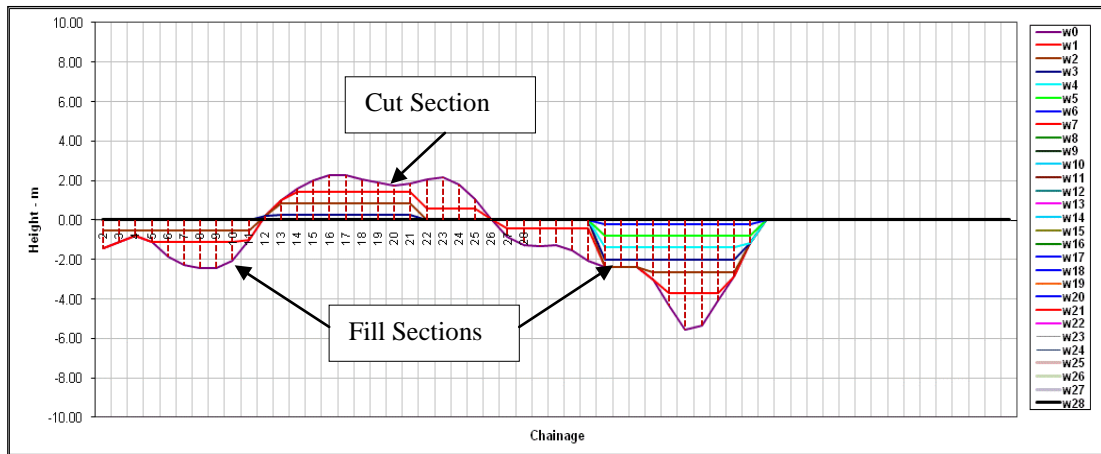


Figure 5.8 Progress profiles of earthwork operations generated by the model

The number of weeks required for a cutting or filling section is shown, for example, as w1 (filling at week 1 in blue colour) and w1 (cutting at week 1 in green colour) in Figures 5.9 and 5.10. Figure 5.9 presents a time-location plan / LBS of earthwork in a road section using two sets of filling and one set of cutting equipment, whereas Figure 5.10 shows a time-location plan using one set of filling and one set of cutting equipment. The 2D coordinates of the start and end points of the activity are indicated in terms of location and time (m, wk).

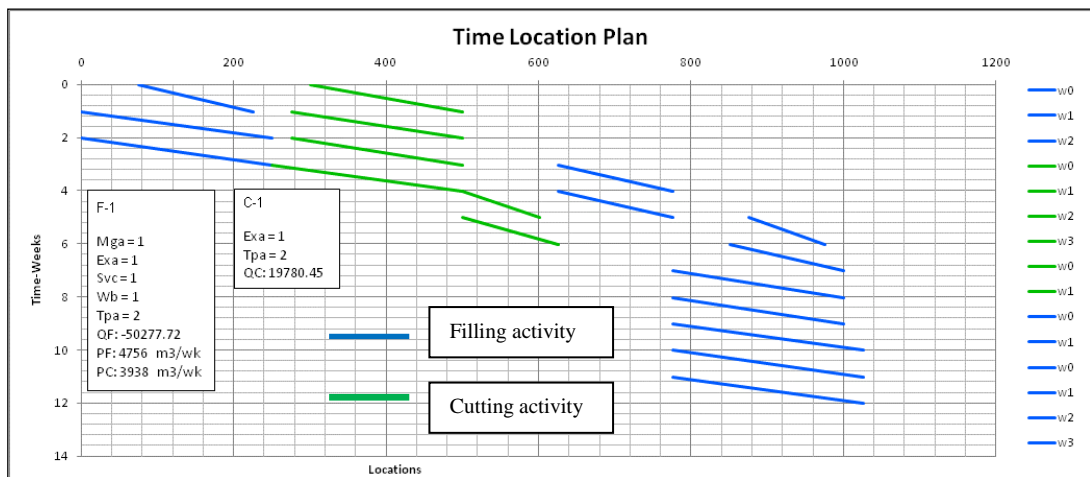


Figure 5.9 Snapshot of a time-location plan of earthwork using one set of construction equipment.

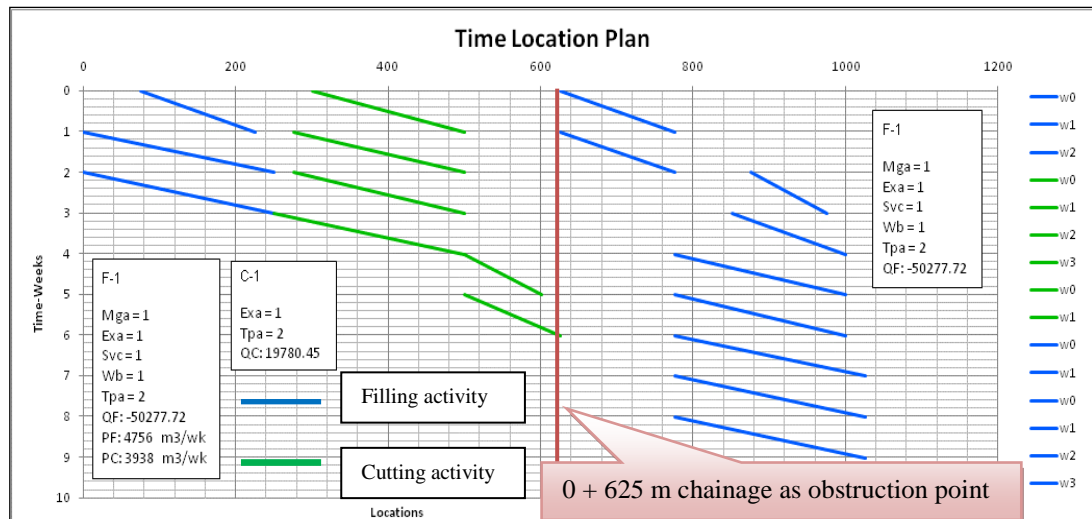


Figure 5.10 Snapshot of a time-location plan of earthwork using two sets of construction equipment

Any variation in the productivity rate due to the soil characteristics, the selection of the equipment types, or the site constraints along the road section was set to have a direct impact on the time-location plan / LBS, to assist the construction planners and managers in controlling activities' progress and in monitoring the production cost at the planning and the construction stages.

Figures 5.9 and 5.10 are two examples of the model functionality for automatically producing location-based schedules with detailed information on the equipment sets, assigned for both the cutting and filling activities. It was developed by simultaneously incorporating two sets of equipment working in the cutting and filling sections. The above figures show the location of the cutting activity in the green colour line and the filling activities in the blue colour line in a weekly schedule, as stated previously; the time-location plan was also integrated with the different productivity rates. This represents the key model output achievement because it improves the accuracy of earthwork planning tasks to avoid, for example, activity conflicts. The time-location plan also includes the site access points, the different equipment sets and the soil characteristics to provide accurate information in the construction schedule. This, in turn, allocates and optimises the available resources along the cutting and the filling sections at the correct locations throughout the earthwork operations.

The next section discusses the development of a time-space module to deal with the identification of congested locations at the early stage of earthwork operation.

5.7 Development of a Space Congestion Plan

This section presents the development processes of another function (component) of the prototype. A “time-space module” has been developed and integrated within the prototype. The module is developed to identify the congested locations at an early stage of earthwork planning by comparing the available space with the required space for a given set of equipment at a construction site. The module provides the early indication of the congested locations to enable the mobilisation of a suitable set of equipment, so that activities conflict, loss of productivity, and equipment idle at the construction site could be avoided.

The module also assists in analysing the impact on space congestion by a simulation process, involving different types of soil characteristics, site access points and site constraints. The next section outlines the detailed development processes and algorithm for the generation of the SCP.

5.8 Algorithm for Generation of Space Congestion Plan

An algorithm was designed to search chainage point (stations) whose sum of earthwork quantities is equivalent to the productivity for a unit of time (week or day). The algorithm first identifies the station that has the highest sectional volume; it then searches for the next nearby station forward and backward to satisfy the condition that the sum of the volume of all the selected stations is equal to the productivity, in such a way that the remaining volume of the selected stations at a particular layer remains the same. This process is repeated at each layer format to achieve the remaining volume at each station, equal to zero (the design level of road) at selected working sections. Referring to the conceptual Figure 4.9 of Chapter 4, the start and the end stations, including the corresponding working length, are identified at each layer. The lengths between two stations are determined. For example, the

sectional lengths for a cutting and a filling section at each layer of a road section are denoted by $L_{c1}, L_{c2}, L_{c3}, \dots, L_{cn}$ and $L_{f1}, L_{f2}, L_{f3}, \dots, L_{fn}$ respectively.

These lengths at each layer between stations increase from the first to the final layers in the earthwork operations. Since working space is proportional to the working length at each layer, the working space/area is also proportional in the same ratio. The working space was determined in this module by multiplying the length of each layer by the width of road. The design width of a road section has been considered in the algorithm because it is a significant factor in the calculation of available working space at each layer in earthwork operations. The details of the data flow diagram for the time-space module are presented in Figure 5.11. The module is divided into two sub-modules: available and required area calculation. The details of both sub-modules are discussed in the next sections.

5.9 Development of Time-Space Module

The time-space module represents an additional functionality of the prototype aimed at identifying the congested locations of working space. This module helps to plan, and to ensure that a suitable set of equipment is chosen according to the available space at the congested locations. This enables project planners to improve site productivity and to reduce earthwork cost throughout the construction operations. The time-space module is divided further into two sub-modules: required area calculation and available space determination. Typical snapshots showing different earthwork operations with different sets of construction equipment are shown in Appendix-E.

5.9.1 Required area calculation sub-module

This sub-module was developed to calculate the required working space for a selected set of construction equipment to perform cutting or filling operations. There are three combinations of construction equipment for cutting operations (C-1, C-2, and C-3) and three sets for filling operations (F-1, F-2, F-3) as shown in Table 5.3.

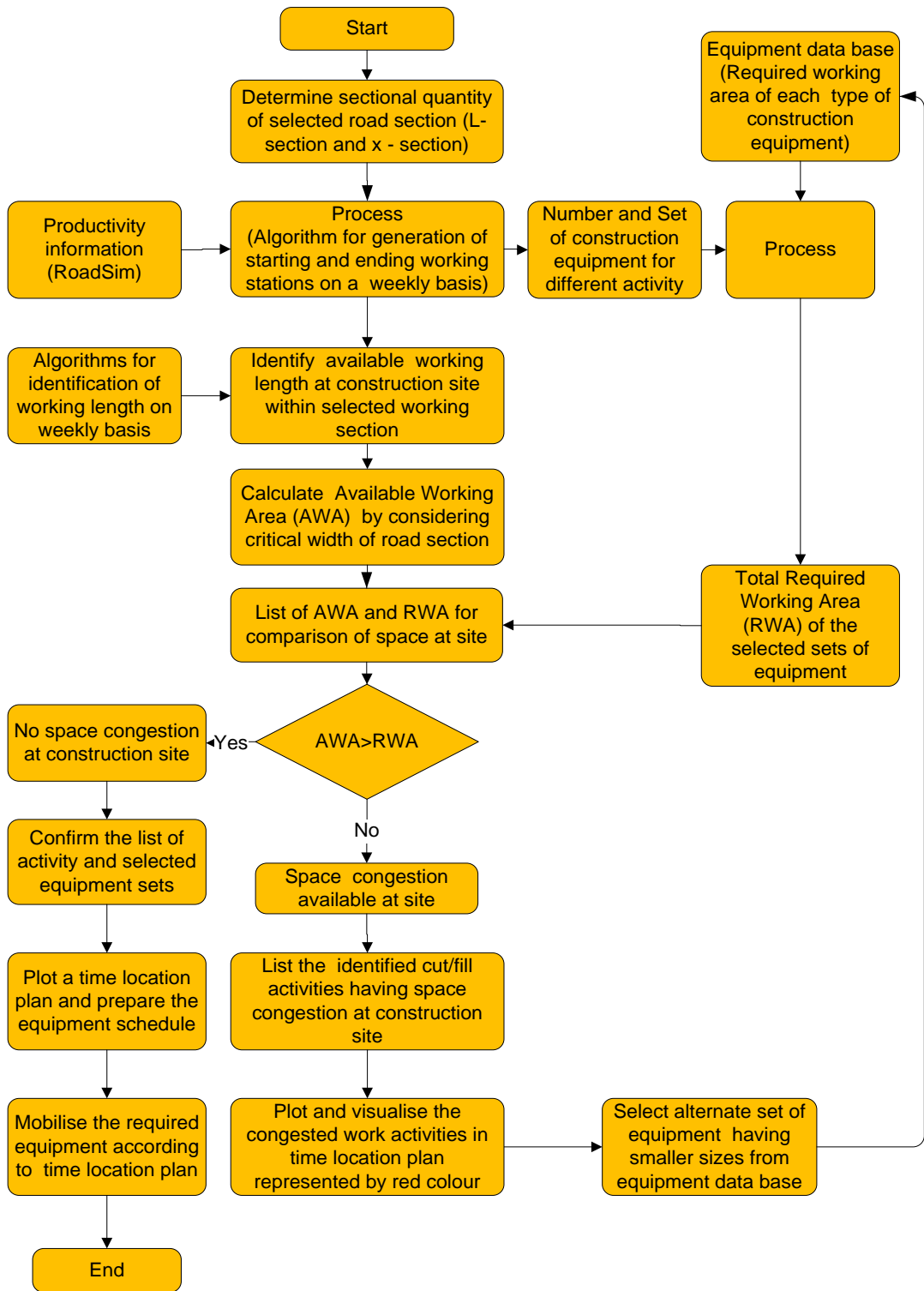


Figure 5.11 Data flow diagram and algorithm for a time-space module

The type and numbers of construction equipment used for a cutting or filling operation is selected from the “RoadSim” simulator. The space required for equipment manoeuvring, worker’s space, material loading/unloading, space for transportation, and space for traffic signs and signals were considered as space factors. In the space calculation sub-module, a safety space factor was incorporated to take into account the above spaces.

Table 5.3 shows a list of the typical construction equipment available at an equipment compound with their required working space/area during construction operations. The list of required space and space factors for different sets of construction equipment was provided by Mota-Engil, which were calculated based on the empirical method and experience of the construction managers. The values presented in Table 5.3 were used to inform the time-space module developed in this thesis

Table 5.3 List of required area for different options (sets of equipment)

SN	Class	Type of Equip.	Required Space of Equip (m ²)	C-1	C-2	C-3	F-1	F-2	F-3	Options	Total Required Area (m ²)
1	01	Ttta	200							C-1	960
2	01	Tttb	220			2			1	C-2	1960
3	01	Tttc	240		2			1		C-3	1920
4	01	Ttt d	260							F-1	2040
5	02	Mga	300				1	3	2	F-2	5520
6	02	Mgb	320							F-3	4400
7	03	Exa	160	2			1				
8	03	Exb	170								
9	03	Exc	180								
10	03	Exd	190								
11	04	Wpla	220			1			2		
12	04	Wplb	240								
13	05	Bka	300								
14	06	Msa	250		2			2			
15	06	Msb	240								
16	07	Oht	150			2			2		
17	08	Svc	160				1	2	2		
18	08	Sfc	170								
19	08	Ptc	180								
20	10	Wb	160				2	5	2		
21	10	Tpa	40	4			2				
22	10	Tpb	180								

The sub-module has the capability to incorporate the types and number of equipment selected by the user, considering the availability of plant at the equipment

compound. The sub-module calculates the required working space by using the algebraic sum of the space required for each set of construction equipment multiplied by a safety factor, as shown in Table 5.3. The details of the abbreviations used for all equipment types, including power and bucket size, are presented in Table 5.4 below.

Table 5.4 Abbreviation of different types of construction equipment (Castro, 2005)

Code	Type of Equipment	Bucket size or weight	Dozer width	Power
Ttta	Track-type tractor - type 1		4.16 m	165 HP
Tttb	Track-type tractor - type 2		4.40 m	215 HP
Tttc	Track-type tractor – type 3		4.96 m	305 HP
Tttc	Track-type tractor – type 4		4.66 m	440 HP
Mga	Motor grader – type 1		3.66 m	185 HP
Mgb	Motor grader – type 2		4.27 m	215 HP
Exa	Excavator - type 1	1.3 m ³		150 HP
Exb	Excavator - type 2	1.6 m ³		220 HP
Exc	Excavator - type 3	2.0 m ³		250 HP
Exc	Excavator - type 4	2.6 m ³		310 HP
Bka	Backhoe loader	0.900 m ³		70 HP
Msa	Wheel tractor scraper- type 1	16 L m ³		330 HP
Msb	Wheel tractor scraper -type 2	20 Lm ³		450 HP
Oht	Articulated dump truck	13 L m ³		260 HP
Sfc	Sheep-foot compactor	20 ton		215 HP
Svc	Vibrating soil compactor	15 000Kg		155 HP
Ptc	Pneumatic tire compactor	35 000Kg		165 HP
Wb	Water tanker	12 m ³		180 HP
Tpa	Tipper truck type 1	10 m ³		200 HP
Tpb	Tipper truck type 2	15 m ³		250 HP

5.9.2 Available area calculation sub-module

The second sub-module focuses on the calculation of the available working space at the earthwork construction site, according to the terrain conditions in respect to time, during the progress of cutting or filling operations. In this sub-module, an algorithm was introduced to calculate the working space by identifying the available length at each layer in both cutting and filling operations as shown in Table 5.5. The width of working section at each layer is considered, as the design width, which is the critical factor for identifying the space congestion at a construction site.

Table 5.5 List of weekly available length and areas for cut-fill activities

S.N	X1 (Start Station)	X2 (End Station)	Y1 (Start Date)	Y2 (End Date)	Cut/ Fill	Working Length	Available Area	Equipment Set/Option	Required Area	Time Space Congestion
w0	0	100	0	1	F	100		F-1	2252	No
w1	0	125	1	2	F	125	3750	F-1	2252	No
w2	0	175	2	3	F	175	5250	F-1	2252	No
w3	0	200	3	4	F	200	6000	F-1	2252	No
w4	0	200	4	5	F	200	6000	F-1	2252	No
w5	0	200	5	6	F	200	6000	F-1	2252	No
w0	200	325	0	1	C	125	3750	C-1	682	No
w1	200	325	1	2	C	125	3750	C-1	682	No
w0	350	500	6	7	F	150	4500	F-1	2252	No
w1	325	525	7	8	F	200	6000	F-1	2252	No
w2	325	525	8	9	F	200	6000	F-1	2252	No
w0	525	625	2	3	C	100	3000	C-1	682	No
w0	650	775	9	10	F	125	3750	F-1	2252	No
w1	625	775	10	11	F	150	4500	F-1	2252	No
w0	775	875	3	4	C	100	3000	C-1	682	No
w0	925	1025	11	12	F	100	3000	F-1	2252	No
w1	875	1075	12	13	F	200	6000	F-1	2252	No
w2	875	1075	13	14	F	200	6000	F-1	2252	No
w0	1100	1175	14	15	F	75	2250	F-1	2252	Yes
w1	1100	1200	15	16	F	100	3000	F-1	2252	No
w2	1075	1200	16	17	F	125	3750	F-1	2252	No
w3	1075	1200	17	18	F	125	3750	F-1	2252	No
w0	1225	1350	4	5	C	125	3750	C-1	682	No
w1	1200	1375	5	6	C	175	5250	C-1	682	No
w2	1200	1425	6	7	C	225	6750	C-1	682	No

The available working space was determined by multiplying the available length at each layer by the road width as shown in the available working area column of Table 5.5. The available working area is directly proportional to the productivity of the filling or cutting activities and it is calculated at each day or week, according to the chosen time unit of productivity. The next section shows an SCP generated by the prototype module and demonstrates the space congestion module functionality, using a typical road section for the earthwork component.

5.9.3 Demonstration of space congestion plan

The sub-module compares the required working area with the available working area. If the available working area is less than the required working area, the cutting or filling activity is considered as a space congested activity; at a construction site otherwise, the space congestion condition does not exist. The congested activity is represented by a ‘Yes’ and uncongested by a ‘No’ in Table 5.5 above. After identifying congested activity and listing it in a table, the sub-module generates a time-location congestion plan of a typical road section as shown in Figures 5.12 and 5.13 below. The activity line, showing in red colour, represents a congested space in a time-location congestion plan (see Figure 5.13).

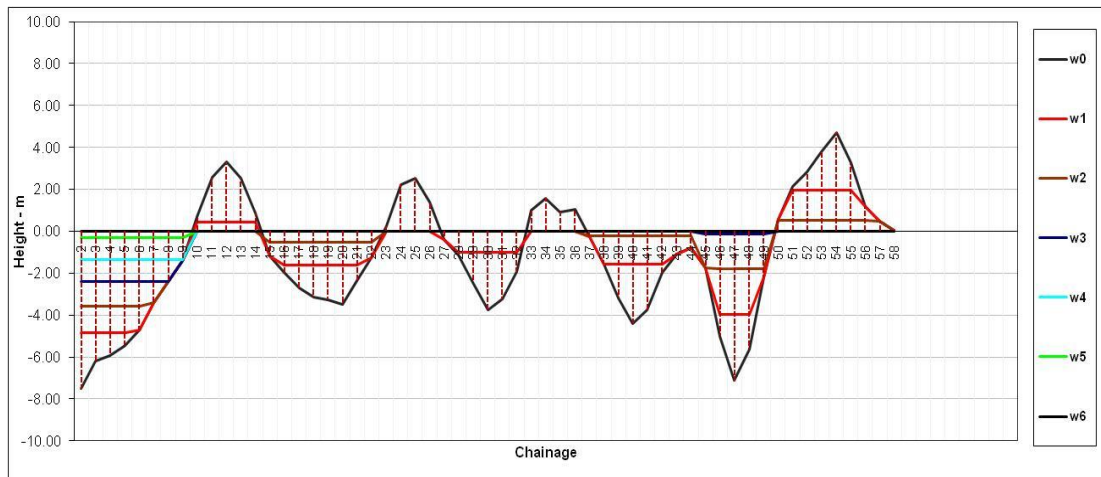


Figure 5.12 Earthwork progress profiles of a selected road section

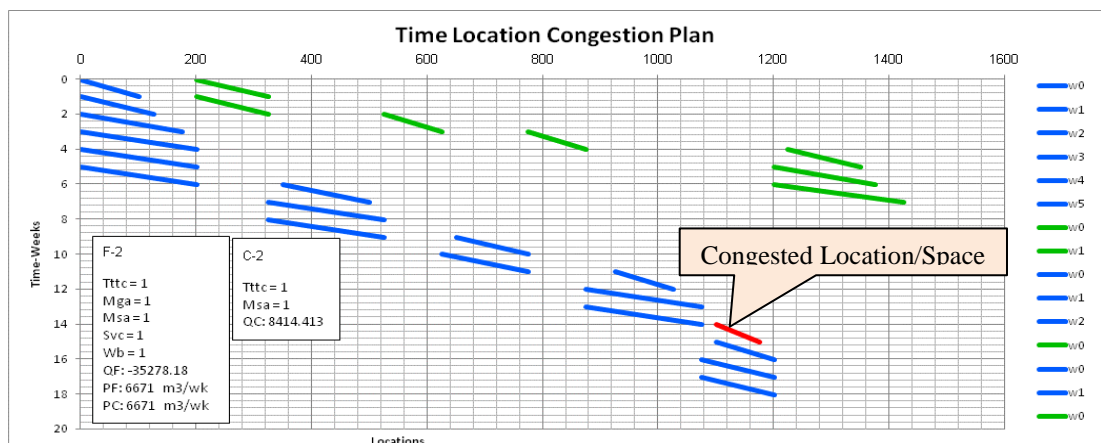


Figure 5.13 Typical view of time-location congestion plan generated by model

5.10 Demonstration of LBS and SCP with a 7 km road section

A 7km road section was selected from a road construction project recently completed in Portugal to demonstrate the model's functionality. Road design and planning data, in addition to the longitudinal profiles, the productivity information, the soil characteristics, the working sections and the site access points, were collected from the company "Mota-Engil" in Portugal. The data generation module of the prototype model (Chapter 4), processes the input data to generate the earthwork progress profiles and the LBS/time-location plan (see Figures 5.14 and 5.15).

Figure 5.14 shows the weekly earthwork progress profiles of the road section produced by the prototype model, showing the cutting and filling sections and their respective locations on a weekly schedule of the earthwork activity. The dotted lines represent the existing time-location plan currently being used in the earthwork construction.

Figure 5.15 presents a time-location plan of a 7km road section showing the actual locations of the earthwork activities on a weekly basis. The figure provides the required accuracy of information relative to the location and the time for the earthwork activities at any particular time. The blue and the green lines represent filling and cutting sections respectively. Additionally, the time-location plan provides the information relating to the different sets of equipment and crews, which can be simultaneously scheduled for progress at a different station point such as 0.0 km, 1.0 km, 3.0 km, 5.0 km and 6.0 km.

The module is capable of incorporating different obstructions according to the availability of the resources and the site constraints, by dividing the whole road section into controllable sections. The plan provides scheduling information concerning the mobilisation and demobilisation schedule of different sets of heavy construction equipment for the cutting and filling operations. As a result, construction managers can produce an equipment procurement schedule for the earthwork operations in road construction projects by using a systematic approach for making decisions and for detailed resource planning.

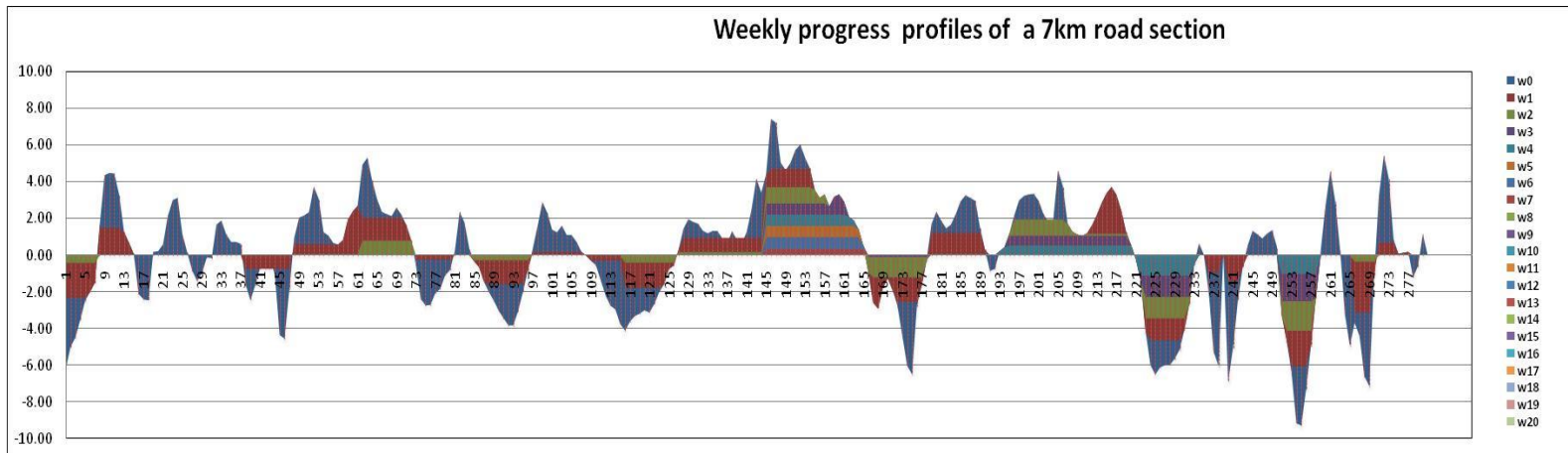


Figure 5.14 Snapshot of the model-generated progress profiles of a 7 km road section

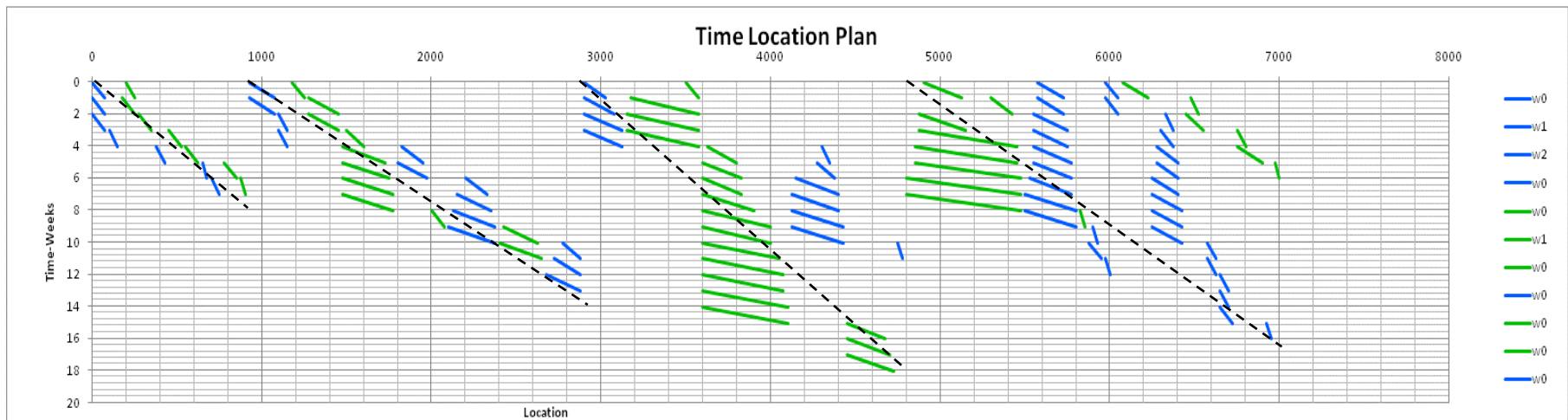


Figure 5.15 Snapshot of model-generated LBS/time-location plan of a 7 km road section

5.11 Summary

This chapter presented the prototype development for generation of a location-based schedule/time-location plan of earthworks components in road construction projects. The model utilised an algorithm to automatically produce an LBS. The algorithm generates LBS by plotting the location and time dimensions in a 2D graph, which is also known as an LBS/time-location plan. The scheduling information of weekly locations of earthwork operations was visually represented in a time-location plan. The different productivity rates were integrated to analyse the impact of different factors, including types of equipment, soil characteristics and site access points / working lengths for the earthwork scheduling. This chapter provides the development of a soil layer module designed to identify intermediate soil layers at a cutting section. The module helps construction managers in analysing the effect of soil characteristics on earthwork schedules and helps to visualise the impact on progress profiles during the earthwork operations by considering “what-if” scenarios of different productivity rates.

The developed LBS assists construction managers and project planners to control budgets, schedule activities and allocate the required resources at the correct locations at the construction stage in road projects. The LBS provides advanced information on working locations and time, to reduce the mobilisation and demobilisation costs of equipment. The LBS also assists in the scheduling and monitoring of day-to-day activities associated with earthworks. This is considered as a key contribution to the road construction scheduling methodology. Furthermore, this section presented a location-based space congestion plan to identify and manage the congested space for earthwork activities at a construction site in road projects. New methodology was introduced for a location-based space planning for the earthwork operations. This was demonstrated using a prototype model with a typical road section, having cutting and filling sections.

The next chapter discusses the development of a visualisation module of the prototype to visualise the earthwork progress profiles and communicate the scheduling information, by generating a time-location plan.

Chapter-6

Visualisation of Scheduling

6.1 Introduction

The previous chapter discussed the development of location-based scheduling of the earthwork component in a road construction project. This chapter presents the development of a Visualisation Module (VM), which is a component of the prototype model. The VM provides the visual information of earthwork scheduling and weekly progress profiles, and communicates the construction process sequences with consideration given to location aspects.

The development processes relating to the visual outputs of the model are explained. These include weekly progress profiles/terrain surfaces, time-location plans, space congestion plans, cost profiles and the cost S-curves, using a single interface. This allows the construction team members to visualise and analyse the location-based scheduling information, and to optimise the allocation of resources considering space constraint in road construction projects.

6.2 Development of Visualisation Component

The VM processes the weekly coordinate data produced by the Data Generation Module (DGM) and transforms it into a visual format based on the earthwork scheduling information. The visualisation of earthwork scheduling information includes:

- Weekly progress profiles/terrain surfaces
- Time-location plan/location-based scheduling
- Space congestion plan
- Cost profiles and cost S-curve of earthworks

The VM of earthworks was developed using the following languages: C#, VBA and MS Excel. The required input data was stored in MS Excel worksheets. Several

VBA macros were developed using the data flow diagram and algorithms (see Chapters 4 and 5). The developed VBA macros process the input data and generate the coordinate data for each function developed in the prototype model.

The VM imports data from each function of the model using Structured Query Language (SQL) inquiry, and transforms the imported data into a visual representation of tabular and graphical information. A snapshot of the visualisation module for generating earthwork scheduling is shown in Figure 6.1.

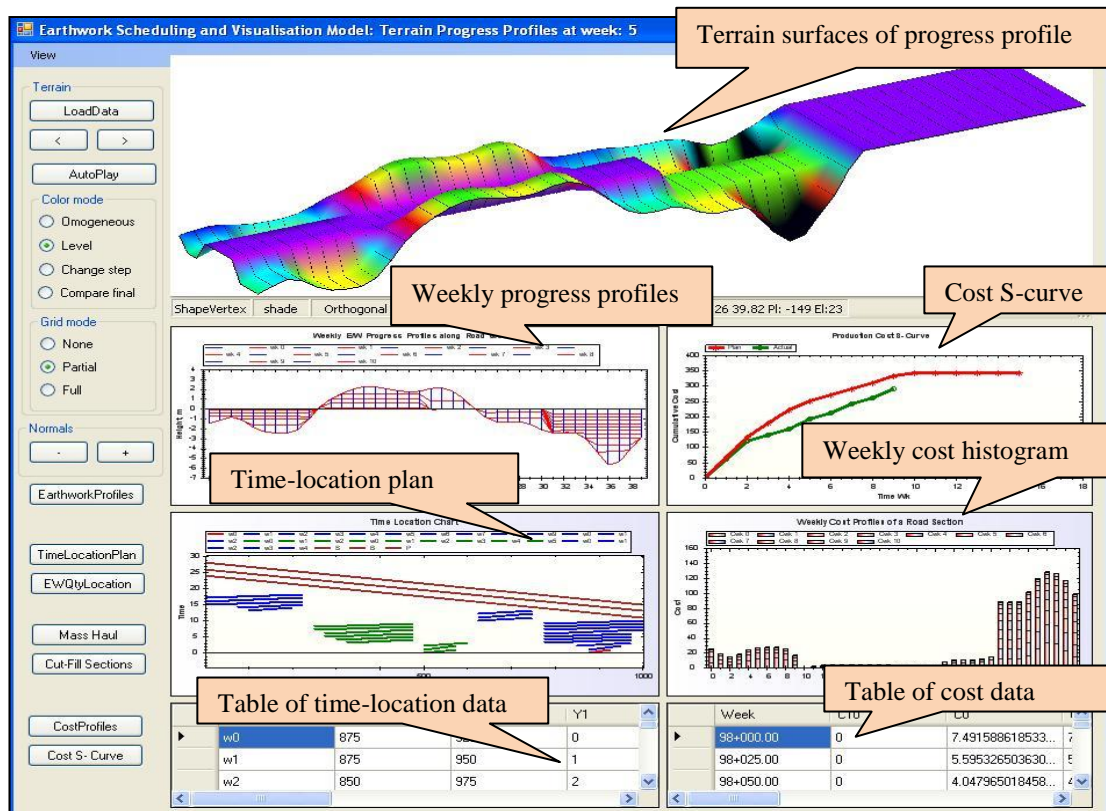


Figure 6.1 Snapshot of the visualisation module of earthworks scheduling

The above figure represents the visual outputs of the model that includes the earthwork progress profiles, terrain surfaces of earthworks, the time-location plan, the space-congestion plan, the cost profiles and the cost S-curve. The VM has the capability to display the weekly progress profiles of earthwork manually or automatically.

The VM produces both a time-location plan and a space congestion plan concurrently in a time-location chart (see Figure 6.2). The time-location plan also

includes information related to the congested locations and pavement activities. The time-location plan generated by the VM shows three lines: the sub-base, the base course and the top surfacing tasks (see Figure 6.2). The VM also provides tabular information on the weekly starting and ending locations throughout the construction operations.

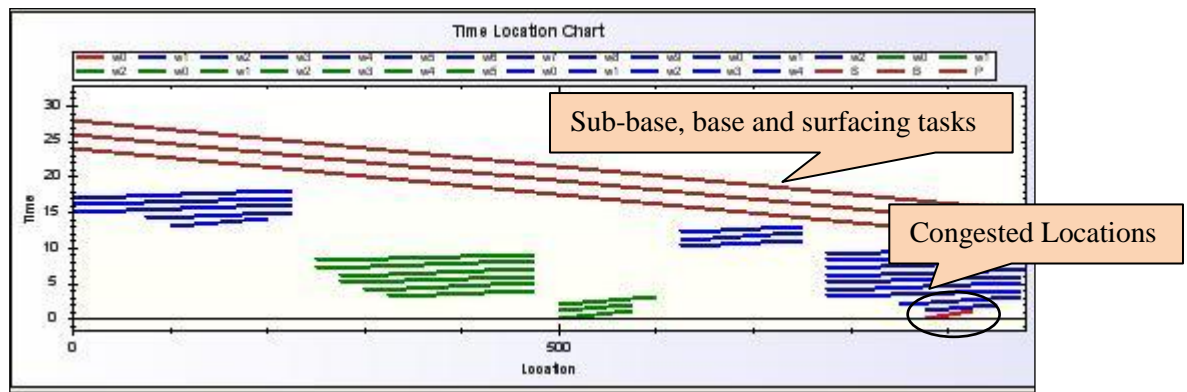


Figure 6.2 Typical view of time-location plan including congested location

The next section discusses the development processes involved in the terrain surfaces of the progress profiles and the cost profiles of the earthworks.

6.2.1 Visualisation of earthwork progress profiles

This section explains the coordinate data integration into the VM for the production of terrain surfaces of earthwork. The detailed coordinate data generation processes associated with the progress profiles were discussed in Chapter 4. The terrain surfaces of the progress profiles are represented on a regular triangulation grid, where the vertex of the regular grid is represented by the progress height of earthwork at each point on a regular grid.

The visual representation of the earthwork progress profiles was developed by integrating the terrain surface of a road section (2D+height) with respect to time. The time dimension in the generation of the terrain surfaces was derived from the unit of productivity data. The development of an interface for the earthwork progress profiles module is described in the following section.

6.2.2 Interface of earthwork progress profiles module

A snapshot of the interface of the earthwork scheduling and visualisation of the prototype model is shown in Figure 6.3. The interface includes the different modules and sub-modules in the prototype. These modules and sub-modules were designed with different VBA macros to account for the range of functionality within the model. The earthwork progress profiles module is also shown in Figure 6.3.

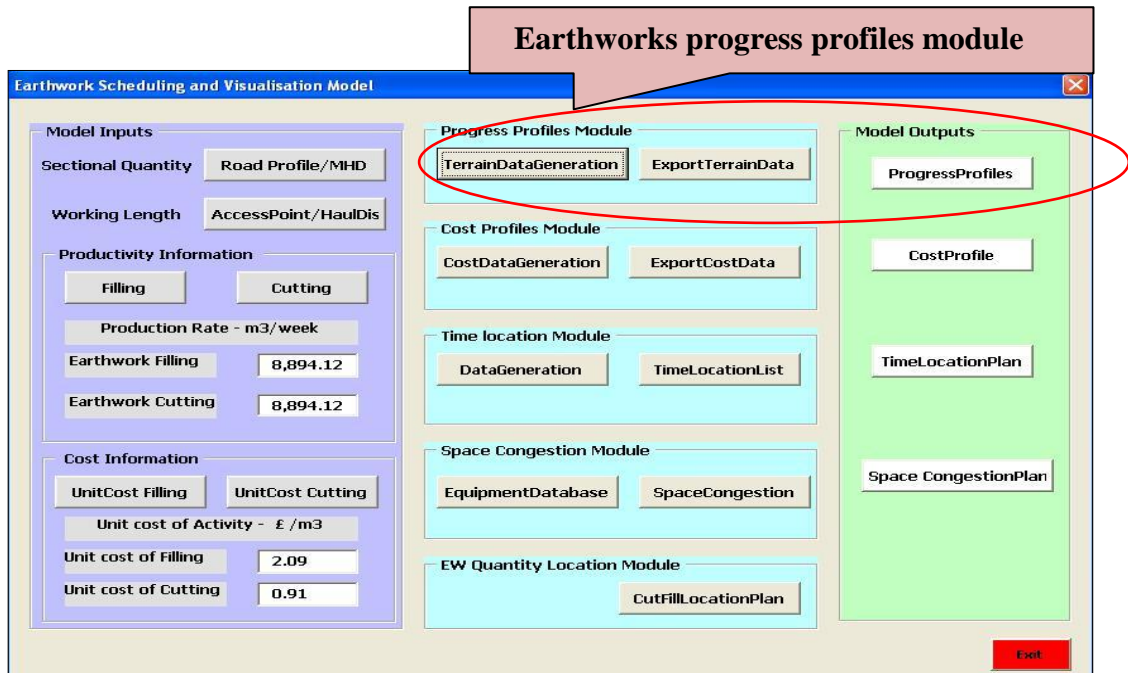


Figure 6.3 Snapshot of the interface of terrain surfaces generation module of earthworks

The progress profiles module includes three sub-modules: the "TerrainDataGeneration", which produces the weekly progress height data; the "ExportTerrainData", which exports the progress height data in a text file; and the "ProgressProfiles", which generates graphical views of the weekly terrain surfaces of the earthwork progress profiles. The details of the algorithm and the development process of the "TerrainDataGeneration" were outlined in Chapter 4. The next section now discusses the "ProgressProfiles" sub-module that produces the terrain surfaces.

6.2.3 Generation of terrain surfaces of earthworks progresses

The "ProgressProfile" sub-module of the VM that produces the terrain surfaces of earthwork profiles was developed using Visual C++ and DirectX. In this module, a regular triangulation grid is produced first by the VM to represent 3D terrain

surfaces of the earthworks profiles at each layer of the construction processes. The X-coordinate is considered along the longitudinal direction and the Y-coordinate along the road cross-direction that represents the width in a road section. The starting point of the regular grid of a terrain surface is considered as the origin (0, 0).

The Z-coordinate represents the vertex of the triangulation grid, which is considered as the height of the road progress surface. The scales for the X, Y and the Z-axes are different. For the X-axis, the length of the road is represented in a 1:25 scale; the width of the road represented in a Y-axis has a 1: 10 scale; and the Z-axis has a 1:1 scale for the height of the terrain surfaces, which represents a section of a road. The coordinate data (Z-axis) is saved as a text file. The file is exported for the automatic generation of the terrain surfaces on a weekly basis throughout the earthwork construction operations. The next section demonstrates the terrain surface generation processes on a weekly basis.

6.2.4 Demonstration of terrain surface generation

A road section with two filling sections and one cutting section was selected to demonstrate the VM functionality in generating the terrain surfaces. After processing the required input data, such as productivity values, sectional quantities of earthwork, working sections and site access points, the DGM generates the coordinate data for the progress height of the earthwork and exports it to the VM by the “ExportTerrainData” sub-module. The VM then transforms the coordinate data into the terrain surfaces of the earthwork progress profiles. Snapshots of the automatically generated earthwork progress profiles and corresponding terrain surfaces produced by the VM are shown below in Figures 6.4 and 6.5 respectively.

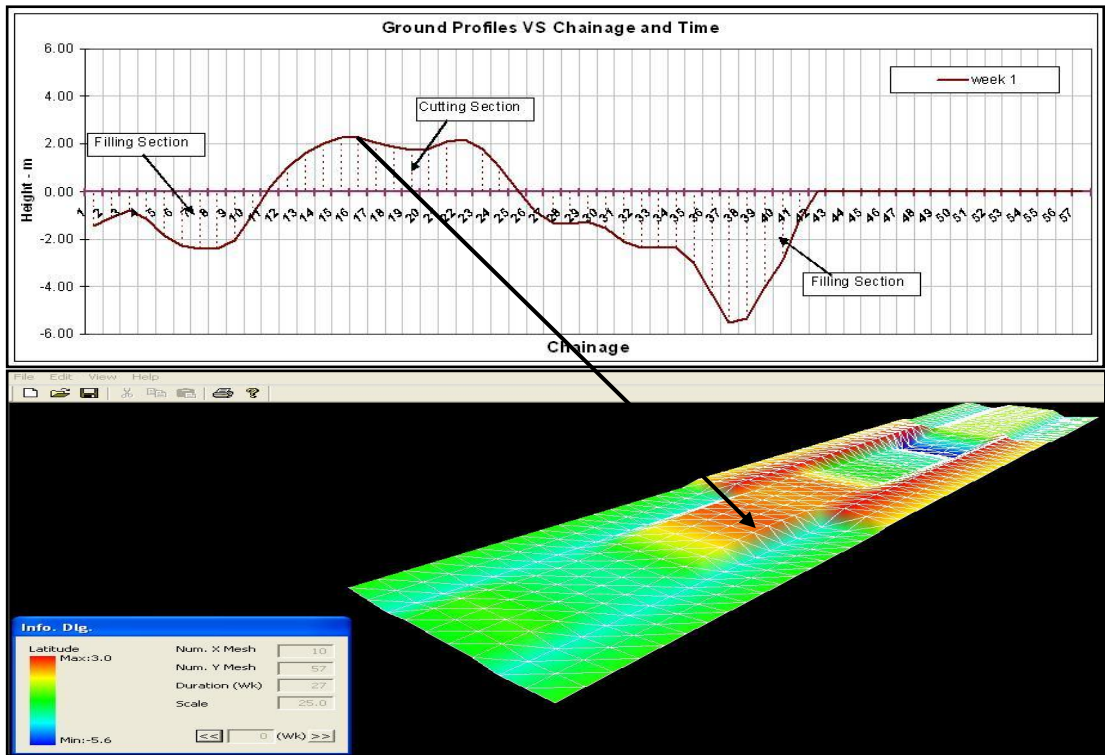


Figure 6.4 Snapshot of earthwork progress profiles and terrain surface at week 1

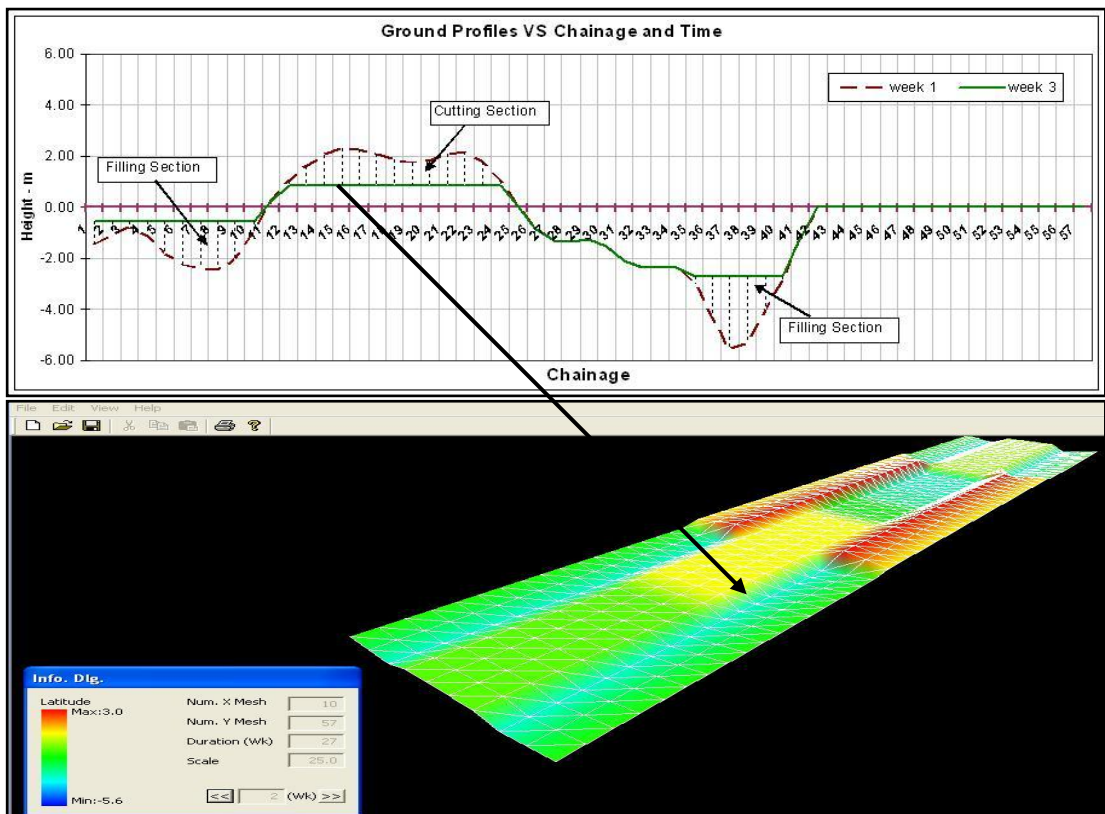


Figure 6.5 Snapshot of earthwork progress profiles and terrain surface at the end of week 3.

Changes in the progress height confirm the realisation of surface changes in respect of time. These changes in the progress of terrain surfaces are shown on a weekly basis. The visualisation model indicates the level of cutting to filling operations by the colour index moving from red to blue respectively (see dialogue boxes in Figures 6.4 and 6.5). Red represents the highest level of the cutting sections and blue represents the depth of filling sections on a weekly basis.

The visual representation of the earthwork progress profiles assists in analysing and visualising the impact on the progress profiles of the earthwork from a location viewpoint. This can be performed by rehearsing, using “what-if” scenarios, different factors associated with the productivity data. These factors include the soil characteristics, the types and number of equipment sets, and the site access points. The next section discusses the detailed development methodology associated with cost profiles and the cost S-curve of earthwork operations in a road project.

6.3 Generation of Location-based Cost Profiles

6.3.1 Introduction

This section explains the objectives of the development processes of the location-based profiles and the cost S-curve of the earthworks component. The research further extends the prototype model by the addition of a cost profile module. The module identifies the cost involved in earthwork on a weekly basis and analyses the cost information from location viewpoints along the road section.

6.3.2 Algorithms for data generation of cost profiles

The algorithm of the cost profiles module is similar to that of the progress profiles module for the generation of weekly earthwork quantities; however, the key input of this module is the unit cost of the cutting and filling activities. This cost was integrated with the variable factors, including the equipment productivity, the haulage distance, site access conditions, working efficiency and soil characteristics at cutting sections. An algorithm was designed for the calculation of the weekly cost

profiles of earthworks. The data flow diagram with the algorithm is shown in Figure 6.6 below.

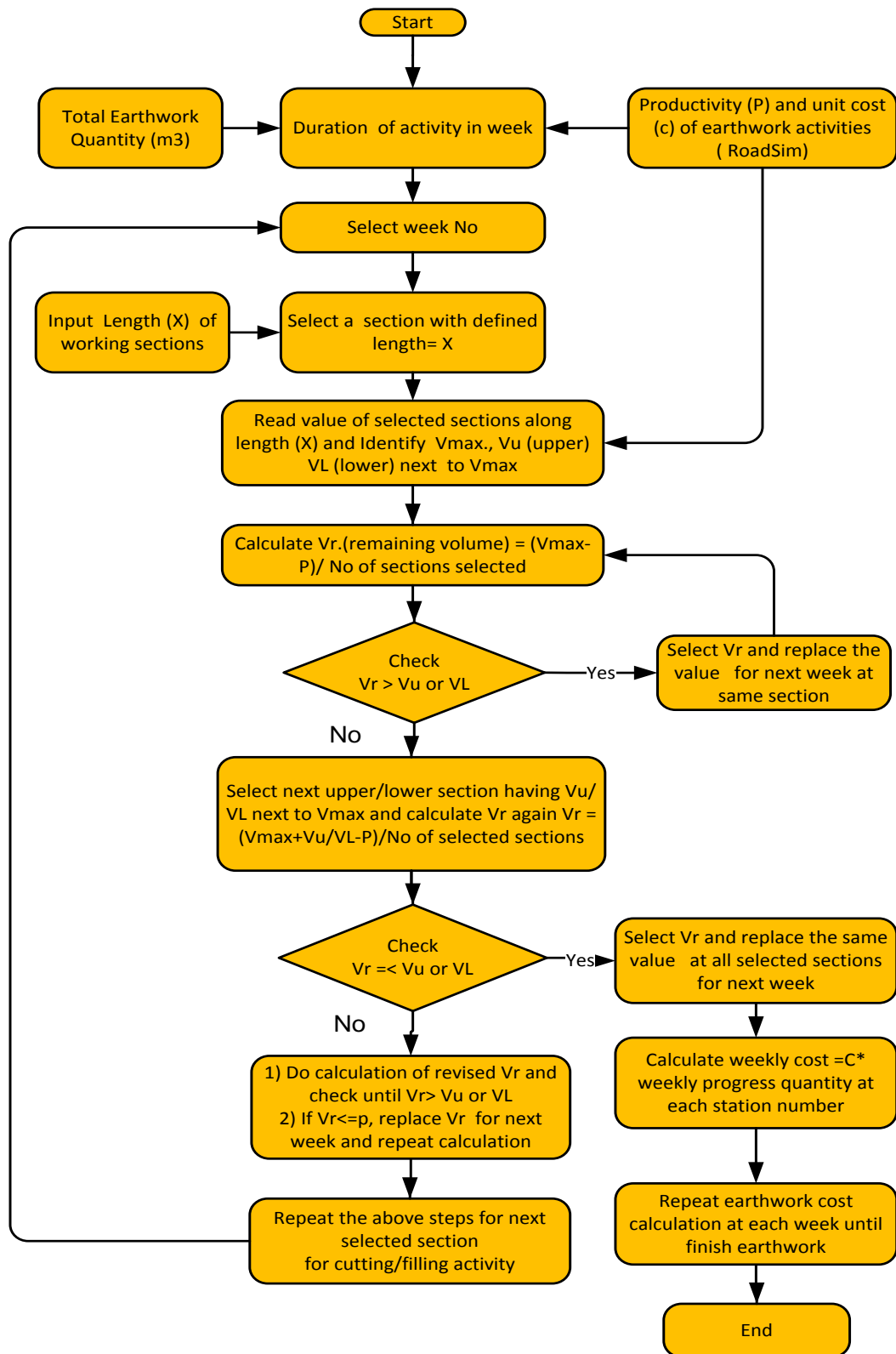


Figure 6.6 Data flow diagram and algorithm for generation of cost profiles

Using the information shown in Figure 6.6, the cost data algorithm was developed using VBA macros. A snapshot of the cost data generation interface is shown in Figure 6.7. The figure highlights the different sub-modules for the cost profiles module. In this module, “CostDataGeneration” produces the weekly cost information at each station, “ExportCostData” exports the cost data in a text file and “CostProfile” generates the cost profiles information on a weekly basis for earthwork.

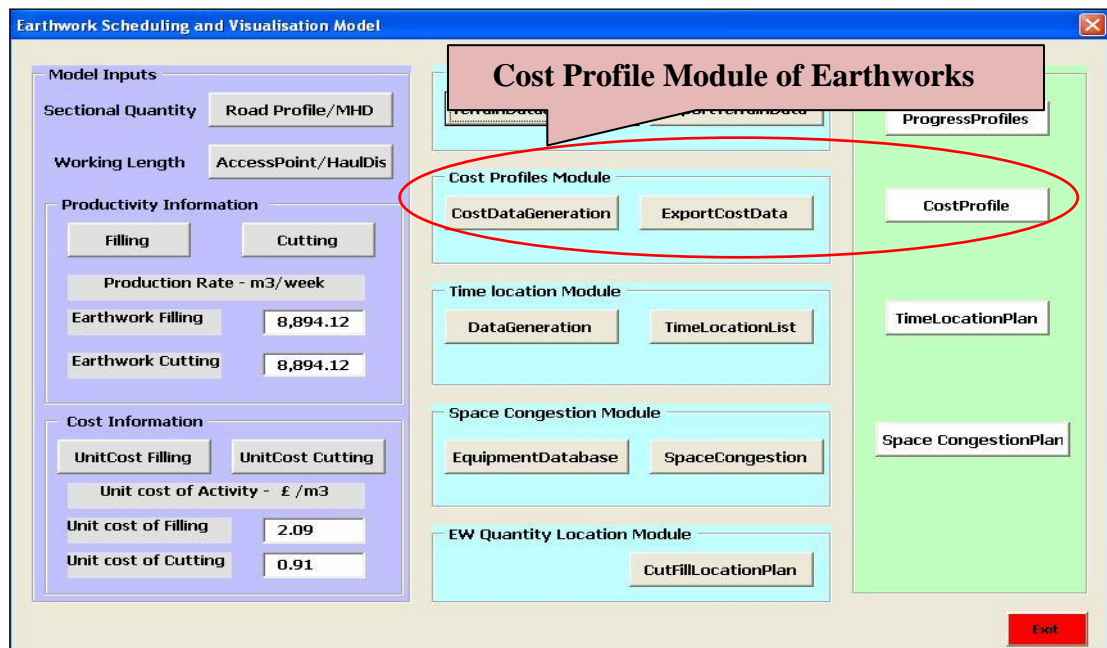


Figure 6.7 Snapshot of the interface of cost-profile generation module

The cost profile module produces the weekly cost information of earthwork at each station/chainage of the road section. A graphical view of the weekly cost profiles/histogram is shown in Figure 6.8 below.

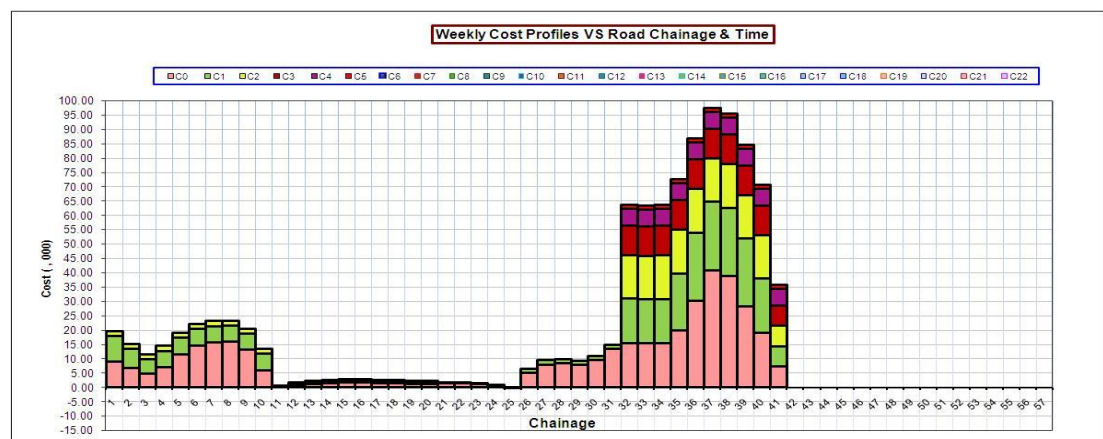


Figure 6.8 Snapshot of the model generated weekly cost profiles

6.4 Cost S-curve

6.4.1 Overview

An S-curve is a popular project management tool, which gives a graphical display of the cumulative cost, the resource hours or other quantities plotted against time. The most important aspect of the S-curve is the comparison between the anticipated baseline costs of a project with the actual costs. In this study, the S-curve was utilised to compare the planned production cost and the actual cost of earthwork operations of a road section on a weekly basis. The next section outlines the generation of the cost S-curve of earthwork operations in a road construction project.

6.4.2 Generation of cost S-curve for earthworks

The cost module was developed to produce weekly cost information and a cumulative cost versus time curve. First, weekly cost information at each location of a road section was generated using a VBA macro that was designed and integrated within the prototype model. Then, the cumulative earthwork production cost of a road section was used to produce the cost S-curve using an MS Excel program. A typical diagram of the cost S-curve was developed using a case study (see Figure 6.9). The figure gives a comparison of the production cost with actual cost of the road section in respect to time. This curve monitors the earthwork costs on a weekly basis in comparison with progress, so that preventative measures can be taken to reduce the earthwork construction cost.

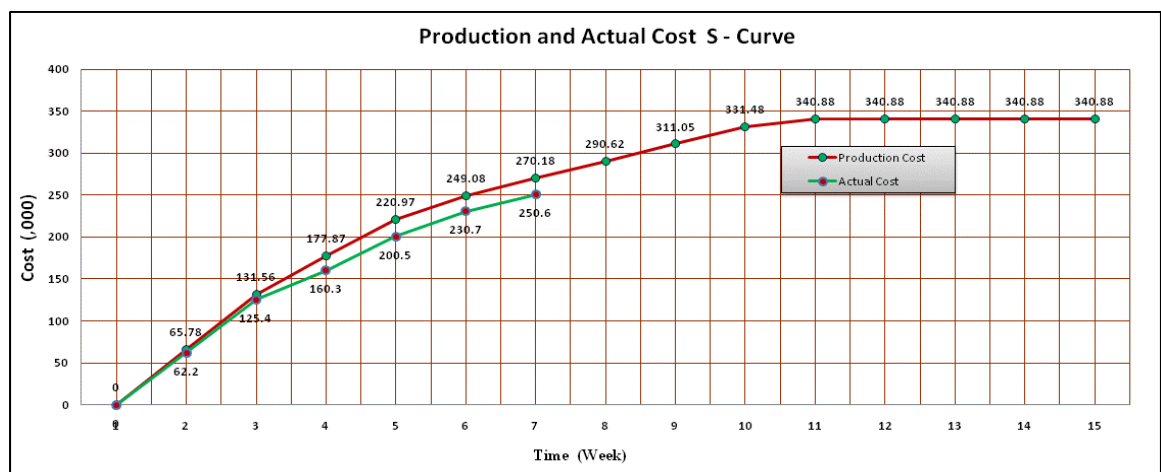


Figure 6.9 Snapshot of the typical cost S-curve produced by the model

6.5 Summary

The chapter outlined the development of the visualisation module component of the prototype model. A window interface was developed to visualise the earthwork scheduling information on a single platform. This included earthwork progress profiles / terrain surfaces, location-based plans, space congestion plans, location-based cost profiles, and cost S-curves. The interface enabled the visual representation of a mass haul diagram and tabular information on progress profiles, weekly cost information, and coordinate data of time and location in a time-location plan.

Typical snapshots of weekly progress profiles and corresponding terrain surfaces of earthwork were presented in this chapter to show the model functionality and its cost profile generation capability. The visualisation component of the prototype model enables construction managers to analyse and simulate earthwork scheduling information from a location viewpoint in road construction projects. The VM assists in improving the communication of the earthwork scheduling information at different stages of earthwork progress and provides a tool for effective communication amongst construction team members, throughout the construction operations.

The next chapter outlines the experiments with the case studies, the sensitivity analysis, and offers an evaluation of the model functions by road constructional professionals.

Chapter - 7

Experiments, Analysis and Validation

7.1 Introduction

The previous chapters discussed the specification, design and development of a prototype model of location-based scheduling (which is known as a time-location plan in this thesis) and the visualisation of the earthwork scheduling information in road construction projects. This chapter presents the details of experiments using design information on road projects, sensitivity analysis results, and validation of the functions of the prototype model through road construction professionals. The chapter also discusses the background of the selected road projects, data collection and analysis, and demonstrates the model functionality with different road sections of road projects.

The chapter presents the comparative results of earthwork duration, location information from a company produced time-location plan, and the time-location plan generated by the prototype. Experiments were carried out to validate the model functionality, including automatic generation of a time-location plan under different site conditions and construction sequences. The optimisation of earthwork quantities was demonstrated in a cut-fill assignment of earthwork with design information of different road sections.

A total of 15 different road sections from two road projects in Portugal were experimented to demonstrate the functionality of the prototype model. The graphical outputs of each model function obtained from case studies experiments are presented in this chapter. The results of sensitivity analysis carried out using critical factors associated with location-based scheduling, including equipment type, site access points and soil characteristics, are presented. The remainder of the chapter describes experiments using the prototype model. The conclusions from the evaluation of the prototype model, using indirect comparison of validation method are discussed, and the findings from the experiments summarised.

7.2 Background of Design Information from Road Projects

This section provides the background to the road projects, which were selected for functionality experiments using the prototype model. The design information was collected from road projects carried out by Mota-Engil, an international construction company based in Portugal. The company provided access to the required data. The location map of the selected road projects is shown in Figure 7.1.



Figure 7.1 Location map of the selected road projects for experiments (Mota-Engil)

7.2.1 Introduction of the design information of road for experiments

The design information was selected from three different road projects; lots 3, 5 and 6 in Portugal. These lots were used to demonstrate the functionality of the prototype model including the automatic generation of progress profiles / terrain surfaces; location-based schedules (time-location plans) and space congestion plans; location-based cost profiles; and the cost S-curves of the earthwork components. The different lots of the road projects which were selected for the experiments are shown below:

- A. 10 km road section (from chainage 90+000 to 100+000 km) was selected from lot no 5 road project
- B. 7 km road section (from chainage 0+000 to 7+000 km) from lot no 6 road project

C. 1.5 km road section (from chainage 90+000 to 91+500 km) from lot no 3 road project

A total 15 different road sections (having 1.0 to 1.5 km lengths) from the different lots of the road projects were selected to demonstrate the functionality of the prototype model and to display the model behaviours. The graphical outputs on the model demonstration exercise of a 10 km road section and 7 km road section are shown in Appendix-H and Appendix-I respectively. The following section discusses data collection and the analysis processes involved in the experiments.

7.2.2 Data collection and analysis

In the course of the demonstration of the model functionality, road design data were provided by the company from the selected projects, namely the L-section, X-section, terrain profiles, and site conditions of different road sections. The design data of different road sections was used to calculate the sectional quantities of the cut and fill activities of earthwork at the required intervals (25m normally). A site access / working length module was developed to identify the economical working sections amongst the cut-fill section of a road section (see Chapter 5) to identify the site access points / working length along the selected road section in relation to the mass haul diagram characteristics. The access points / working lengths generated by the model could be modified by construction/planning managers if site conditions and other constraints were deemed to be unsuitable for earthwork operations. A cut-fill optimisation module (see Appendix-D) was used to identify the optimum allocation quantities and the direction of earthworks movement between cut-fill sections of a road section.

After collecting the required inputs data of the model, the Data Generation Module (DGM) was used to generate the coordinate data for progress profiles and location-based scheduling of earthwork. The time-location algorithm processes the coordinate data generated by the DGM and then produces location-based schedules (time-location plans) of earthworks. Similarly, the space location algorithm generates the space congestion plans, and the cost algorithm produces location-based cost profiles

and the cost S-curves. The next section explains the experiments with design data of road projects.

7.3 Experiments with design information from road projects

7.3.1 Experiments with progress profiles generation functionality

In what refers to the road section from chainage 90+000 to 91+500 of lot no 3 – selected for experimentation – an exercise aimed at the production of automatic progress profiles generation functionality of the prototype model, was carried out using productivity data. The purpose of this function was the analysis and visualisation of the effects on the progress profiles and the earthworks scheduling from a location viewpoint.

The DGM was developed to produce the weekly coordinate data based on the productivity provided by the company, which was related to the equipment used during the construction processes, and to summarise the required data for processing in the visualisation module. The visualisation module processes the input data and transforms it into visual profiles of the earthwork operations throughout the construction processes. A snapshot of the interface (form) is shown in Figure 7.2.

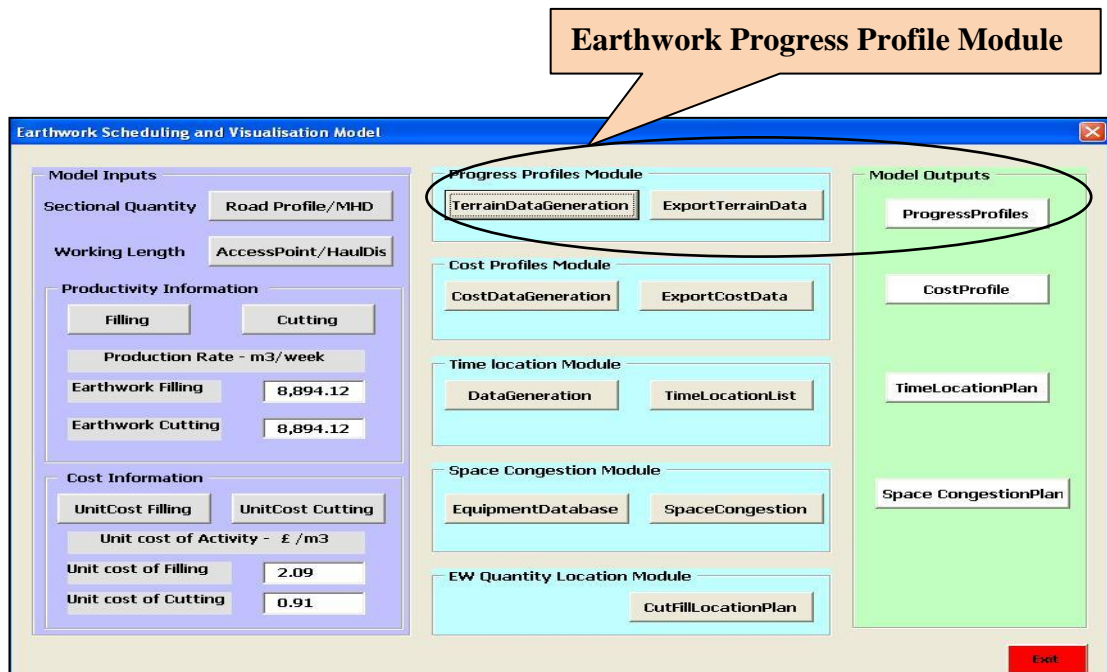


Figure 7.2 Snapshot of earthwork scheduling and visualisation model

The interface represents the model input, process and outputs of the prototype. Firstly, sectional quantities of a selected road section were calculated using the road design information from the longitudinal and cross-sectional profiles of the road section. Secondly, the site access points and the working lengths were identified and listed in the input sheet for the use in the DGM. Thirdly, the productivity values of the earthwork activities were calculated by inserting the information related to equipment types, soil characteristics and site working conditions through a productivity sub-module, as shown in Figure 7.3.

Option1	Option2	Option3
Excavator Excavating	Motor Grader Hauling	Bulldozer Dozing
EqCode: Exaj	EqCode: Msa	EqCode: Tttb
RotAngle: 45	Ke: Average	Ke: Average
%CutHeight: 100	φ (phi): Gravel	φ (phi): Gravel
Material: Sandy-clay	D (m.) [50,500]: 100	D (m.) < 50: 20
MatCondition: Hard	Bulldozer Pushing	Payloader Loading
Ke: Poor	EqCode: Tttc	EqCode: Wplb
φ (phi): Sandy clay	Ke: Rather poor	WorkingConditions: Adverse
Tipper Truck Hauling	φ (phi): Gravel	Ke: Rather poor
EqCode: Oht	D (m.) [0,30]: 30	φ (phi): Gravel
TravellingRoad: Site or minor road	Motor Grader Levelling	D (m.) < 15: 10
Ke: Average	EqCode: Mga	Tipper Truck Hauling
D (km.): 20	TypeofWork: Mass earthworks	EqCode: Oht
Vm (km/h): 50	ThicknessRange: 0.20 - 0.40	TravellingRoad: Site or minor road
Motor Grader Levelling	Ke: Average	Ke: Average
EqCode: Mga	Thickness (m. in): .3	D (km.): 20
TypeofWork: Mass earthworks	Water Truck Watering	Vm (km/h): 10
ThicknessRange: 0.20 - 0.40	EqCode: wh	Motor Grader Levelling

Figure 7.3 Snapshot of productivity calculation sub-module (Castro, 2005)

After calculating the required input information, the DGM module was used to generate the coordinate data of the earthwork progress profiles of the selected road section. Then, the “DataExport” sub-module (see Figure 7.2) was used to filter and export the coordinate data into the visualisation module. The “ProgressProfile” sub-module (see Figure 7.2) was used to process the exported data to generate the weekly progress profiles and terrain surfaces of earthworks. The earthwork progress profiles generated by the model are shown in Figures 7.4 and 7.5.

Figure 7.4 represents a total of ten profiles of the earthwork progress generated by the model at different weeks throughout construction. The w0 represents the earthwork profiles at start of the work/original ground profiles, whereas from w1 to

w9 represent the progress profiles of earthwork at the end of week 1 to week 9 respectively. The arrows in Figure 7.4 show the movement direction of the earthwork from cut to fill sections or cut to spoil at landfills.

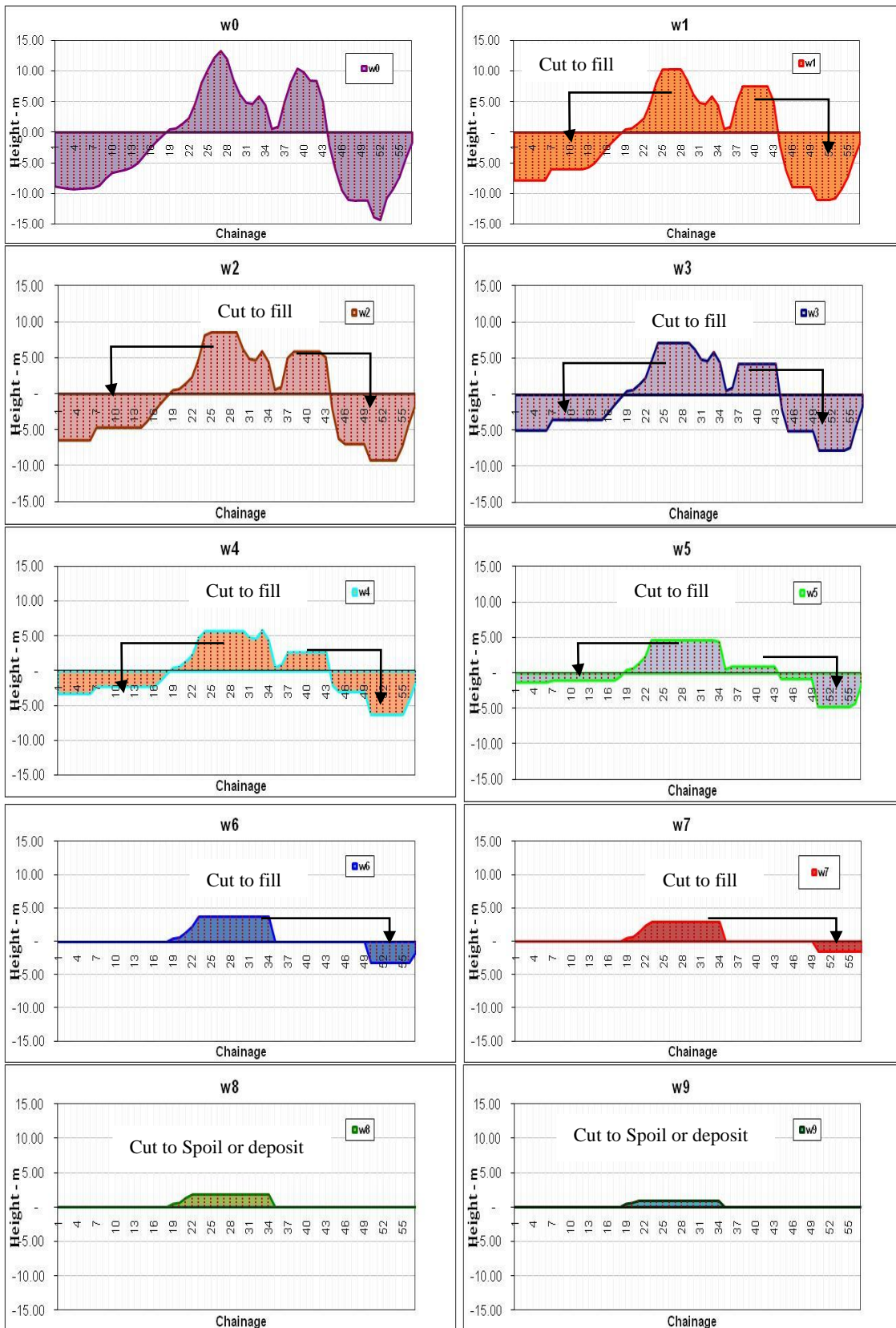


Figure 7.4 Weekly earthwork progress profiles of a selected road section.

7.3.2 Generation of terrain surfaces of earthwork progress profiles

Figures 7.5(a) and 7.5(b) show snapshots of the 3D terrain surface of the earthwork progress profiles generated by the visualisation module at the end of week 4 and 10 respectively. This represents the terrain surfaces of the progress profiles in a road project at different stages throughout the earthwork construction operations. The height of cutting and the depth of filling section are represented by colour index from red to blue respectively as shown in both Figures 7.5(a) and (b).

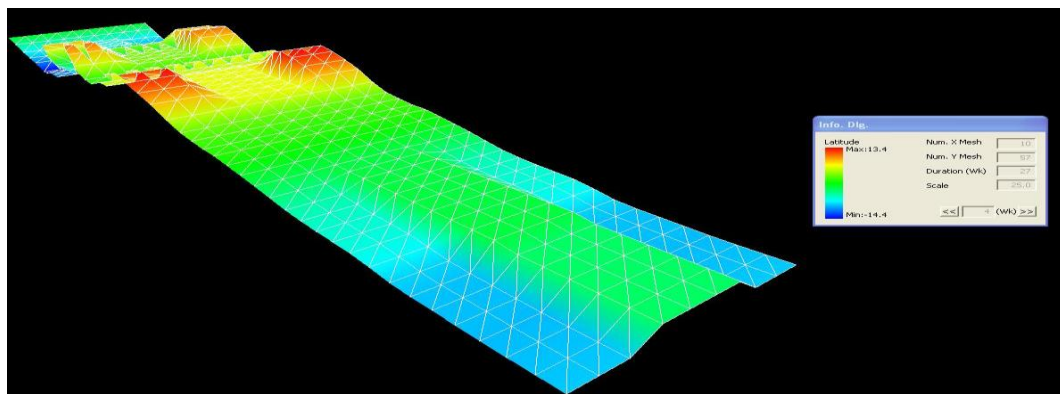


Figure 7.5(a) Snapshot of terrain surface generated by model at week 4

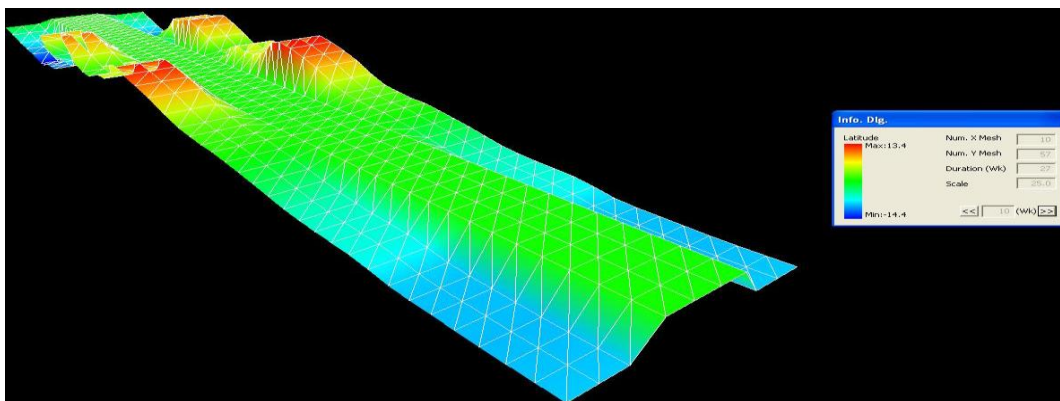


Figure 7.5(b) Snap shot of terrain surface generated by the model at week 10

In the above figures, the red colour represents the highest ground level and the blue colour represents the lowest points on the road surface. The yellow colour represents road profiles at week 4 and the green colour represents the design road level of road terrain surfaces at the end of week 10.

7.3.3 Experiments with different productivity rates

This section presents an experiment to show earthwork progress profile generation capability at different productivity values. For the experiment, three sets of productivity values (minimum, average and maximum) were calculated under different site conditions using a productivity simulator (see Figure 7.3). Three sets of productivity values were identified, assuming three scenarios: good, average and poor site working conditions. The experiment was carried out to visualise the effect on the progress profiles of the road section at the end of week 5. Figures 8.6 (a), (b) and (c) show the prototype's capability of generating progress profiles of earthworks, taking into account different productivity rates and assisting to identify the effects on the progress height of earthworks at a particular week.

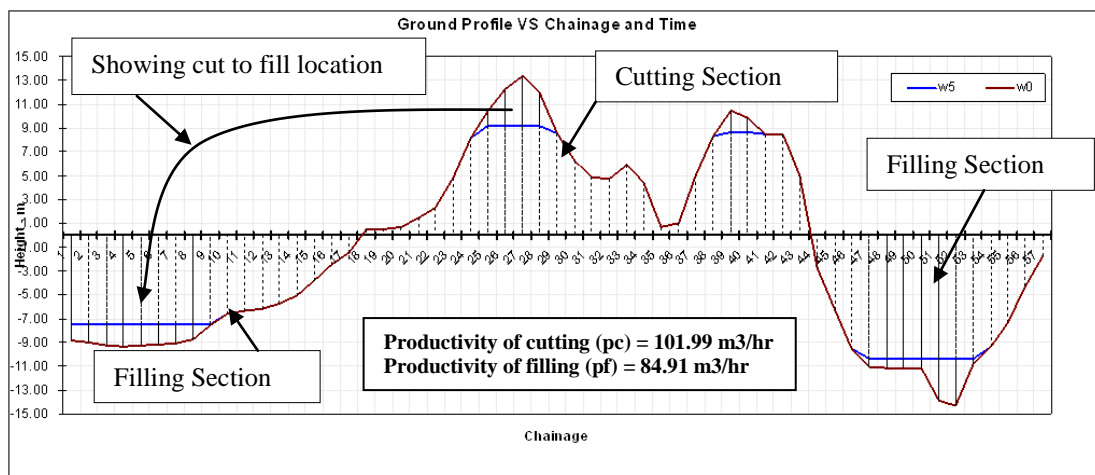


Figure 7.6 (a) Progress profiles of a road section at minimum productivity

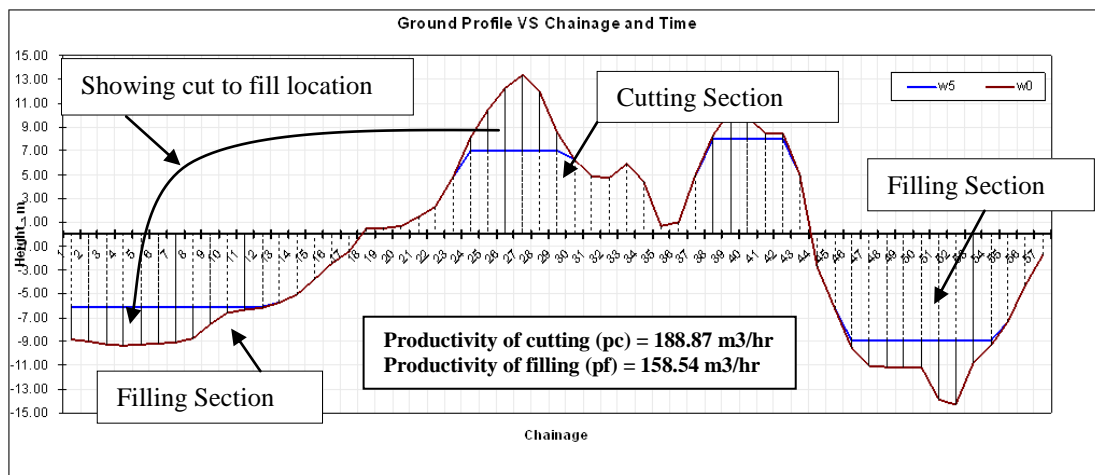


Figure 7.6 (b) Progress profiles of a road section at the average productivity

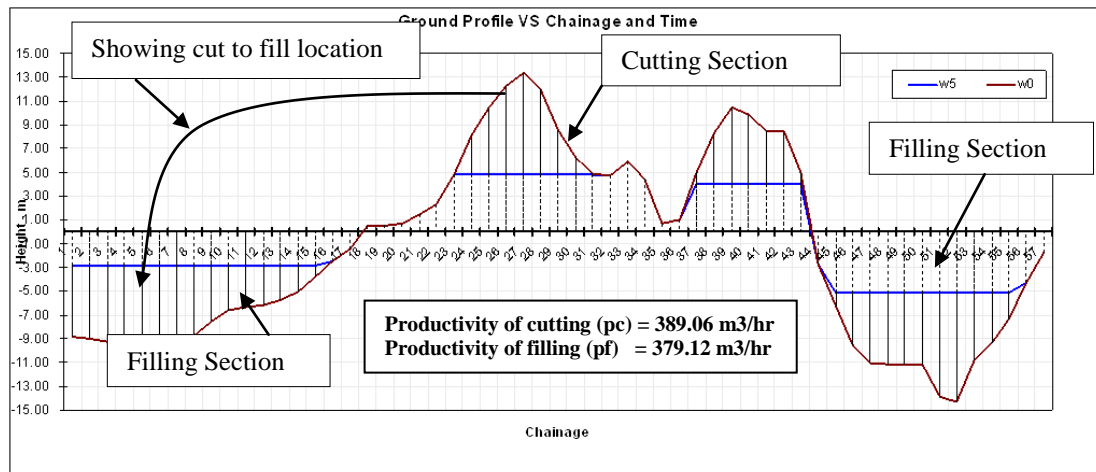


Figure 7.6 (c) Progress profiles of a road section at the maximum productivity

These profiles represent differences of earthwork progress height at the three sets of productivity values (minimum, average and maximum). These figures confirmed the model's capability to integrate different productivity rates. The variation in earthwork progress height at the end of week 5, due to different productivity values, confirmed that the prototype model was capable of generating earthwork progress profiles for the different site conditions and with regard to the constraints that affects productivity with earthwork construction.

Similarly, the terrain surfaces of the road sections throughout the construction operations could be generated on weekly basis. The next section discusses the experiments carried out to establish model functionality in the automatic generation of location-based schedules (time-location plans) and the optimisation of earthwork quantities in a cut-fill assignment.

7.4 Experiments with Earthwork Optimisation Module

7.4.1 Experiment with a 1.4 km section from lot no 6 road project

A 1.4 km road section from lot no 6 road project was selected for experimental purposes to analyse and test the key model functions. These functions include automatic generation of location-based scheduling / time-location plan, a space congestion plan, and the optimisation of earthwork allocation quantities in addition to the direction of earthwork movement in a cut-fill assignment. The selected road section included five filling sections known as Fill-1(F1), Fill-2(F2), Fill-3(F3), Fill-

4(F4) and Fill-5(F5), whereas four cutting sections were known as Cut-1(C1), Cut-2(C-2), Cut-3(C3) and Cut-4(C4), with different quantities. A longitudinal profile of the road section is shown in Figure 7.7 below.

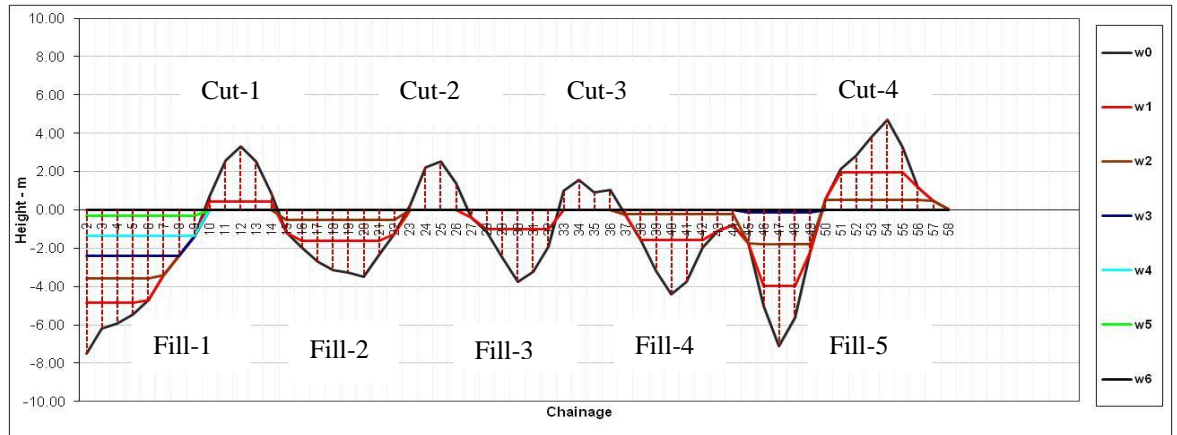


Figure 7.7 Longitudinal profile of a selected road section with weekly profiles

As stated in Chapter 5, there is a requirement to plan the possible sources and destinations of earthwork quantities (m^3) in a cut-fill assignment. This includes how much is needed to be borrowed from the cut or borrow pits and to deposit the volume removed to a landfill site. The optimisation module was developed to identify the optimum allocation quantities and movement direction of earthworks in a cut-fill assignment (see Appendix-D).

Table 7.1 Unit cost table for earthworks allocation of a 1.4 km road section

Unit Cost of Earthworks (€/m ³)						
	Destinations					
	Fill-1	Fill-2	Fill-3	Fill-4	Fill-5	Land- Fill
Cut-1	0.82	0.81	2.19	3.19	4.00	4.00
Cut-2	2.38	0.75	0.88	1.63	2.44	4.05
Cut-3	3.63	2.00	0.63	0.38	1.19	4.10
Cut-4	6.06	4.44	3.06	2.06	1.25	4.15
Borw-1	7.10	7.40	7.50	7.60	7.90	
Borw-2	9.10	9.50	9.60	9.80	9.90	

As explained previously, the unit cost coefficient is a function of equipment type, haulage distance, soil characteristics and working site conditions within the productivity and cost simulator of “RoadSim”. A list of cut and fill sections, including the respective sectional earthwork quantities, was calculated and presented in a table (see Appendix-D).

After running the earthwork optimisation function with the information of a road section shown in Figure 7.7 and Table 7.1 above, a matrix table was produced with the information on the optimised quantities, the direction of movement, and the total cost of earthworks for a cut-fill assignment (see Table 7.2).

Table 7.2 Matrix table with optimised earthwork quantities of a 1.4 km section

Number of cut and fill sections								Total Qty	Available Qty
	Fill-1	Fill-2	Fill-3	Fill-4	Fill-5	Land Fill			
Cut-1	-	8,414	-	-	-	-	8,414	8,414	
Cut-2	-	5,320	-	-	-	-	5,320	5,320	
Cut-3	-	-	-	3,590	-	-	3,590	3,590	
Cut-4	-	-	-	-	16,542	-	16,542	16,542	
Borw-1	35,278	2,744	10,968	11,130	4,048	-	64,168	64,168	
Borw-2	-	-	-	-	-	-	0	0	
Total Qty	35,278	16,478	10,968	14,720	20,590	0			
Req. Qty	35,278	16,478	10,968	14,720	20,590	0			
Total cost Earthworks								502,454.79	

Using the information presented in Table 7.2, a graphical view of the earthwork optimised quantities (m³), including the movement direction of cut-fill sections, is presented in Figure 7.8 below.

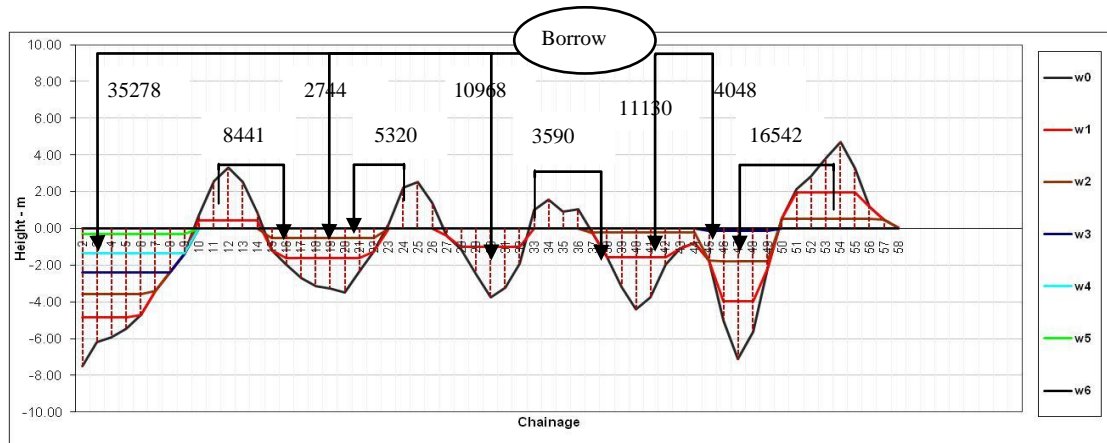


Figure 7.8 Graphical view of earthwork allocated quantities of a 1.4 km section

The next section presents another experiment to test the optimisation function of the prototype model with a different road section which was selected from the lot 5 road projects in Portugal.

7.4.2 Experiment with 1 km section from lot no 5 road project

A road section from lot 5 (from chainage 98+000 to 99+000) was selected for a second experiment designed to analyse the model optimisation function. The selected road section includes three filling and two cutting sections with different sectional quantities. A longitudinal profile of the road section is shown in Figure 7.9.

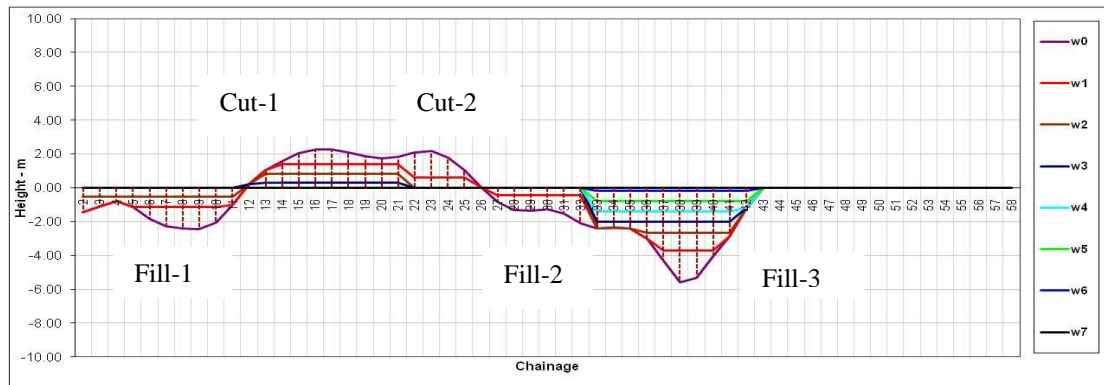


Figure 7.9 Longitudinal profile of 1.0 km road section with weekly profiles

To indicate the optimisation functionality of the model, a unit cost table was developed using road profiles and the “RoadSim” simulator, and the identified unit cost is shown in Table 7.3.

Table 7.3 Unit cost table of earthworks allocation of 1.0 km road

Unit Cost of Earthworks (€per m ³)				
	Destinations			
	Fill-1	Fill-2	Fill-3	Land- Fill
Cut-1	1.25	1.63	2.63	4.00
Cut-2	2.19	0.69	1.69	4.05
Borw-1	7.10	7.40	7.50	
Borw-2	9.10	9.50	9.60	

Using the unit cost data presented in Table 7.3, the cut-fill optimisation module produced a matrix table that provides the information on the optimised quantities, and the direction of movement with the total costs of the earthwork operations for a cut-fill assignment (see Table 7.4).

Table 7.4 Matrix table with optimised earthwork quantities of a 1.0 km section

Number of cut and fill sections						
	Fill-1	Fill-2	Fill-3	Land Fill	Total Qty	Available Qty
Cut-1	13,523.26	408.72	-	-	13,932	13,932
Cut-2	-	5,848.47	-	-	5,848	5,848
Borw-1	-	500.17	29,997.10	-	30,497	30,497
Borw-2	-	-	-	-	0	
Total Qty	13,523	6,757	29,997	0		
Req. Qty	13,523	6,757	29,997			
Earthworks cost	21,589.07					

Using the information presented in Table 7.4, a graphical view of the earthwork optimised quantities (m^3) and the movement direction between cut-fill sections of the selected road section is presented in Figure 7.10 below.

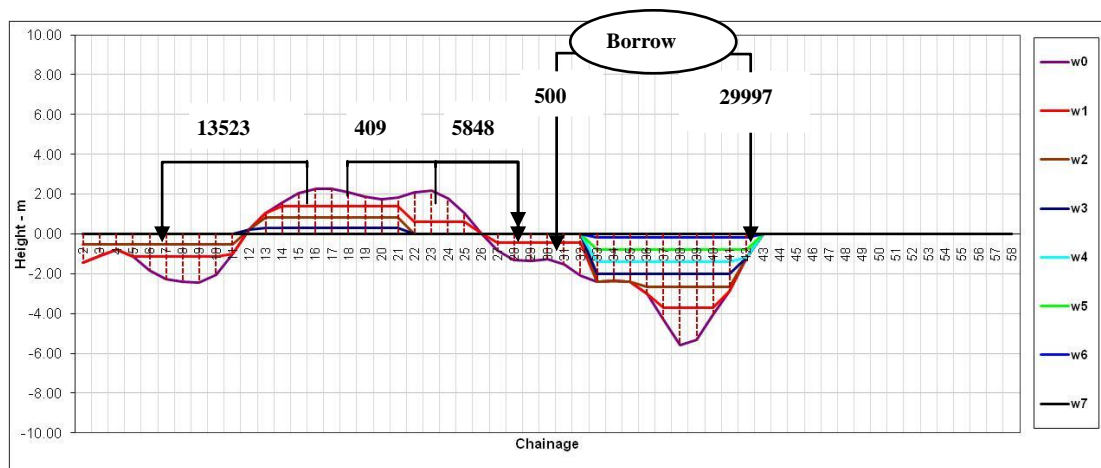


Figure 7.10 Graphical view of earthwork allocated quantities of 1km road section

The next section presents the sensitivity report generated by the optimisation module for a cut-fill assignment in the road section selected for the experiment. The experiment result shows that the total minimum earthwork cost is euro 21,589.07 considering the unit cost of earthworks presented in Table 7.3 above. The sensitivity report provides the sensitivity effects of unit cost for each cut-fill section as follows.

7.4.3 Sensitivity reports of earthwork optimisation module

A sensitivity report of unit cost reduction of the optimised quantities of earthworks in cut-fill assignment is shown in Table 7.5. The sensitivity report presented in Table 7.5 reveals how much the unit cost of haulage can be reduced without affecting the optimised quantities of earthwork in a cut-fill assignment. For example, the unit cost

of earthworks between cut-1 to fill-3 and cut-2 to fill-1 can be reduced by a unit cost of euro 1.0 and 1.87 respectively (see Table 7.5) without affecting the total cost of the earthworks. The results also help the construction manager to plan the earthwork quantities and its associated resources whilst also considering the associated costs.

Table 7.5 Sensitivity report produced by earthwork optimisation module

Name	Earthwork Quantity	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
Cut-1 Fill-1	13,523.26	-	1.25	0.375	1E+30
Cut-1 Fill-2	408.72	-	1.625	1	0.375
Cut-1 Fill-3	-	1.00	2.625	1E+30	1
Cut-1 Land Fill	-	-	0	0.937499976	1E+30
Cut-2 Fill-1	-	1.87	2.1875	1E+30	1.875
Cut-2 Fill-2	5,848.47	-	0.6875	0.9375	1E+30
Cut-2 Fill-3	-	1.00	1.6875	1E+30	1
Cut-2 Land Fill	-	0.94	0	1E+30	0.937499976
Borw-1 Fill-1	-	0.37	0	1E+30	0.375
Borw-1 Fill-2	500.17	-	0	0	1
Borw-1 Fill-3	29,997.10	-	0	1	0
Borw-1 Land Fill	-	1.62	0	1E+30	1.624999959
Borw-2 Fill-1	-	0.37	0	1E+30	0.37499999
Borw-2 Fill-2	-	-	0	1E+30	0
Borw-2 Fill-3	-	-	0	0	1E+30
Borw-2 Land Fill	-	1.62	0	1E+30	1.624999959
Constraints					
Name	Earthwork Quantity	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
Total Fill-1	13,523	1	13523.26074	0	13523.26074
Total Fill-2	6,757	2	6757.365234	0	408.7207031
Total Fill-3	29,997	2	29997.09766	0	408.7207031
Total Land Fill	0	0	0	0	0
Cut-1 Total	13,932	0	13931.98145	1E+30	0
Cut-2 Total	5,848	-1	5848.472168	408.7207031	0
Borw-1 Total	30,497	-2	30497.27002	408.7207031	0
Borw-2 Total	0	-2	0	408.7207135	0

After identification of the earthwork allocation plan and the direction of earthwork movement in a cut-fill assignment, a time-location plan was generated. The next section discusses the experiment designed to test the time-location plan generation capability of the model, considering different options and site conditions.

7.5 Experiments with LBS/time-location plan for different options

A road project with 4-cut and 5-fill sections (Figure 7.7) was selected to test the model functionality for automatic generation of a location-based schedule (time-location plan) considering different aspects of site conditions. The outputs produced by the model are given below. A total of 18 weeks was required to complete earthwork operations for the selected road section when one equipment set for both cut and fill sections was mobilised at a weekly productivity rate of 6671 m³/wk and an effective working time of 30hrs per week. A total of 7 different options were included in the experiment, considering different site conditions and construction sequences, and aiming to test the model's functionality of generating location-based schedules. The different options considered in the experiments are discussed below:

7.5.1 Option 1: Construction sequences (C1-C4 and F1-F5)

In this option, the construction sequences of cut and fill sections were selected from C1 to C4 and F1 to F5. The earthwork operations included fill from cut sections with one set of both cutting and filling construction equipment. The construction operations for both cut and fill sections were performed from the start to end stations in the forward direction (Figure 7.11).

The optimised earthwork quantities (m³) and movement direction between cut and fill sections are shown in Figure 7.11, with a road profile and arrow diagram showing the construction sequences of cut-fill operations in a time-location plan. The optimum allocation of earthwork was developed using a cut-fill algorithm (Chapter 5). Similarly, other options (from 2 to 7) consider the allocation of earthworks quantities similarly, but the sequences of constructions are different between cut-fill sections, including a borrow pit for the selected road section.

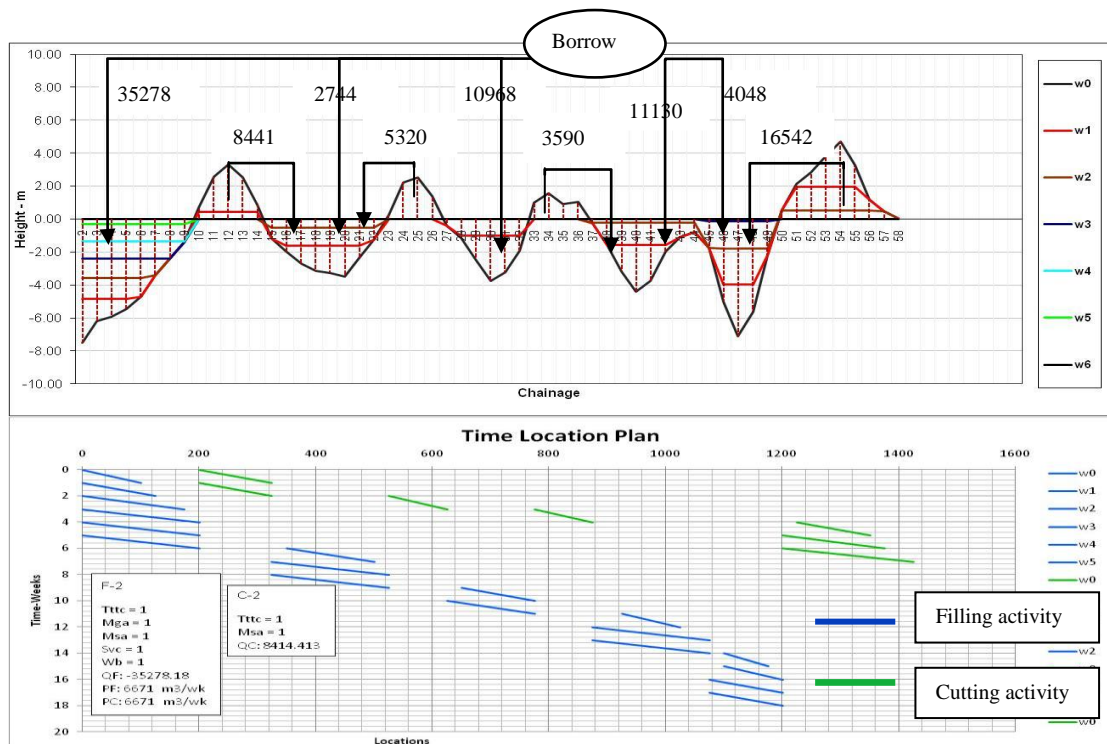


Figure 7.11 Time-location plan generated by the prototype model with option 1

7.5.2 Option 2: Construction sequences (C4-C2 and F5-F1)

In this option, the construction sequences of the cut and fill sections were selected from C4 to C1 and from F5 to F1, considering one-set of construction equipment.

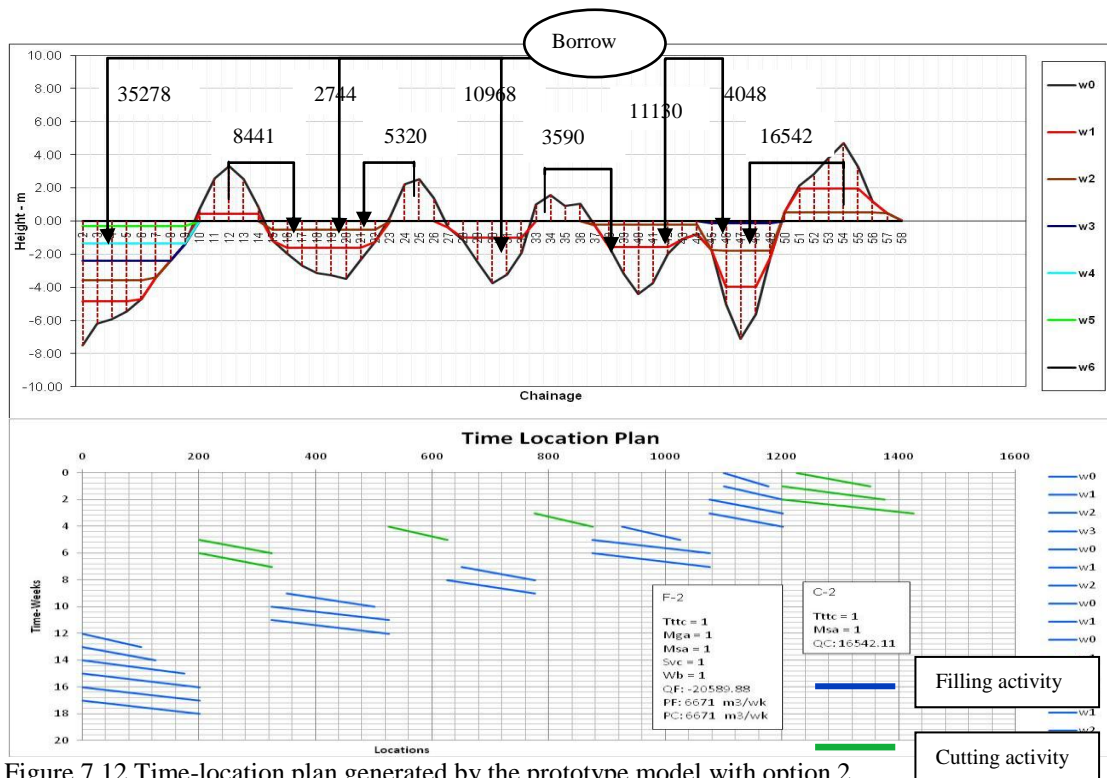


Figure 7.12 Time-location plan generated by the prototype model with option 2

The construction operations for both cut and fill sections were performed assuming the sequences from the end to start stations in a backward direction. The time-location plan generated by the model considering option 2 is shown in Figure 7.12.

7.5.3 Option 3: Construction sequences (C4-C1 and F1-F5)

In this option, the construction sequences of the cut and fill sections were selected from C4 to C1 and from F1 to F5 with one set of construction equipment. The cutting operation was performed in a backward direction from the end to start stations of the selected road section, and the filing operations performed from the start to end stations in the forward direction. The time-location plan generated by the model under option 3 is shown in Figure 7.13.

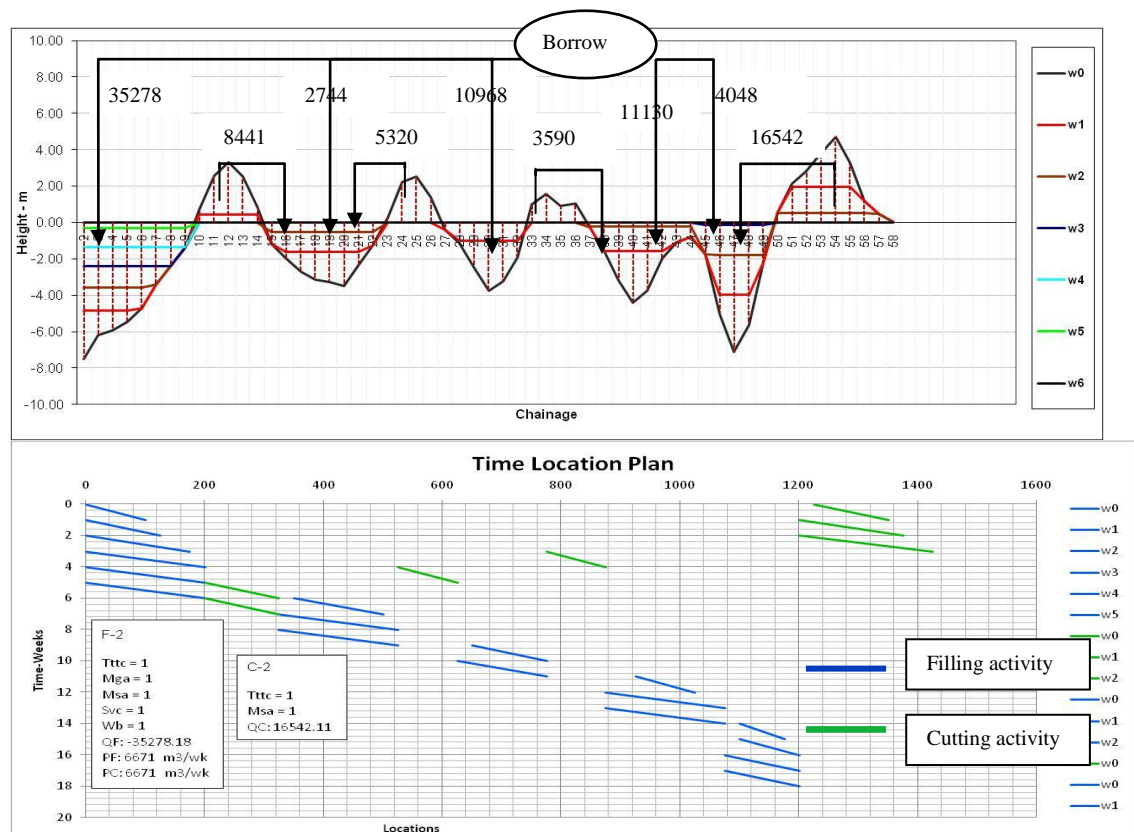


Figure 7.13 Time-location plan generated by the prototype model with option 3

7.5.4 Option 4: Construction sequences (C1-C4 and F5-F1)

In this option, the construction sequences for both cut and fill sections were selected from C4 to C1 and from F1 to F5 with one set of construction equipment. The

cutting operations were assumed to take place from the start to end stations in the forward direction, and the filling operations from the end to start stations in the backward direction. The time-location plan generated by the model under option 4 is shown in Figure 7.14.

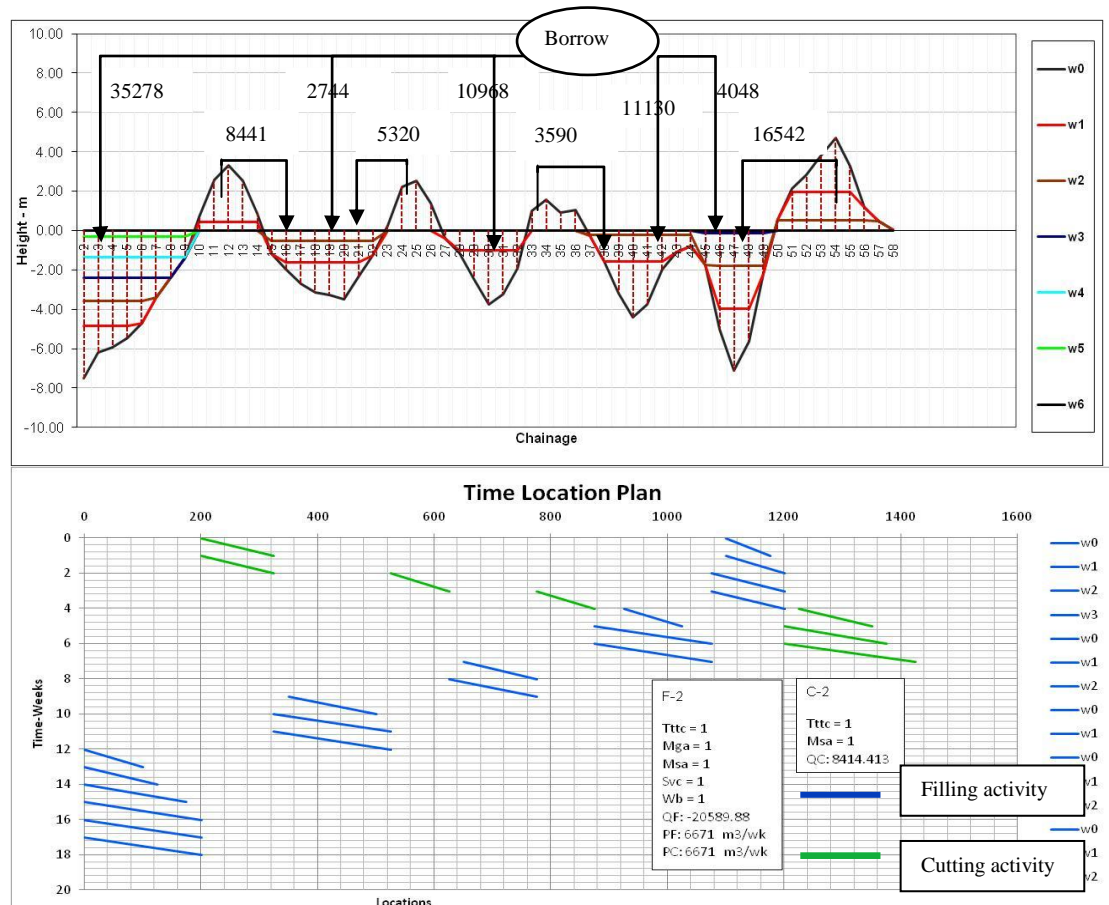


Figure 7.14 Time-location plan generated by the prototype model with option 4

7.5.5 Option 5: Considering obstruction at point A (0+625)

In this option, the construction sequences for both cut and fill sections were selected from C1 to C4 and from F1 to F5 with two sets of construction equipment. One set of equipment was mobilised at the start of the road section and the second set was mobilised at chainage (0+625m) due to an obstruction at point A (Figure 7.15). The time-location plan generated by the model under option 5 is shown in Figure 7.15.

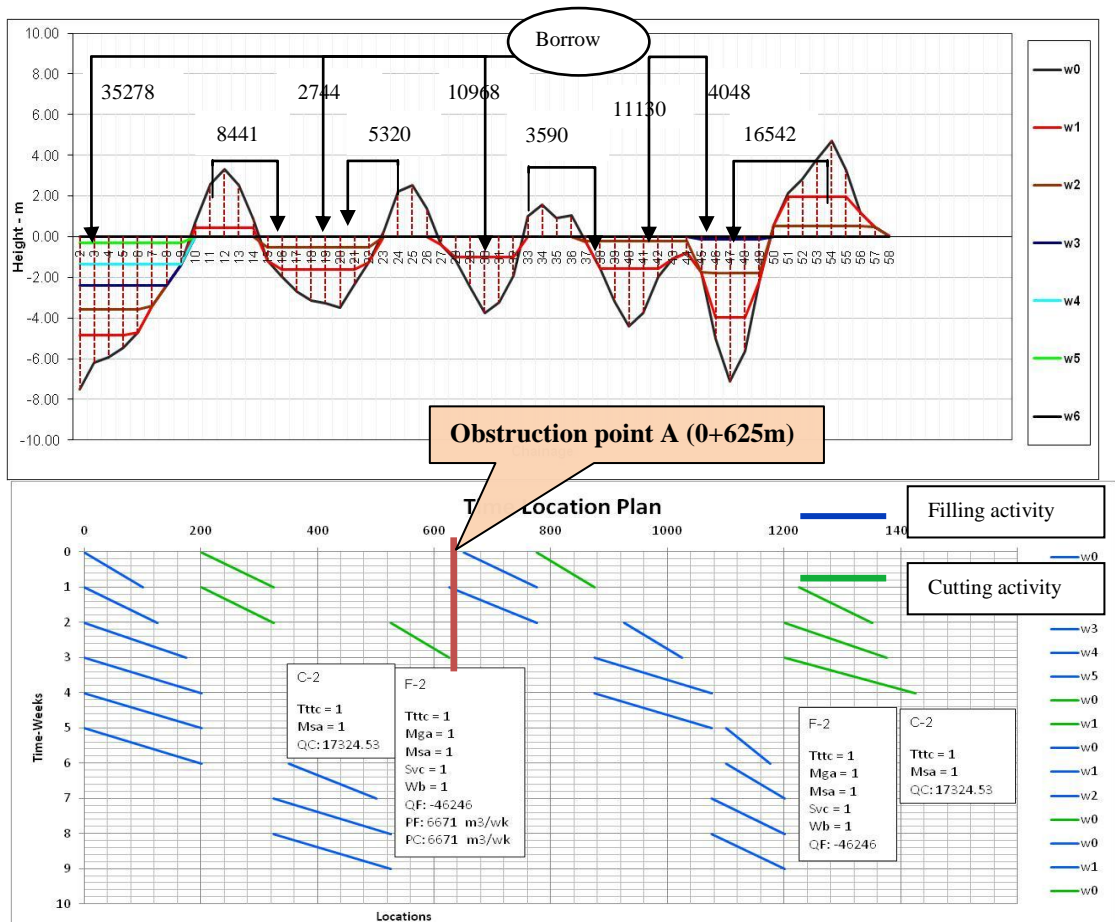


Figure 7.15 Time-location plan generated by the prototype model with option 5

7.5.6 Option 6: Time-location with daily productivity (1779 m³/day)

In this option, the construction sequences for both cut and fill sections were selected from C1 to C4 and from F1 to F5 with two sets of equipment similar to option 5, but the time-location plan was generated on a daily basis. The time-location plan produced by the model considering option 6 is shown in Figure 7.16. The time-location plan showed a total duration of 30 days when operation was performed at a rate of 1779 m³/day, while 8 hours were assumed as working hours per day, and two sets of construction equipment were utilised (see Figure 7.16).

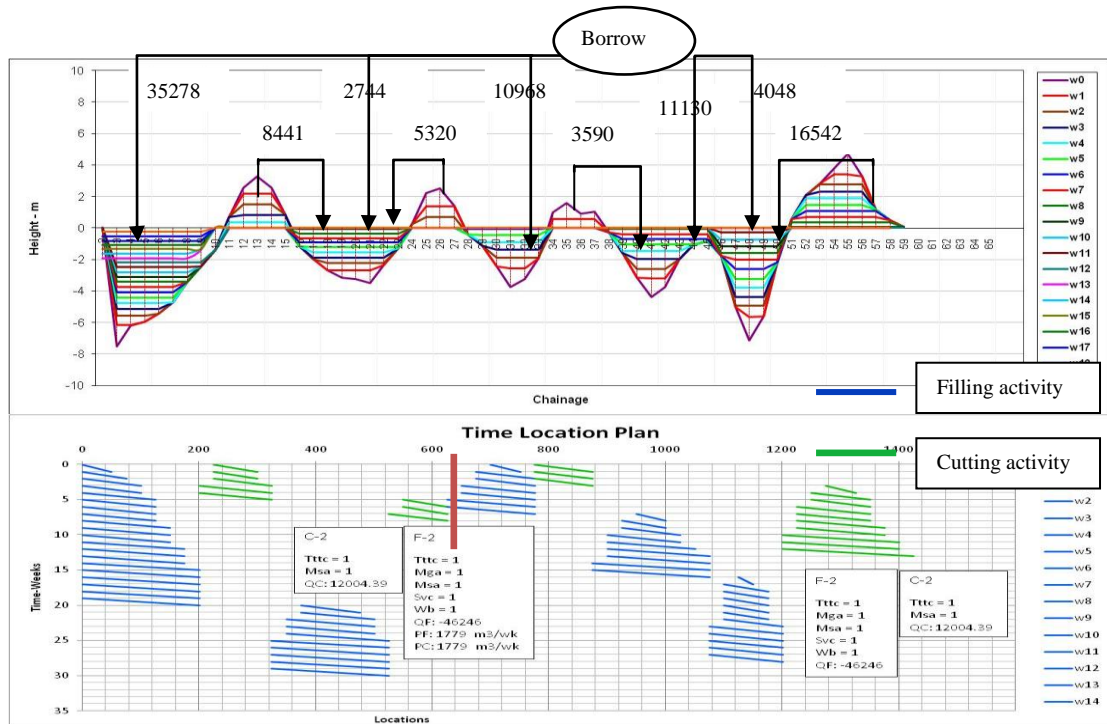


Figure 7.16 Time-location plan generated by the prototype model with option 6

7.5.7 Option 7: Time-location plan with space congestion

In this option, the construction sequences of cut and fill sections were selected from C1 to C4 and from F1 to F5, with one set of equipment. The congestion location shows only at first week and the fill-5 section in red colour in the time-location congestion plan. The plan was generated by the model under option 7 (Figure 7.17).

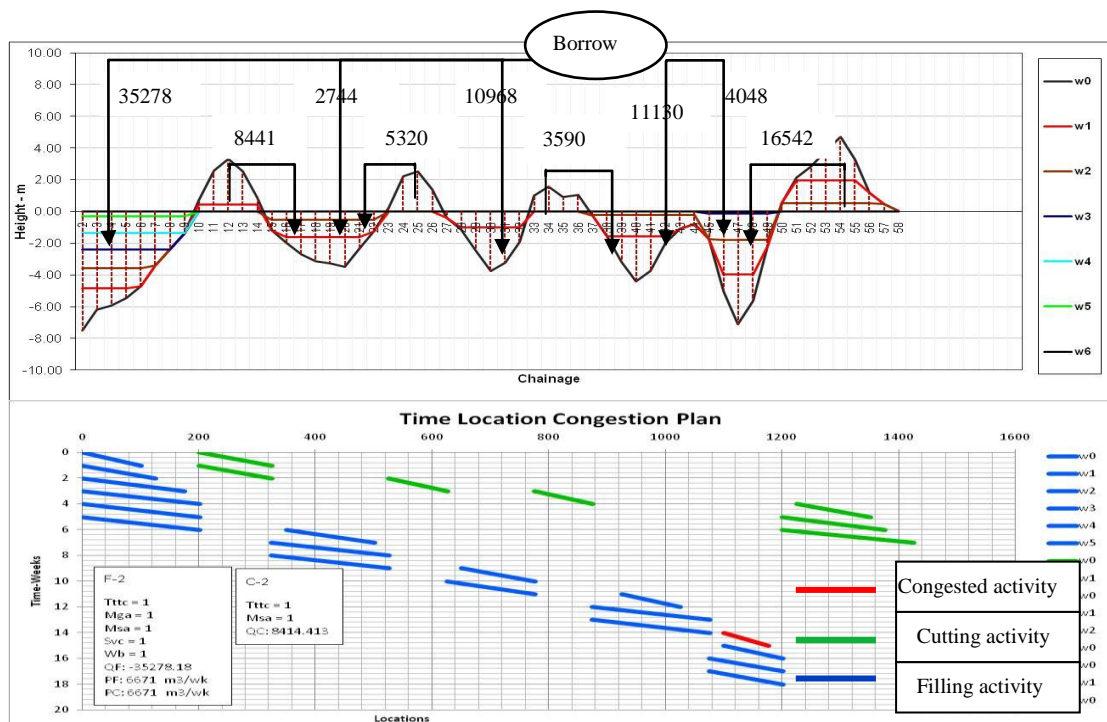


Figure 7.17 Time-location congestion plan generated by the model with option 7

7.6 Sensitivity analysis with different planning variables

A sensitivity analysis was carried out to identify and analyse the effects on the earthwork construction duration in a road project using ‘what-if’ scenarios. The analysis was completed using the critical factors associated with productivity data and overall construction duration of earthwork operations, including site access points, type of equipment and soil characteristics. The sensitivity analysis was conducted assuming that the critical factors varied, but other critical factors affecting earthwork productivity were assumed as a constant. The sensitivity analysis was performed by considering a road section with two fill sections and one cut section for earthwork operations (Figure 7.18).

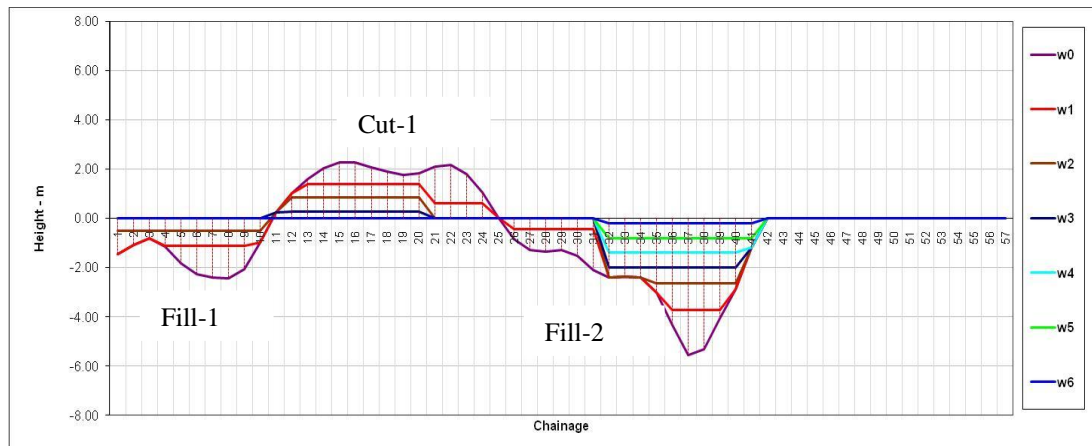


Figure 7.18 Typical road section selected for sensitivity analysis

7.6.1 Case for site access points (working length)

The sensitivity results are presented in Figure 7.19. The results showed a total duration of 7 days for the fill-1 and fill-2 sections and 3 days for the cut-1 section for three and five numbers of access points, whereas other variables and resources were assumed as being constant. However, the total duration was 9 days for fill-1 and fill-2 sections and 4 days for the cut-1 section of earthwork operations when considering six- access points, i.e. longer than for a smaller number of access points, suggesting model validity. The conclusions are that adopting a smaller number of access points is more economical, and that there is a reduction in resources wastage for the same quantity of earthwork activity for the same road sections.

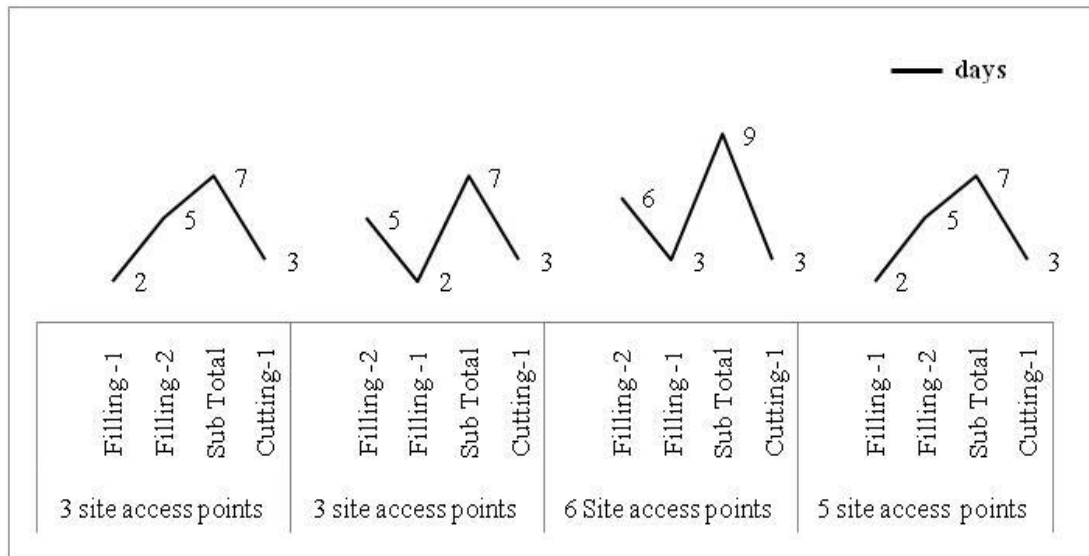


Figure 7.19 Sensitivity analysis results of production time (days) for different site access points

7.6.2 Case of different types of equipment

The sensitivity analysis with different types of equipment on the time-location plan is presented in Figure 7.20. The results show that total duration was 35 days for fill-1 and fill-2 sections and 18 days for the cut-1 section of earthwork using a type -1 excavator (Exa). On the other hand, the total duration were 35 days for fill-1 and fill-2 sections and 14 days for the cut-1 section of earthwork using type-2 excavators (Exb) when assuming other variables and resources unchanged. The total duration, however, was 34 days for fill-1 and fill-2 sections, and 12 days for the cut-1 section when using type-3 excavators (Exc), while the total duration was 26 days for fill-1 and fill-2 sections and 9 days for the cut-1 section of earthwork operations using type-4 excavators (Exd).

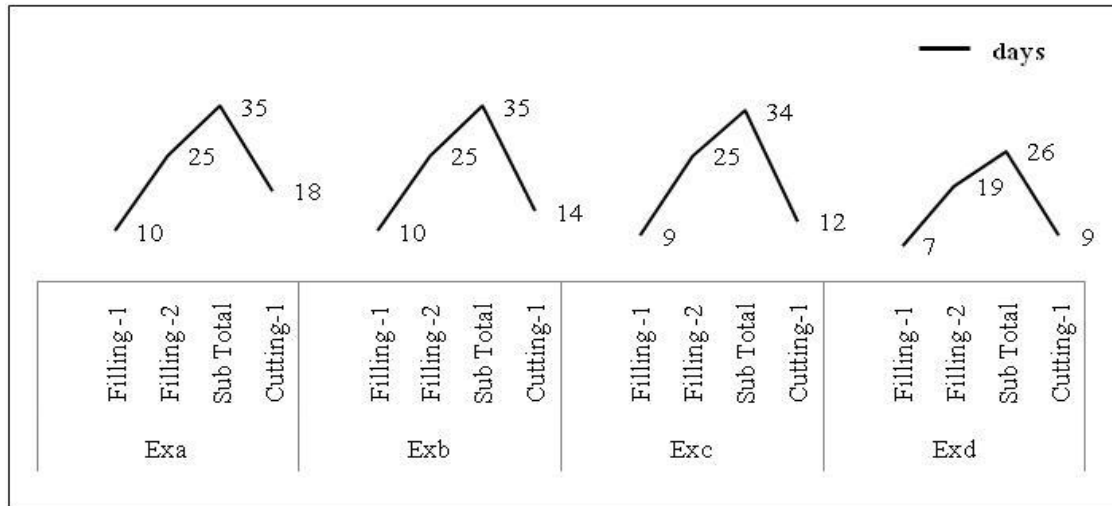


Figure 7.20 Sensitivity analysis results of production time (days) for different types of equipment

The above results revealed that higher productivity equipment is more economical because it utilises less time and minimises resources to complete the same quantity of earthwork in comparison to lower productivity equipment, assuming other conditions and factors remain the same, again suggesting model validity. Since the construction duration of earthwork is different for the different types of equipment, it is logical to plan higher productivity equipment if site conditions allow, to complete earthwork operations and to reduce heavy construction equipment idle time.

7.6.3 Case of different soil characteristics

The results presented in Figure 7.21, show that the total duration was 40 days for fill-1 and fill-2 earthwork operations, since the soil characteristics for the filling sections were assumed the same throughout the road section. However, the total duration for the cutting section at different layers was different in relation to soil types. The sensitivity results show that the duration of cut-1 sections are 20, 19, 21 and 23 days for different types of soil for sand, sand-clay, clay dry and clay wet respectively. Again, this suggests that the model results are valid.

Therefore, the above results confirm that sand-clay soil at a cutting section requires minimum time in comparison with sand, clay-dry and clay-wet. Clay-wet soil needs significantly more time to complete an equal quantity of earthwork under similar site constraints in comparison to other soil characteristics.

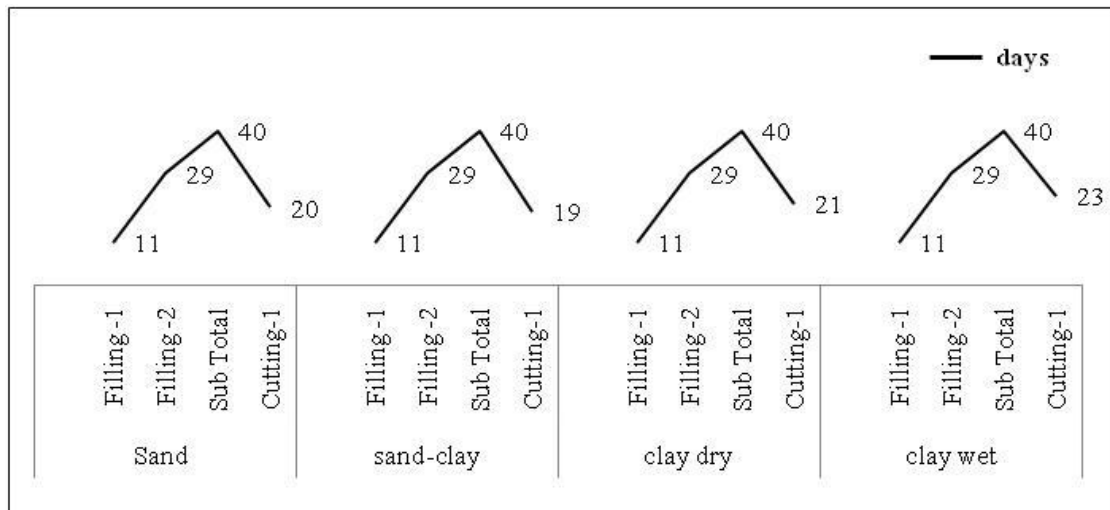


Figure 7.21 Sensitivity analysis results of production time (days) for different soil characteristics

It is concluded from the sensitivity analysis that the model can assist project planners and construction managers in a simulation analysis using ‘what-if’ scenarios, and in producing a location-based schedule and resource planning taking into account:

- different site conditions
- type of equipment
- soil characteristics and site access points

The results of the sensitivity analysis confirm that site access points, types of equipment and soil characteristics are the most critical variables, which have a direct impact on productivity and resource planning for earthwork operations. In the sensitivity analysis, the productivity of different types of equipment (for example; Exa, Exb, Exc, and Exd) were used to analyse the production time with ‘what if’ scenarios under different soil conditions (for example, sand, sand-clay, clay dry and clay wet) with different working sections (site access points) along a road section. With the aid of the model, and subject to its limitations outlined earlier, project planners and construction managers can analyse and simulate the sensitivity of the variables affecting productivity to improve construction scheduling and the resource planning of earthwork operations. Intervention at the early planning stages (additional plan/schedule/resource optimisation) should assist in reducing the adverse impacts of the factors considered in the model and their associated costs.

7.7 Comparison between company produced and model generated time-location plan

A case study of a 7 km road section was selected with the assistance of a company (Mota-Engil) for the validation of the time-location plan (location-based scheduling) produced by the prototype model. The working sections, sectional quantities of earthwork, and productivity data, which were used by the company to produce the plan, were also used to generate a time-location plan using the prototype model so that the discrepancy in results in terms of duration could be avoided. The duration of earthworks shown in a time-location plan provided by the company (Figure 7.22) was compared with the duration generated by the prototype model (Figure 7.23). The comparative results including detailed information on weekly working locations of the road section, quantities, productivity information, and duration of the cut and fill activities, are presented in Table 7.6. The detailed information in relation to the weekly locations of each road section in tabular form is presented in Figures 7.24 and 7.25 below.

Table 7.6 Comparison of results between company-provided and model-generated time-location plan

S. N.	Road Section	Length (m)	E/W Quantity (m ³)	Cut/Fill Activity	Productivity m ³ /wk	Company-produced Results		Model-generated Results		Variations Percentage
						Time (wks)	Location	Time (wks)	Location	
1	0+000 - 0+925	925	32,400	Cut	2309	14.03	0+000 & 0+925	15	Table 1 of Fig. 7.24	6.45%
			34,433	Fill		14.91		15		0.58%
						Duration		15		
2	0+925 - 2+675	1750	64,700	Cut	3464	18.68	0+925 & 2+675	21	Table 2 of Fig. 7.24	11.06%
			51,352	Fill		14.82		16		7.35%
						Duration		21		
3	2+675 - 3+600	925	23,357	Cut	5196	4.50	2+675 & 3+600	5	Table 3 of Fig. 7.25	10.10%
			36,204	Fill		6.97		8		12.90%
						Duration		8		
4	3+600 - 7+000	3400	204,294	Cut	10392	19.56	3+600 & 7+000	22	Table 4 of Fig. 7.25	10.64%
			213,168	Fill		19.64		23		10.81%
						Duration		23		

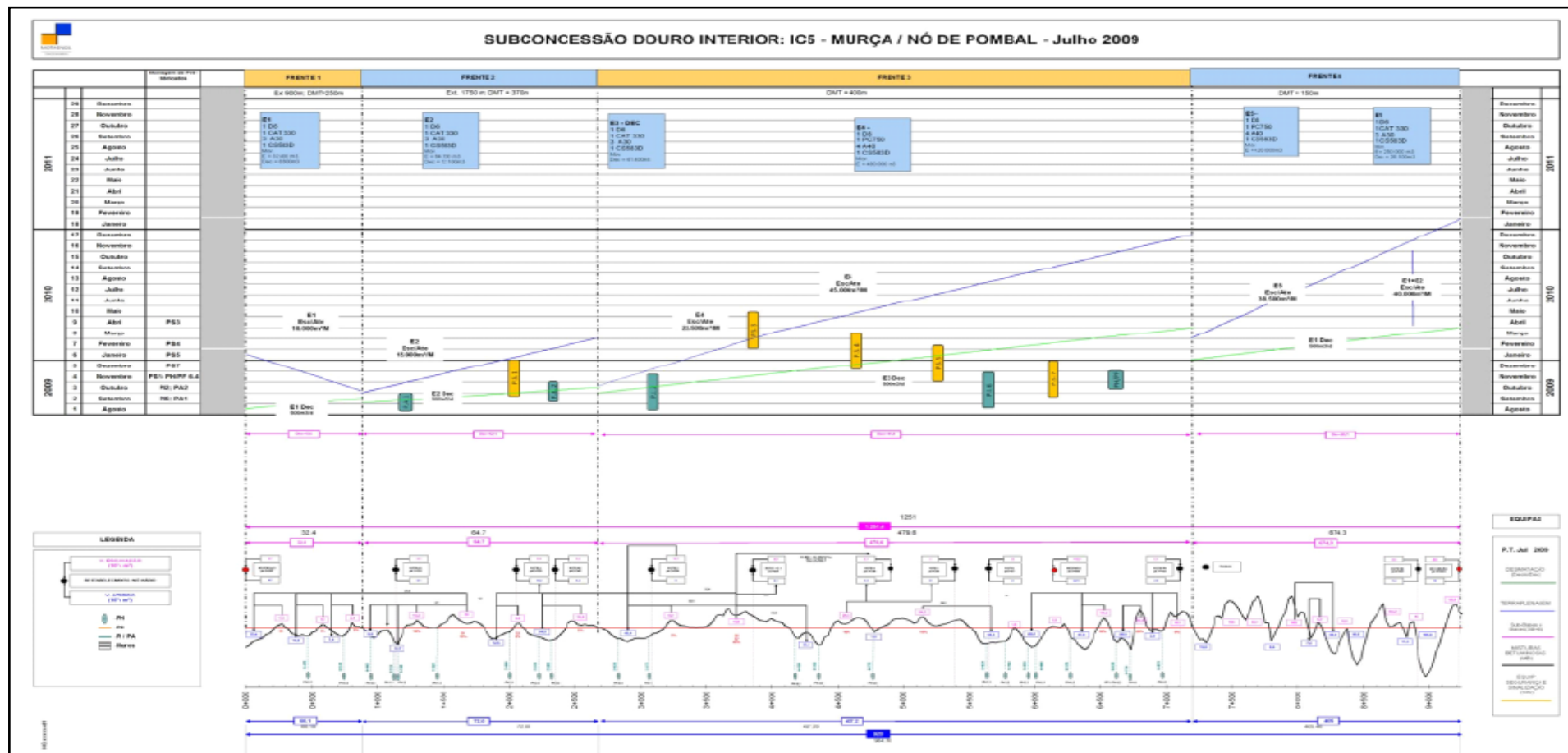
The comparison results (presented in Table 7.6) show that the model-simulated production duration of earthworks is higher by 8.7 % (average) than the company-

estimated production duration of earthworks. The variations in the production duration are due to the methods of determining production time of earthworks. The production duration shown in the model-generated results (Table 7.6) was calculated by rounding the values of duration for each cut and fill section, whereas the production duration shown in the company-produced results (Table 7.6) was calculated by dividing whole quantities with productivity (production rate) of earthwork for each sub-section.

Figure 7.22 represents a time-location plan for a 7 km road project, which was developed and utilised by the company. The plan was produced by dividing the road section into four sub-sections (0+000 to 0+925, 0+925 to 2+675, 2+675 to 3+600 and 3+600 to 7+000). Each section was planned separately, with different sets of equipment with different production rates. Each section of the time-location plan shows the start and the finish date with the corresponding working locations as well as the quantities of earthworks. The information provided in the company-produced time-location plan was presented in Table 7.6 and it was compared with the weekly information provided by the model-generated time-location plan (Figure 7.23) below.



Figure 7.22 Company-produced time-location plan of a 7 km road section
(See enlarged image of Figure 7.22 on page 174 for more clear information)



(Enlarged image of figure 7.22 in A3 size for detailed and clear information of company-provided time-location plan of a 7 km road section)

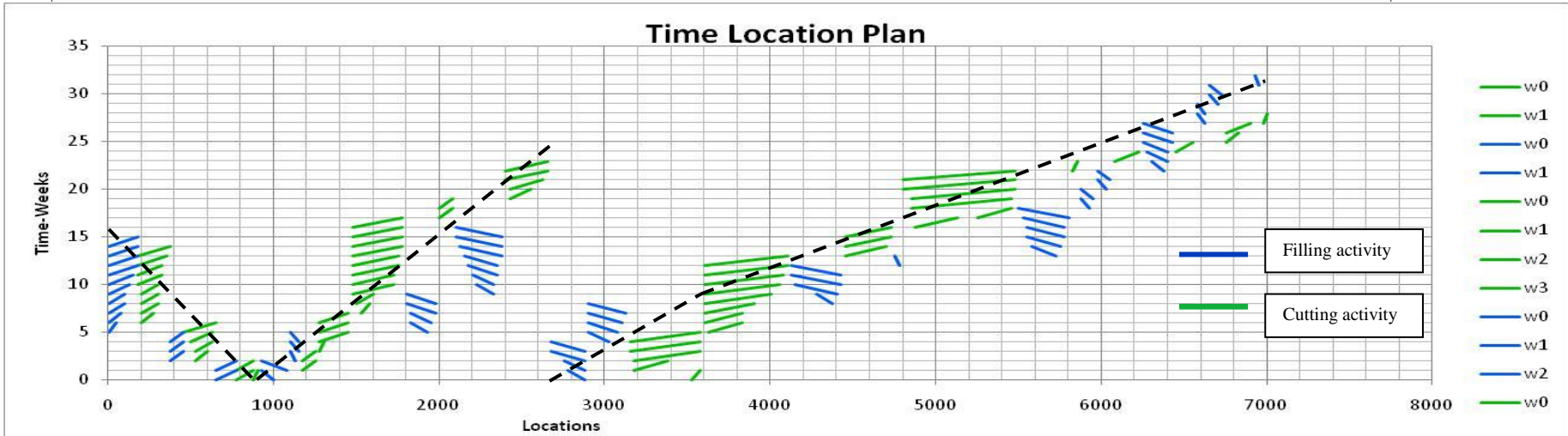
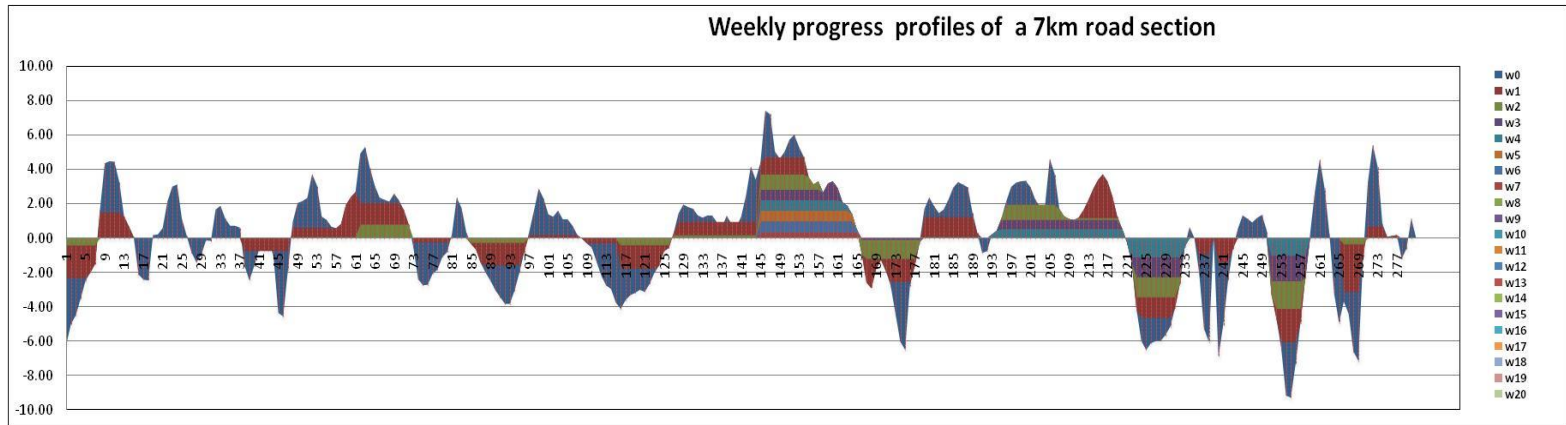


Figure 7.23 Model-generated time-location plan of a 7 km road section

Based on the results (presented in Table 7.6 and Figures 7.23, 7.24 and 7.25), it is concluded that the model has enough capability to provide scheduling information of weekly locations of earthwork operations for both cut and fill sections in the form of graphs and tables. The time-location plan produced by the company, however, only provides the start and the end location of a road section (Figure 7.23, with dotted lines).

Table 1: List of weekly locations of earthworks Road section 0 to 0+925 (Productivity 2309 m ³ /wk)						Table 2: List of weekly locations of earthworks Road section 0+925 to 2+675 (Productivity 3464 m ³ /wk)					
SN	X1 (Start Station) m	X2 (End Station) m	Y1 (Start Date)	Y2 (End Date)	Fill/Cut	SN	X1 (Start Station) m	X2 (End Station) m	Y1 (Start Date) wk	(End Date)	Fill/Cut
w0	0	50	0	1	F	w0	1100	1150	0	1	F
w1	0	75	1	2	F	w1	1100	1175	1	2	F
w2	0	100	2	3	F	w2	925	1025	2	3	F
w3	0	100	3	4	F	w3	925	1175	3	4	F
w4	0	125	4	5	F	w4	925	1175	4	5	F
w5	0	150	5	6	F	w0	1200	1325	0	1	C
w6	0	175	6	7	F	w1	1200	1350	1	2	C
w7	0	175	7	8	F	w2	1175	1475	2	3	C
w8	0	175	8	9	F	w3	1175	1475	3	4	C
w9	0	175	9	10	F	w4	1175	1475	4	5	C
w0	200	275	0	1	C	w0	1525	1600	5	6	C
w1	200	300	1	2	C	w1	1500	1625	6	7	C
w2	200	300	2	3	C	w2	1475	1750	7	8	C
w3	200	300	3	4	C	w3	1475	1750	8	9	C
w4	175	325	4	5	C	w4	1475	1775	9	10	C
w5	175	325	5	6	C	w5	1475	1775	10	11	C
w6	175	350	6	7	C	w6	1475	1800	11	12	C
w7	175	375	7	8	C	w7	1475	1800	12	13	C
w0	375	450	10	11	F	w8	1475	1800	13	14	C
w1	375	450	11	12	F	w9	1475	1800	14	15	C
w2	375	450	12	13	F	w0	1825	1950	5	6	F
w0	525	600	8	9	C	w1	1825	1975	6	7	F
w1	525	625	9	10	C	w2	1800	2000	7	8	F
w2	500	625	10	11	C	w3	1800	2000	8	9	F
w3	450	650	11	12	C	w0	2000	2100	15	16	C
w0	650	775	13	14	F	w1	2000	2100	16	17	C
w1	650	775	14	15	F	w0	2225	2350	9	10	F
w0	775	900	12	13	C	w1	2200	2350	10	11	F
w1	775	925	13	14	C	w2	2175	2375	11	12	F
w2	775	925	14	15	C	w3	2150	2375	12	13	F
						w4	2125	2400	13	14	F
						w5	2100	2400	14	15	F
						w6	2100	2400	15	16	F
						w0	2425	2575	17	18	C
						w1	2425	2650	18	19	C
						w2	2400	2675	19	20	C
						w3	2400	2675	20	21	C

Figure 7.24 Weekly locations information from chainage (0+000 to 2+675).

Table 3: List of weekly locations of earthworks Road section 2+675 to 3+600 (Productivity 5192 m ³ /wk)						Table 4: List of weekly locations of earthworks Road section 3+600 to 7+000 (Productivity 10385 m ³ /wk)					
SN	X1 (Start Station) m	X2 (End Station) m	Y1 (Start Date) wk	Y2 (End Date) wk	Fill/Cut	SN	X1 (Start Station) m	X2 (End Station) m	Y1 (Start Date) wk	Y2 (End Date) wk	Fill/Cut
w0	2775	2875	1	0	F	w0	3625	3825	0	1	C
w1	2750	2875	2	1	F	w1	3600	3825	1	2	C
w2	2675	2875	3	2	F	w2	3600	3900	2	3	C
w3	2675	2875	4	3	F	w3	3600	4000	3	4	C
w0	2900	3025	5	4	F	w4	3600	4050	4	5	C
w1	2900	3075	6	5	F	w5	3600	4075	5	6	C
w2	2900	3100	7	6	F	w6	3600	4100	6	7	C
w3	2900	3125	8	7	F	w7	3600	4100	7	8	C
w0	3525	3575	0	1	C	w0	4275	4375	1	0	F
w1	3175	3375	1	2	C	w1	4150	4400	2	1	F
w2	3175	3575	2	3	C	w2	4125	4425	3	2	F
w3	3150	3575	3	4	C	w3	4125	4425	4	3	F
w4	3150	3575	4	5	C	w0	4450	4700	8	9	C
						w1	4450	4725	9	10	C
						w2	4450	4725	10	11	C
						w0	4750	4775	5	4	F
						w0	4875	5125	11	12	C
						w1	5250	5450	12	13	C
						w2	4850	5450	13	14	C
						w3	4850	5475	14	15	C
						w4	4800	5475	15	16	C
						w5	4800	5475	16	17	C
						w0	5575	5725	6	5	F
						w1	5550	5750	7	6	F
						w2	5550	5775	8	7	F
						w3	5525	5775	9	8	F
						w4	5500	5800	10	9	F
						w0	5825	5850	17	18	C
						w0	5875	5925	11	10	F
						w1	5875	5950	12	11	F
						w0	5975	6025	13	12	F
						w1	5975	6050	14	13	F
						w0	6075	6225	18	19	C
						w0	6300	6375	15	14	F
						w1	6275	6400	16	15	F
						w2	6250	6400	17	16	F
						w3	6250	6425	18	17	F
						w4	6250	6425	19	18	F
						w0	6450	6550	19	20	C
						w0	6575	6625	20	19	F
						w1	6575	6625	21	20	F
						w0	6650	6700	22	21	F
						w1	6650	6725	23	22	F
						w0	6750	6825	20	21	C
						w1	6975	7000	21	22	C

Figure 7.25 Weekly locations information from chainage (2+675 to 7+000).

The model is capable of providing detailed information (smaller sections) on weekly locations of both cutting and filling sections separately. This represents a significant improvement when compared to existing practices in earthwork operations. Additionally, several experiments were carried out at the earthwork construction site of a road project of lot 5 in Portugal by Mota-Engil. The results of the experiments showed that the actual productivity rate was 2.34% lower than the model-simulated productivity value of earthworks. The difference in productivity was due to the delay in earthwork

progress and the variations in soil characteristics at the cutting section. As a result, it was concluded that the model-produced location-based schedules which also provide the information on weekly locations are acceptable for earthwork operations in road construction projects (again demonstrating the model's validity within the limitations outlined earlier). Location-based scheduling should result in improved resource planning, including the mobilisation and demobilisation of the construction equipment for earthworks.

7.8 Evaluation of the Prototype Model

This section discusses the evaluation processes and explores the value of the prototype model associated with the practical applications. As part of the evaluation of the model, a proper validation method called “indirect comparison” was used in this study (Ho et al, 2009). This method is used when practitioners implement a new method on a real project, but there is no direct comparison for how the method performs against an existing method. As an alternative, the method is evaluated, based on the practitioner's past experience performing the tasks using traditional methods on similar types of projects (Collier and Fischer, 1996; Manning and Messer, 2008; Torrent and Caldas, 2009, cited in Ho et al, 2009).

Evaluation of the prototype model was carried out by demonstrating the functions of the prototype model to road construction professionals through site meetings. After demonstrating the model functions, participants were requested to answer the questions stated in the evaluation form (Appendix-F), taking into account their experiences in road projects. A total of five meetings at construction sites were conducted for the evaluation of the model functionality. Two examples of the responses are presented in Appendix-F. The following road construction professionals within UK-based construction companies participated in the evaluation process of the model:

1. Niall Fraser: Director, C.A. Blackwell (Contracts) Ltd.
2. Steve Clarke: Managing Director, C.A. Blackwell (Contracts) Ltd.

3. Jess Yates: Contract manager, C.A. Blackwell (Contracts) Ltd.
4. Alan Day: Planning manager, C.A. Blackwell (Contracts) Ltd.
5. Hayden Green: Project manager, Balfour Beatty Regional Civil Engineering Ltd.
6. Paul McLaughlin: Contract and planning manager, Balfour Beatty Regional Civil Engineering Ltd.
7. Chris Beadle: Construction manager, A-one Integrated Highway Services, UK.
8. David Wheatley: Programme manager, A-one Integrated Highway Services, UK.

This section also summarises the findings and views obtained from the demonstration and presents the outcomes of the discussion amongst the road professionals who participated in the evaluation processes. In order to validate the functionality of the prototype model, road professionals' points of view in respect of the practical applications of the model were sought, and encapsulated through the evaluation form. The views and opinions expressed by the participants are summarised in the following sub-categories.

7.8.1 As a decision support system

- The majority of the participants agreed that the prototype model is a very useful tool in supporting initial strategic decisions at the planning stage, due to its capability to present the implications of different equipment at required locations and when necessary.
- Improved management of resource scheduling from location aspects would be a major benefit.
- Participants also argued that the model will be a useful tool to optimise the earthwork allocation on complex linear projects with multiple cuttings and embankments.

7.8.2 Improvement in construction planning and scheduling

- The majority of participants had the impression that the model may be able to add value to contractor planning, and to optimise the use of plant for earthwork contractors who have a large fleet of construction plant.

- Some of the participants also agreed that the model provides accuracy in establishing the cut/fill balance points in a linear project, and in planning to accommodate the surplus or deficit materials.
- Nonetheless, a few participants pointed out that further improvement in the model is necessary prior to the model's application at a construction site.

7.8.3 As a communication tool for scheduling information

- Most of the participants agreed that the model is very good as a communication tool for all the construction team members, and makes it easy to communicate earthwork scheduling information amongst all stakeholders; however, the input data may be too complicated to set up initially.
- The visualisation process for earthwork operations would also be useful in showing “the layman” what the construction would look like at various stages. However, a few participants highlighted that an experienced team would already have the scheduling information provided by the model.

7.8.4 Benefits of the system to planners / construction managers

- The majority of participants agreed that running various strategies with the model using ‘what-if’ scenarios would allow optimisation of resources in earthwork operations.
- The information associated with the location of equipment mobilisation is useful. However, its use is more limited in the UK, because British contractors may not have a sufficiently large plant fleet to call upon in order to change equipment as work progresses on a weekly schedule.
- The potential benefits of this system are more suitable to other parts of the world, or for European markets, where linear projects with earthwork components are relatively large in number in comparison to the UK.

7.8.5 Identification of space/location conflict at construction site

- Most of the participants felt that the model is a useful tool for identifying space congestion (which has a significant impact on site productivity), as well as from

a health and safety point of view, but that it needs additional development to make it more effective at a construction site.

- A few participants pointed out that managing space congestion is not the first priority for experienced managers, but that the model is relatively useful for non-specialists who need to address space/location conflicts at a construction site.

7.8.6 Potential benefits in terms of cost and time

- Some of the participants agreed that the model would be of the most benefit to non-specialists, because specialists and experienced planners should already be able to mentally visualise the earthwork processes.
- The visual outputs of the prototype model would help construction managers show their supervisors why decisions have been made and what the benefits of the model are.
- Some participants articulated that the model is a useful tool for the right projects, such as major road projects or a Speed 2 rail project, where time and cost can be saved by allocating the resources effectively in earthwork operations at required locations and when necessary.

7.8.7 Barrier to implementation in terms of people or technology

- The majority of participants shared the view that training for staff and the model's dependency on new technology are the main barriers to implementing the model at a construction site.
- The system needs an operator with advanced computer skills. However, most of the supervisors who control plant on a daily/weekly basis are not computer trained, and do not like using computers or adopting a new technology.
- Nevertheless, some of the participants agreed that the visualisation capability of the model would help break down the traditional reluctance of people to accept a new technology.

Taking into account the different road professionals' points of view, above, and despite some desired improvements to the prototype model, it is concluded that the model is still

a very useful decision-supporting tool, particularly in road construction projects. It assists construction managers in earthwork scheduling and in the visualisation of scheduling information from location aspects in relation to resources utilisation.

7.9 Summary

This chapter discussed testing, experimentation, analysis and evaluation of the prototype model. The chapter presented a range of different experiments and a case study from road projects to demonstrate the prototype model's functionality. The automatic production of earthwork progress profiles under different productivity values was outlined. The model generated location-based schedules (time-location plans), which were tested with different site constraints (seven different options were considered).

The optimisation module was demonstrated using two road sections with the aid of a sensitivity analysis. The outcomes from the sensitivity analysis and experiments were presented by analysing the effects on earthwork duration due to different factors associated with scheduling, such as site access points, soil characteristics and different equipment types. The comparison results found that the model-generated time-location plan provides detailed scheduling information on weekly locations associated with assigned resources, whereas the company-produced time-location plan lacks weekly information on locations throughout the earthwork operations.

Finally, experienced road construction professionals evaluated the model. From the professional viewpoints, it is concluded that the model is a very useful tool in supporting the initial strategic decisions at the planning stage and provides the scheduling information more effectively from the location aspects. Running various strategies with the model would allow optimisation of resources, including construction equipment useful in the earthwork operations. The next chapter discusses the conclusions from the research study and recommendations for future study.

Chapter -8

Conclusions and Recommendations

8.1 Introduction

The research discussed in this thesis was applied to road construction projects. It was concerned with the development of a methodology and a prototype model for location-based earthwork scheduling and the visualisation of scheduling information. The functionalities of the prototype model were demonstrated with road construction projects to justify its relevance and significance to the construction industry. This chapter summarises the conclusions, which are drawn from the research study, and describes the potential benefits of the prototype model. This chapter also outlines the limitations of the research and provides recommendations for further developments.

8.2 Conclusions of the Research Study

The conclusions drawn from the research study are summarised under different sections as follows: - the literature review, the construction industry survey, experiments with different functionalities of the prototype model (including cut-fill optimisation), and the evaluation of the model from road construction professionals.

8.2.1 Literature review

A comprehensive literature review was carried out to investigate the existing practices and limitations associated with earthwork scheduling techniques, and with the visualisation of earthwork processes, including scheduling information in road construction projects. This addresses the first objective of this study; conclusions from the literature review are summarised below:

- The review has concluded that existing linear scheduling methods are unable to provide detailed information on the weekly locations required for construction scheduling and resource planning, particularly in earthworks in linear projects.

- The key issues facing road construction sites are the variation in site productivity rates of earthworks from day to day and location to location along a road section, because of factors such as the topography of existing terrain, soil characteristics, weather, site working conditions, resource constraints, and other unpredictable factors. These factors have a direct impact on earthwork scheduling and resource planning.
- Earthwork activities significantly affect other road activities and the overall performance of construction site operations due to the distinctive characteristics of earthwork in linear construction projects.
- Existing 4D modelling of earthwork activities lacks integration of the different productivity rates which may vary due to the unique characteristics of earthwork along a road section. As a result, the 4D models could not provide the progress profiles of earthwork at different rates of productivity.
- The visualisation of scheduling information from the location aspects on a weekly basis is missing in the existing linear schedules of earthworks; therefore, construction managers are faced with difficulties when identifying information on the space or activities' conflicts, and on resource constraints in earthwork operations.
- The literature review showed that the linear scheduling method is a valuable technique for planning and monitoring the progress of linear projects such as roads, pipelines and railways. It also helps in time-extension claims in case of variations in earthwork quantities at a particular location at the construction stage.
- There are significant limitations around the traditional planning and scheduling techniques in terms of providing detailed and weekly information, on working locations, in earthwork operations, particularly in linear projects.

- The past research studies related to location-based planning show that the improved schedule overview, establishment of workflow and enhanced project control from location aspects are the three major constructive implications of location-based scheduling.

8.2.2 Construction Industry Survey

The second objective of this study was fulfilled by undertaking a construction industry survey. It was conducted to identify the existing practices, limitations and critical factors affecting the earthwork scheduling and visualisation of construction processes in linear projects.

The survey was conducted with thirty construction companies that are mainly involved in linear construction projects such as roads, railways, pipelines and other civil engineering projects. The sample (construction companies) was randomly selected considering their expertise in past projects. The survey was conducted using semi-structured questionnaires and interview techniques. The questionnaires were distributed through email, post and in person. Fifty construction companies were invited to participate in the survey and thirty responses (60%) were received.

The following are the conclusions drawn from the industry survey:

- It was found that mass haul diagrams and past experiences were commonly used in earthwork planning, despite the availability of commercial tools. This is mainly due to the complexity and cost associated with these tools.
- The majority of the companies use weekly schedules for the execution and monitoring of earthwork activities; certain companies, however, were still using monthly schedules for execution and monitoring purposes.

- Most of the construction companies accepted that change orders, relocation of utilities and poor construction planning techniques are the major causes of project delays.
- Productivity of construction machinery, selection of construction methods, soil characteristics and site access points are the key critical factors that affect the earthwork planning and construction operations.
- Visualisation of earthwork progress profiles provides information on the construction sequences and space/location allocation. This also helps to effectively analyse space congestion, and assists in communicating the scheduling information amongst project stakeholders.

The survey findings revealed that visualisation techniques are vital for making better decisions in resource planning for earthwork operations through the visual simulation of construction processes from location aspects.

8.2.3 The prototype model of earthwork scheduling and visualisation

A methodology was developed by outlining a framework of a prototype for earthwork scheduling and the visualisation of progress profiles. The findings from the survey and the literature were used in the development of the specification design of the prototype model. Specifications of the model were arranged into three components: inputs, process and outputs. The generation of location-based schedules of earthwork is a key functionality of the model. Other functionalities include earthwork progress profiles, location-based costing, and a space congestion plan for earthworks. The development methodology of algorithms, model specifications and the design of data flow diagrams of the model's functionality were explained and presented in Chapter 4. This meets the third objective of this study.

According to the designed specifications, a computer-based prototype model was developed using MS Excel solver and creating VBA macros to achieve the economical

allocation of earthwork in a cut-fill assignment. The visualisation module was developed with the C# programming language to process the data and produce graphical outputs of the model. The detailed development processes of the model functionalities were discussed and presented in Chapter 5. This process satisfies the fourth objective of the study.

The following conclusions are drawn from the prototype model of earthwork scheduling and the visualisation of scheduling information.

8.2.3.1 Location-based scheduling (Time-location plan)

- The model generates location-based schedules of earthworks and provides detailed daily or weekly locations information.
- The model generates daily or weekly information on working locations and earthwork quantities in location-based schedules according to the provided productivity rates of earthwork activities.
- The model is useful in visually analysing the earthwork scheduling information of resource allocation from the location viewpoints.
- The sensitivity analysis of critical factors such as types of equipment, soil characteristics and site access points showed that these factors affect earthwork scheduling in resource planning from the location aspects.

8.2.3.2 Space congestion plan

- The space congestion plan identifies the congested locations, particularly at the early stage of earthwork operations, and provides an early indication of congested locations. Therefore, a suitable set of construction equipment could be mobilised at correct locations, and when necessary, to avoid the space congestion and inactive hours of heavy construction equipment.

- The model helps to analyse the impacts on space congestion by simulating different types of equipment and site access points by means of “what-if” scenarios.

8.2.3.3 Location-based costing and cost S-curve

- The model generates location-based cost profiles and S-curves. The cost profiles help to identify weekly cost requirements of earthworks throughout construction operations.
- The cost S-curve helps to compare the planned and actual production cost of earthworks in road construction projects.

8.2.4 Visualisation of earthwork progress profiles

The second key functionality of the prototype model is the visualisation aspect of scheduling information from location viewpoints. This includes the visual representation of the weekly progress profiles, location-based scheduling, cost profiles and space congestion plans of earthworks in road construction projects.

- The model automates the generation of the virtual surfaces of progress profiles and provides the visual information of construction sequences from the location viewpoints.
- The model is useful in visualising the impact on earthwork scheduling and resource planning by rehearsing “what-if scenarios” with different factors associated with productivity, including soil characteristics, types of equipment, and working locations.
- The model is a valuable tool in communicating the scheduling information of construction sequences, the resource allocation plans, and the proposed methods

for earthwork operations. It is also valuable in providing information to create a consensus amongst project stakeholders.

8.2.5 Cut-fill optimisation of earthworks

A cut-fill optimisation algorithm was adapted and used to calculate the optimum cut to fill, fill from borrow pits and cut to landfill, and quantities and direction of earthwork.

The optimisation algorithm was designed by integrating a mass haul diagram, the unit cost of haulage and the Excel solver. In this context, a matrix table of cut-fill sections was first generated and then the optimisation algorithm was incorporated into the table, using a VBA macro, including the respective sectional quantities of earthwork in a road section. The table also incorporated borrow pits and landfill sites for borrowing the shortfall quantities and depositing the surplus quantities. The following conclusions are drawn from the cut-fill optimisation module:

- The cut-fill optimisation helps project planners and construction managers to identify the optimal quantities and directions of movement in a cut-fill assignment of the earthwork component in a road construction project.
- The cut-fill optimisation modules also integrated borrow pits and landfill sites to optimise the minimum earthwork haulage cost.

8.2.6 Conclusions from the experiments with road projects

The model functionalities were demonstrated with the design information of road projects, and experiments were run to evaluate the functionalities of the prototype model. A company-produced location-based plan was compared with a model-produced location-based plan of earthwork projects in Portugal. The details of the experiments and a demonstration of results were presented in Chapter 8. The construction industry reviews were conducted to evaluate the practical benefits of the model. A sensitivity analysis was carried out to test the effect of the earthwork schedule. This meets the sixth and final objective of the study.

The following conclusions are drawn from the experiments with the road projects:

- Experiments were carried out at an earthwork construction site in Portugal. The results of the experiment found that the actual productivity was 2.34% lower than the model-simulated productivity value of earthworks. Hence, it is concluded that the model-generated location-based schedules are acceptable for use as a location-based scheduling tool in earthwork operations in road projects.
- It can be concluded that the results of the experiment show that the developed location-based schedule is capable of generating daily or weekly locations of earthworks, whereas the existing time-location plans only provide the start and the end locations of a road section in earthwork operations.
- The space congestion plan is valuable for decision-making in mobilising a suitable set of construction equipment and avoiding the equipment being idle.
- The location-based costing and cost S-curve helps construction managers or cost planners to produce more accurately cash-flow diagrams on a weekly basis.
- The cut-fill optimisation helps the project planners to optimise the earthwork quantities and identify the direction of movement between cut-fill sections, fill from borrows or cut to landfill sections, including associated costs.

The following conclusions are drawn from the results of sensitivity analysis:

- The results of sensitivity analysis in the case of site access points showed that a lower number of access points is more economical, and reduces the wastage of resources, to complete the same quantity of earthworks in comparison to a higher number of site access points for the same sections in road construction projects.
- The results of sensitivity analysis in the case of different types of equipment revealed that higher productivity equipment is more economical by utilising less time and minimum resources to complete the same quantity of earthwork in comparison to lower productivity equipment. It is logical to plan for the higher

productivity equipment if the site conditions allow the mobilising of such equipment. Thus, the idle time of resources use could be reduced by selecting a suitable set of equipment and its associated crew.

- The results of sensitivity analysis in the case of different soil characteristics confirmed that sand-clay soil at a cutting section requires the minimum time in comparison with sand, clay-dry and clay-wet, whereas clay-wet soil needs more time to complete the equal quantity of earthwork under similar site constraints in comparison to other soil characteristics.

8.2.7 Conclusions from the model evaluation with road practitioners

The following are the conclusions drawn from the road construction professionals during the demonstration and the evaluation processes of the developed prototype model:

- The visual representation of location-based schedules and the visualisation of the scheduling information assist initial strategic decision-making in earthwork scheduling and equipment planning from the location aspects.
- The model helps in communicating the scheduling information proposed by a construction company amongst project stakeholders at the tender stages, and it assists to show “the layman” about the construction sequences and the effects of what the construction process will look at various stages in earthwork operations.
- The model is a useful tool in providing accuracy in establishing cut/fill balance points and in optimising the use of plant for earthworks in complex linear projects.
- The model could be valuable in analysing the sensitivity of the factors associated with earthwork scheduling and the visualisation of resource plans from the location aspects using ‘what-if’ scenarios, but these aspects of the model need further improvement.

- The model is valuable tool for a contractor that has a large fleet of construction plant and wishes to optimise the number and types of plant. The model is more suitable for earthwork operations in other parts of the world and the European market, where, earthworks mostly take place in a linear construction project.
- The model is useful for the right projects, such as a large road project or Speed 2 rail project, where time and cost can be saved by allocating the critical resources effectively at the required locations, and when necessary, along a linear project.
- Training the staff and dependency on new technology are key barriers to implementing the proposed model in the earthwork construction site; however, the visualisation capability of the model would assist acceptance of the new technology, and help to break down the traditional reluctance of construction staff to accept new technologies.
- The improved management of resource scheduling from the location aspect is one of the key benefits of the model. However, the model needs further improvement in order to be more useful at a construction site.

8.3 Research Contributions

The research contributions to knowledge and practice (theoretical and practical contributions) from this research study are summarised as follows:

a) Theoretical contributions:

- The development of a theoretical framework and specification for a prototype of earthwork scheduling by integrating road design data, sectional quantities, different productivity rates, algorithms, site access points, and location-based theory is considered as a key contribution.
- The development of a prototype model constituted by a new methodology for the generation of location-based earthwork scheduling and visualisation of the

scheduling information from location aspects is the main contribution to knowledge.

- The development of a unique algorithm by deriving a time dimension from the productivity data for the automatic generation of location-based schedules and the progress profiles of earthwork is also considered a key contribution.
- The integration of variable productivity values with the model, and its capability to analyse the sensitivity of critical factors on earthwork scheduling and the visualisation of progress profiles, are further contributions to knowledge of the developments in earthworks modelling.

b) The practical contributions are as follows:

- The model is valuable in identifying the congested space at an early stage of earthwork construction and in optimising the suitable sets of construction plant according to the available space.
- The model is beneficial in optimising earthwork quantities, and helps to identify the direction of earthwork movement between cut and fill sections, including borrow pits and landfill sites in road construction projects.
- The model is capable of providing location-based costing information and a cost S-curve for monitoring cost performance, thereby developing a precise cash-flow plan for the earthworks.
- The model is valuable in showing “the layman at site” the effect of what the construction would look like at various stages of the earthwork construction. Therefore, it is a good communication tool for visualising the construction processes of earthworks and for communicating the scheduling information among project stakeholders.
- The location-based scheduling is also a valuable tool in claiming for time extensions, particularly in the case of variation in earthwork quantities, and in

predicting the conflict of work activities or space congestion at an early stage of the earthwork operation in linear construction projects.

- The model's capability to improve the overview of location-based scheduling, to assist in resources planning and monitoring site progress more effectively from the location aspects, and to provide weekly information of locations in the earthwork operations, are the key practical contributions of the prototype model in the study.

8.4 Scope and Limitations

The scope of this research study is limited to new road projects, particularly for the earthwork operations in linear construction projects. The following limitations are noted:

- The research study excluded rock excavation and only considered regular excavation, given that rock excavation is performed differently, and is considered a separate specialist activity, within earthwork operations.
- The study included only typical cross-sections with a trapezoidal shape and regular side slopes, which are often used in road construction, particularly in terrain with flat and regular transverse slopes, but excluded steep terrain. The impact of weather is excluded in the location-based scheduling, but it can be considered by adding a few days when producing a construction schedule.
- The sectional volume of earthwork was calculated using the "average end-area" method, and it is represented at the end-station between two stations along a road section. An enhancement of the research could, however, be made by adopting a new technique that could provide more accurate estimation of sectional volume.
- The prototype model assumed that the minimum working length must be equal to the length of two times the station interval (this means the minimum length is

equal to 50m if interval is equal to 25m) for generating a time-location plan / location-based schedule of earthworks in road projects.

- The prototype model, however, is flexible enough to generate a location-based earthwork scheduling from a 1.0km- up to a 7 km-length of road section between two cross-obstructions, such as rivers, bridges, tunnels and intersections.

The study assumed that a road project divides into multiple sections, considering the cross-obstructions such as intersections, bridges and rail crossings, and that each section in the road project is considered as a separate working section for generating location-based scheduling of earthworks. The prototype model, however, requires further development to extend its capability and application to other linear projects such as pipe-laying projects, irrigation and navigation channels, and railway projects. The next section highlights the possible recommendations for future research studies.

8.5 Recommendations for Future Research

The research could be further extended to include other road tasks for generating location-based scheduling and visualisation of a construction process. The model could be used in different linear projects, such as oil and gas pipeline projects, irrigation canals and navigation channels, for generating a time-location plan and helps to visualise the scheduling information from the location aspects. It is recommended that the developed prototype model can be further advanced in the following areas:

- The model can be improved by integrating other road activities such as sub-base and base work, pavements, side drains, road marking, road furniture and lighting, culverts and bridge construction. This will help to advance the functionality of the model, particularly in identifying the conflicting work activities and in controlling site progress more effectively from the location aspects.
- There is room for integration of different road cross-sections, particularly available in hilly roads, like box cut, partial cut and fill. Since hilly roads have

distinctive cross-sections, there is a need to investigate a new technique to analyse the progress profiles and to visualise the scheduling information of construction processes in the steep-terrain conditions.

- The optimisation module can be advanced by considering the environmental factors, including CO₂ emission, in addition to the haulage unit cost for a cut-fill assignment. Since the environmental issues are becoming highly sensitive, the optimisation algorithm could provide better allocation of earthworks, considering different factors associated with the environment in road construction projects.
- There may be a possibility of integrating the model with UC-win/Road software to produce a real-time visual simulation for analysing the progress and space congestion of road activities from location aspects. This will provide a real-time visual model for the stakeholders and general public.

8.6 Summary

Finally, it was concluded that the prototype model is capable of automatically generating location-based schedules and visually analysing the scheduling information of earthworks from the location viewpoints. Road construction professionals agreed that the developed model is valuable in resource planning at the required locations, and when necessary, throughout the earthwork operations, particularly in linear projects. The model is also useful in communicating the earthwork scheduling information amongst project stakeholders, allowing for the sensitivity analysis of critical factors associated with the productivity rates. Consequently, the model works as a logical decision-making tool in producing location-based schedules and resource planning for earthworks in a lean and effective manner, which, in turn, improves the site productivity, scheduling overview, workflow establishment, and control of site progress, and reduces the production time and costs of earthwork operations in road construction projects.

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10. Nova Point Civil Construction, <http://www.novapoint.com>
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14. VICO ConstructorTM, <http://www.vicosoftware.com/>
15. VIR-MEEC, <http://sst.tees.ac.uk/ccir/>

Appendix - A

List of Research Publications

The following are the publications arising from the research study included in this thesis.

Journal Papers

1. Shah, R. K., Dawood, N. and Castro, S. (2008), “Automatic Generation of Progress Profiles for Earthwork Operations using 4D Visualisation Model”, *Journal of Information Technology in Construction, IT Con.* Vol. (13), pp 491-506.
2. Shah, R. K. and Dawood, N. (2011), “An innovative approach for generation of a time-location plan in road construction projects”, *Journal of Construction Management and Economics*, 29(5), pp 435-448.

International Conference Papers

3. Shah, R. K. and Dawood, N. (2007), “Development of Innovative Visualisation Model in Road Construction”, *Proceedings of CIB 24th W78 International Conference on Bringing ITC Knowledge to Work*, pp 499-504, June 26-29, Maribor, Slovenia.
4. Dawood, N. and Shah, R. K. (2007), “An Innovative Approach for Improvement of Communications through Visual Schedule Model in Road Construction”, *Proceedings of 7th International Conference on Construction Application of Virtual Reality*, pp 216-223, October 22-23, PA, USA.

5. Dawood, N., Shah, R. K., and Castro, S. (2007), "Development of Visual Schedule Model (VSM) Framework for Road Construction", *International Workshop on Computing in Civil Engineering*, Pittsburgh, USA.
6. Shah, R. K. and Dawood, N. (2008), "A Conceptual Framework of Simulation and Visualisation of Earthwork Construction Process in Road Construction Projects", *ARCOM Workshop on ICT in Construction & Built Environment*, 14 March 2008, University of Salford, Manchester, UK.
7. Shah, R. K. and Dawood, N. (2008), "Improving Communication of Scheduling Information of Earthwork Construction Process using 4D Visualisation Model in Road Projects" *Proceedings of CIB 25th W78 International Conference on Improving the management of construction projects through IT adoption*, 15-17 July 2008, Santiago, Chile.
8. Shah, R. K. and Dawood, N. (2008), "A Framework of a Virtual Earthworks Activities Model (4D-ERCON) for Road Construction Projects", *Proceedings of 8th International Conference on Construction Application of Virtual Reality (CONVR)*: 20-21 October 2008, Kuala Lumpur, Malaysia.
9. Shah, R. K., Dawood, N., Dean, J. and Castro, S. (2009), "A 4D planning tool: Automatic Generation of Progress and Cost Profiles using Variable Productivity Data in Earthwork Construction", *Proceeding of the CSCE 2009 Annual General Conference, ICS-055- 1 to 10*, 27-30 May 2009, Newfoundland, Canada.
10. Shah, R. K., Dawood, N., Dean, J. and Castro, S. (2009), "A Virtual Construction Model of 4D Planning in Road Project", *ARCOM 25th International Conference*, pp 1091-1100, 7-9 Sep 2009, Nottingham, UK.
11. Shah, R. K., Dawood, N., Dean, J. and Castro, S. (2009), "An Innovative Approach for Generation of Virtual Construction Model and Time-location Plan

for Road Construction Projects”, *CIB 26th W78 International Conference on managing IT in Construction*”, pp 577-585, 1-3 October 2009, Istanbul, Turkey.

12. Shah, R. K. and Dawood, N. (2009), “Automatic Generation of Time Location Plan in Road Construction Projects”, *Proceedings of 9th International Conference on Construction Application of Virtual Reality (CONVR)*, pp 197-206, 5-6 Nov 2009, Sydney, Australia.
13. Shah R K, Dawood, N., Dean, J and Castro, S (2011), “Earthwork Scheduling and Optimisation in Road Construction Projects”, *Annual research symposium and conference at Teesside University*, 17 May, 2011, Middlesbrough, UK.

Appendix- B

A Sample of Questionnaire

The purpose of this questionnaire is to identify the techniques and methodologies currently being used for planning and executing infrastructure projects. The content of the questionnaire will include construction planning and scheduling techniques, available software, existing construction methods for earthmoving operations, critical factors that affect productivity and other influencing factors. The availability of this information will help the researcher to uncover the issues involved to aid the development of a new software model intended to help project managers/planners to produce effective plans to improve the productivity and profitability of such construction projects.

This survey is being conducted as part of a research project at the University of Teesside and it is intended to identify current practices and problems for earthwork planning in the construction industries and ways to improve them through the utilisation of advanced visual planning techniques. Thank you in anticipation of your contribution towards this research project and you can be assured that your response will be treated in the strictest of confidence.

A. General Questions:

1. What is your principle type of infrastructure construction work?

- Road/Highway
- Railways
- Tunnelling
- Pipeline
- Others please specify.....

2. What is the value of projects you are involved in?

- Under £ 10 million
- £10-25 million

- £ 26- 50 million
- Over £ 50 million

B. Tender/Bidding Stage:

3. What is your company policy for developing the construction schedule?

- a. Develop schedule only when required by contract
- b. Develop schedule for all projects of the company
- c. Develop schedule only for some of the project
- d. Others:

4. What is the basis for the development of a construction schedule?

- a. Project cost
- b. Project Duration
- c. Complexity of job
- d. A+B contracts
- e. Other, please specify.....

5. How do you develop construction schedules for your company?

- a. One planner does the entire schedule.
- b. Two or more planners are responsible for developing schedule.
- c. Does your company use a consultant to develop the schedule?
- d. Other, please specify.....

6. How many of your projects finish late? -----% of total

7. Of those late projects, how many are late due to a schedule problem? ----% (of late projects)

8. What are the typical problems that cause delays in your construction projects?

- a. Poor construction planning
- b. Relation of utilities

- c. Contractors equipment
- d. Other, please specify.....

C. Detail Construction Planning and Scheduling Stage:

Please tick mark the following question according to their options:

- A** = *Always*
- B** = *Sometimes*
- C** = *As and when Necessary*
- D** = *Control Impaired as a Result*
- NE** = *No Experience*

9. What planning and scheduling methods are used in linear construction projects?

		A	B	C	D	NE
a.	Bar Chart					
b.	Critical path method (CPM)					
c.	Time-Location Chart					
d.	Hand Drawn on paper					
e.	Other, please specify					

10. What are the existing practices and techniques used during the development of detailed construction schedules in your company?

		A	B	C	D	NE
a.	Past experience					
b.	Intuitive method					
c.	Decision on site: thumb rule/random					
d.	Other, please specify					

11. What is the planning and scheduling software currently used in your company?

		A	B	C	D	NE
a.	Power Project					
b.	MS Project					
c.	Primavera (P3)					
d.	Sure Track					
e.	Linear schedule method (TILOS)					
f.	Other, please specify					

12. How often do you update construction schedules?

		A	B	C	D	NE
a.	Weekly					
b.	Bi-Weekly					
c.	Monthly					
e.	Other, please specify :					

13. What are the techniques used in earthwork planning?

		A	B	C	D	NE
a.	Mass haul diagram					
b.	What If – Scenarios:					
c.	Decision on site by experience					
d.	Commercial software like: DynaRoad /Inroad					
e.	Other, please specify					

14. At what stage, visualisation techniques such as (3D CAD + time) or virtual reality (VR) simulation for planning of construction process will be beneficial?

		A	B	C	D	NE
a.	Tender/bidding stage					
b.	Detail planning stage					
c.	At site operation level					
d.	Other, please specify					

15. Please rank the following question in order of priority (1-5, 1 less important and 5 most important)

a. How much are the following factors critical for earthwork planning in projects?

- Number of site access points
- Soil characteristics
- Method of construction
- Type of equipment availability
- Location of borrow pit/dump site
- Conditions of access roads
- Haulage distance

D. Practical Importance of a Visual schedule in Construction:

16. Please rank the following questions in order of priority (1-5, 5 most important, 1 less important):

In your opinion, how will the availability of visualisation techniques (such as automatic generation of road profile + time) rank in importance towards improving performance in relation to the following factors?

- Improve communication among stakeholder at site level
- Prior information of construction sequences
- To identify crew/equipment interface
- To assist for updating the schedules
- To reduce the waiting time for resources

17. What do you recommend to improve the current process of scheduling projects?

18. Linear scheduling is a location-based method of scheduling driven by production rate. Do you feel that a linear scheduling method would be useful to your company?

Please rank. (1= not useful and 5 very useful) 1, 2, 3, 4, 5

19. Please provide additional comments regarding the application and importance of visual scheduling in linear construction projects.

Thank you

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Appendix- C

Derivation of a mathematical equation

In road construction projects, typical cross-sections are similar to the ones depicted in figures C-1 and C-2 and have been considered for the derivation of a mathematical equation to calculate the weekly progress height of earthwork activity between intermediate stages during the construction processes. Other typical sections, which are rarely seen in real practice, have not been included in this research study. The assumptions made for the development of mathematical equation for two cases (a) and (b) are explained below.

Case (a) typical road cross-section in flat terrain

Figure c-1 shows a typical road cross-section, which is used regularly in road projects built on a flat terrain. This was selected to derive a mathematical equation for the calculation of earthwork progress height on a weekly or daily basis.

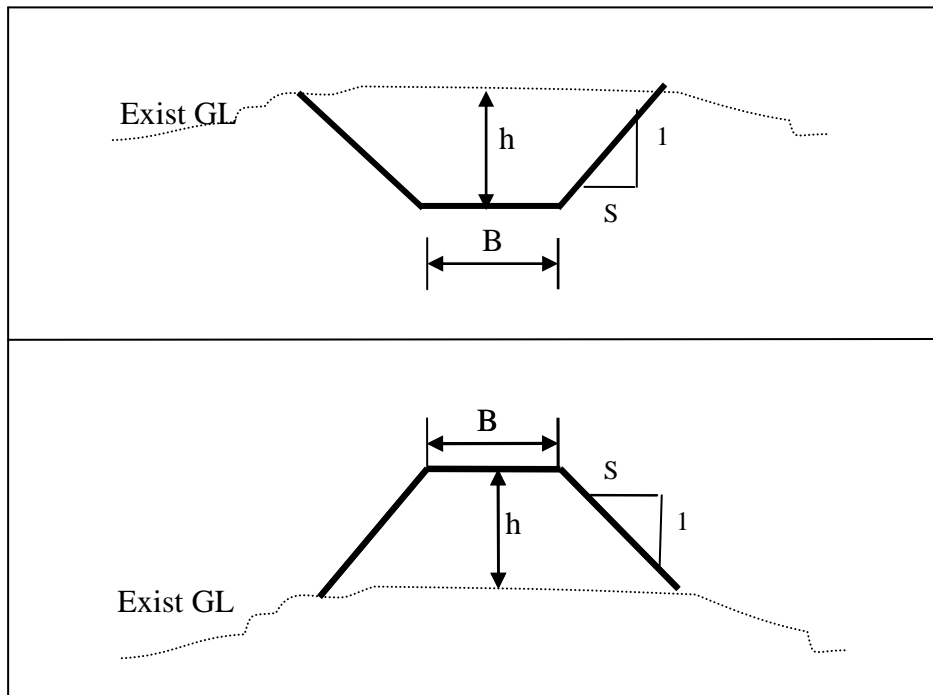


Figure C-1: Typical road cross-section for cutting and filling in flat terrain

During the derivation of a mathematical equation, the following assumptions were made:

- Typical cross-section for equation derivation was assumed as being a trapezoidal shape having side slope S: 1.
- A_i = Cross-sectional area of trapezoidal at section i. = $Bh_i + Sh_i^2$
- i = Number of section varies from ($i = 1 \dots \dots n$) along the road.
- S = Side slope
- B = Design width of road
- h = Height between existing ground level and design level at a road section.
- V_i = Volume of earthwork for cut/fill activities at section i
- L = Length between two sections.

$$A_i = \frac{V_i}{L}$$

$$Sh_i^2 + Bh_i + \left(\frac{V_i}{L}\right) = 0 \quad (1)$$

After deriving equation 1 as a quadratic equation, the equation for calculation of the progress height of the typical cross-section (h_i) was established as shown in equation 2. It is used to calculate earthwork progress height at each construction layer.

$$h_i = \frac{-B \pm \sqrt{(B^2 + 4SV_i/L)}}{2S} \quad (2)$$

Case (b) typical road cross-section with transverse slope

Another typical road cross-section, most commonly found in uneven terrain surfaces with a transverse slope, is shown in Figure C-2, and was used to derive the mathematical equation for height calculation along the road section.

The equations 4 and 5, which are found after the derivation of a quadratic equation for sectional volume of the typical section shown in Figure C-2 for the calculation of sectional area (A_i) and height of the section (h_i), are shown below:

$$A_i = \frac{V_i}{L} \quad (3)$$

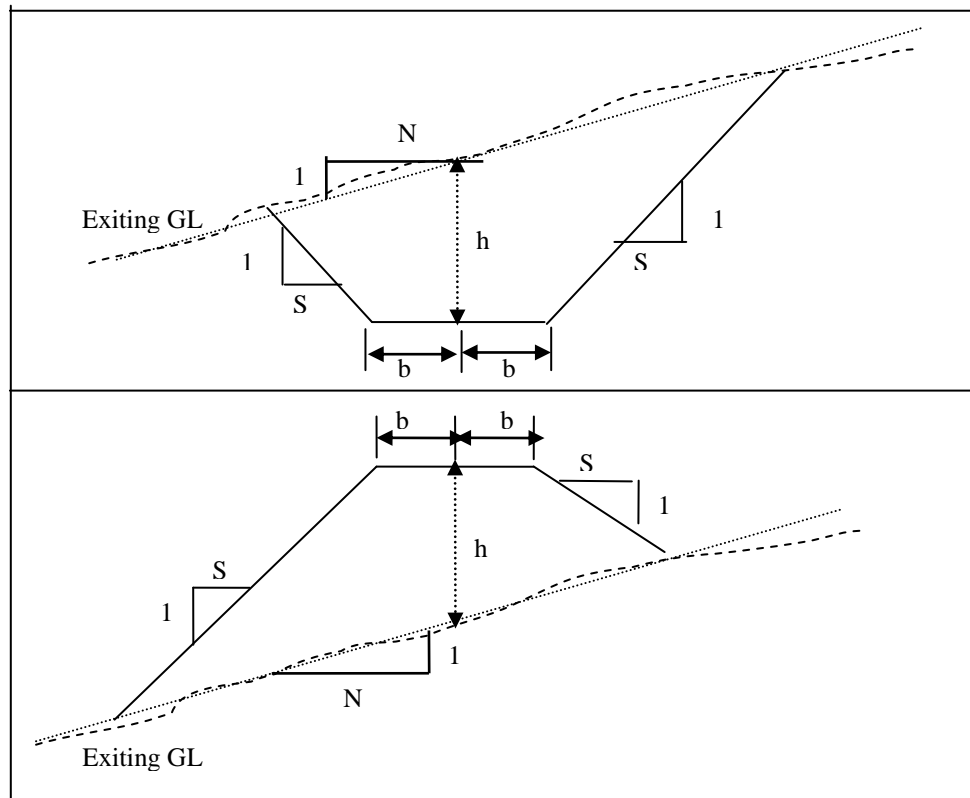


Figure C-2 typical road cross-sections of cutting and filling in slope terrain.

$$A_i = \frac{[b^2S + N^2h(2b + Sh)]}{(N^2 - S^2)} \quad (4)$$

Equation 5 can be obtained by equating equation 3 and 4, as shown below:

$$\frac{V_i}{L} = \frac{[b^2S + N^2h(2b + Sh)]}{(N^2 - S^2)} \quad (5)$$

After simplifying the above equation 5 as a quadratic equation for the calculation of height (h_i) in term of geometrical parameters including b , N , S and V_i , Equation 6 can be obtained, which is presented below.

$$h_i = -\left(\frac{b}{S}\right) \pm \left[\left(\frac{1}{S}\right) \sqrt{\left(\frac{V_i S}{L} + b^2\right) \times \left(1 - \frac{S^2}{N^2}\right)}\right] \quad (6)$$

Whereas:

- h_i = Height of cross-section at section i
- i = Number of section varies from ($i = 1, 2, 3, \dots, n$) along the road
- N = Transverse slope of existing ground Horizontal: Vertical ($N: 1$)
- S = Side slope of cross-section Horizontal: Vertical ($S: 1$)
- b = Half width of road section.
- V_i = Sectional volume of cut/fill activity at cross-section i
- A_i = Sectional area of cut/fill activity at cross-section i
- L = Length between two sections.

An example for the calculation of the height defined as the z -coordinate is illustrated below for a road project that was completed recently in Portugal.

Illustration of derived mathematical equation

Data for illustration is selected from lot no 3 of a road project in Portugal.

Assuming at a cross-section (i) is selected between chainage 0+025 ~ 0+050,

Volume (V_i) = - 2834.70 m³ (\pm) sign shows the cutting and filling volume

Side slopes $S: 1 = 1.5:1$

Width of road (B) = 26.1 m

Chainage interval (L) = 25 m

Using equation 2 shown above:

$$\text{Height } (h_i) = \frac{-B \pm \sqrt{(B^2 + 4SV_i/L)}}{2S}$$

In the above equation, only a positive sign is considered for the feasible value in this case.

$$h_i = \frac{-26.1 + \sqrt{(26.1)^2 + \frac{4 * 1.5 * 2834.70}{25}}}{2 * 1.5}$$

$$h_i = -8.39$$

Here, the negative value of height shows the height of the filling section and the positive value shows the cutting section. The following section describes the data generation process for the prototype model.

Appendix-D

Earthwork Optimisation

Introduction

This appendix presents the earthwork optimisation module (a component) of the prototype model. The optimisation of the allocation of earthwork quantities and haulage costs between cut and fill sections, fill from borrow pits or from cut to landfill sites is explained. The appendix explains the development processes involved in the cut-fill optimisation algorithm of the earthwork component in a road or railway project. The detailed processes for the development of a cut-fill optimisation algorithm are presented in the following sections.

Background to earthwork optimisation

At the planning stage of an earthwork component, basic managerial questions arise, for example: “how much earth should be moved from where to where?”, and “how the resource should be utilised more efficiently?” (Akay, 2004; Son et al, 2005). Construction managers and project planners require a systematic approach and innovative tools to address these issues. The industry survey revealed that construction practitioners commonly rely on heuristic knowledge, based on past experience, and less on a systematic approach. This appendix presents a new approach for solving the earthwork allocation problem. The approach is developed by integrating existing techniques: a mass haul diagram, a unit cost identified “RoadSim” simulator, and an Excel solver.

This section concentrates on the concepts and processes required for the development of the earthwork optimisation module. The objective of the module is to simplify the calculation of optimal haulage quantities, identify the movement direction, and state the minimisation of the total costs of the cut-fill assignments. Previous and existing research studies utilised many optimisation techniques in the earthwork planning for the cut-fill assignment; however, the determination of the suitability of any single optimisation

technique remains a complex task. Since earthwork allocation problems largely depend on haulage distance and the associated costs of transportation between cut and fill sections, this problem can be considered as a linear problem. Therefore, a linear programming (LP) optimisation technique was selected as a suitable methodology for solving the problems involved.

Previous studies in earthwork optimisation

A number of research studies have been conducted into solving the earthwork allocation problems of cut-fill assignments using LP optimisation technique. For example, Stark and Nicholls (1972) applied the LP technique to the allocation of earthwork between cut and fill sections in linear construction projects. Further studies were conducted into advancing the LP by several researchers including Mayer and Stark (1981), Nandgaonkar (1981), Essa (1987 and 1988), Alkass (1988), Jayawardane and Harris (1990), Akay (2004) and Son et al (2005), who considered different aspects for a cut-fill assignment of earthworks. The different aspects of earthwork optimisation methods which have been analysed by past researchers were discussed in Chapter 2.

Moreover, Yang et al (2010) developed a mathematical model to optimise a cut-fill assignment and division of a large road project into smaller sections for the construction phase. They have used LP to optimise allocation quantities and presented the results in a matrix table. The above studies revealed that the LP can provide an optimal solution for the allocation of earthwork quantities associated with a cut-fill assignment and that it also assists in determining the corresponding amount of earth mass to be hauled. They also highlighted that the LP is a useful method for identifying the optimum allocation of earthwork quantities by minimising the earthwork haulage cost. Taking into account the above points, LP is considered an appropriate optimisation technique to provide the necessary solution for a cut-fill assignment in earthwork operations. The next section discusses the concept and development of an algorithm for earthwork optimisation for the solution of cut-fill assignments in road projects.

Development of earthwork optimisation

This section describes the development of an algorithm for earthwork optimisation aimed at resolving the problem of earthwork allocation between cut and fill sections along a road section. The optimisation module was designed by integrating the mass haul diagram, “RoadSim” simulator, and Excel solver which is built within MS Excel using a Simplex algorithm. The data flow diagram of cut-fill algorithm has been used for understanding the earthwork optimisation process (see figure D-1).

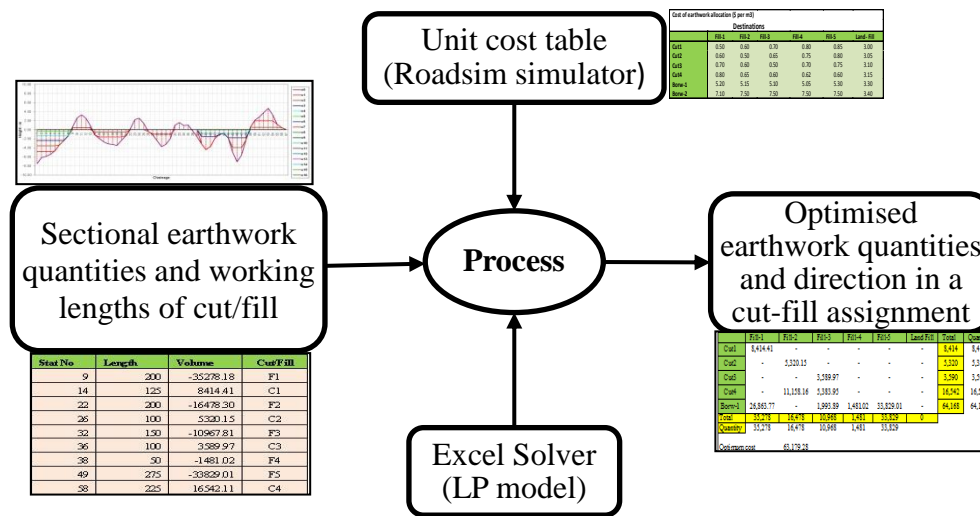


Figure D-1 Data flow diagram of cut-fill algorithm for earthwork optimisation

The inputs of the optimisation module – sectional quantities with the working length of cut and fill operations, and the unit cost table of earthworks – were generated within the model, and processed to obtain the optimised quantities of earthworks. A list of cut and fill sections with corresponding quantities was identified first and represented in a table (see Figure D-1).

Excel solver was utilised to optimise the quantities of earthwork allocation for a cut-fill assignment. The solver which is a built-in function of MS Excel based on a Simplex algorithm is widely used for solving linear optimisation problems. The unit cost of the earthwork movement is used as a decision coefficient and haulage quantities are

considered as decision variables in the LP model. The minimisation of the earthwork haulage cost is the objective function of the LP model. The unit cost of the earthwork allocation was calculated using the “RoadSim” simulator developed by Dawood and Castro (2009). The unit cost of the earthworks was determined by considering the types and horsepower of the construction equipment used for haulage operations, site working conditions, haulage distance and soil characteristics, along a road section.

In the optimisation module, a new algorithm was designed to automatically generate a matrix table as shown in Table D-1. The table represents the number of cuts, fills, borrows and landfills available in a road section with the respective quantities of each cut-fill section. The numbers of cut and fill sections with the respective working length of each section was identified first. Then, a table of the unit cost of earthwork allocation was developed for cut-fill assignments (see Table D-2).

The matrix table produced by the algorithm provides the information on optimum allocated quantities and direction of movement of earthworks in cut-fill assignments. The algorithm also determines the additional earthwork quantities needed to be borrowed from other sources or deposited at landfill sites (see Table D-1). The next section discusses the development of an algorithm for producing a matrix table for a cut-fill assignment in road projects.

Generation of a matrix table of cut-fill assignment

The objective of the algorithm is to generate a cut-fill matrix table including the information on borrows and landfills (see Table D-1). To develop the algorithm, the following assumptions were made.

A typical road section which shows cut and fill sections, two borrow pits and a landfill site was selected to formulate a cut-fill optimisation module (see Figure D-2).

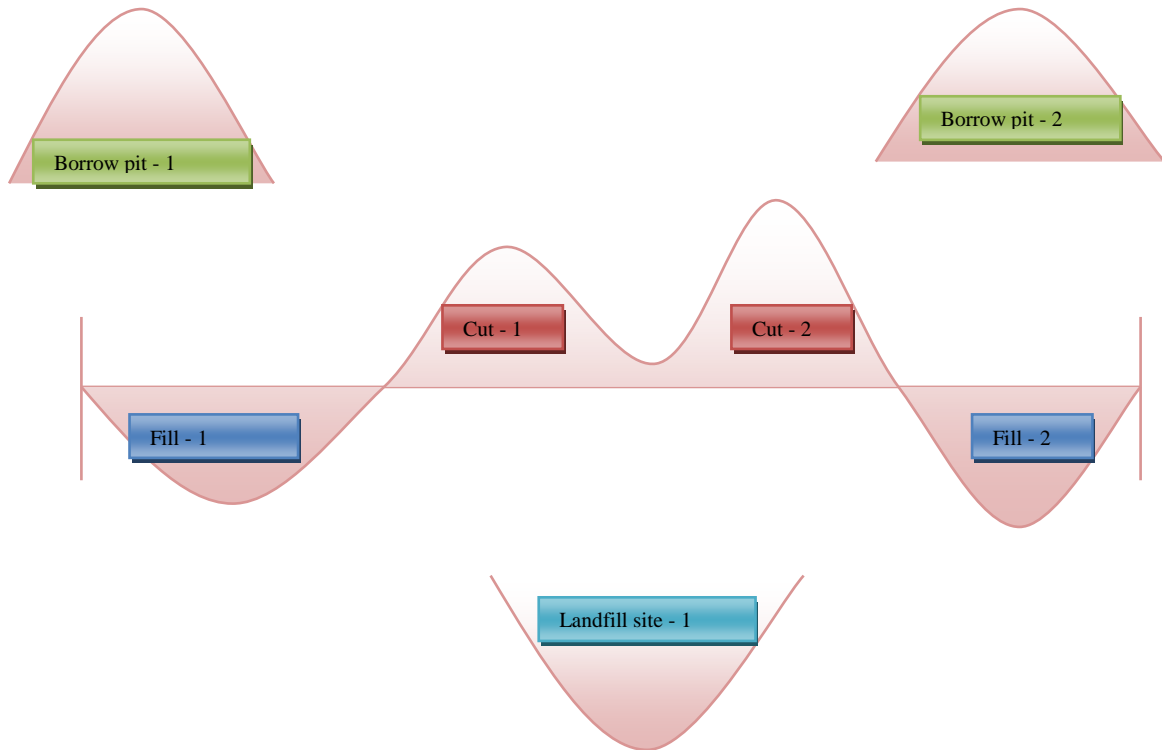


Figure D-2 Typical road section including cut-fill, borrow and landfill sections.

Referring to Figure D-2 above, it is assumed that the quantities of earth to be moved to fill sections (F_i) or deposited at a landfill section (K) from cut sections (C_j) are denoted by $X(i, j)$ and $X_{LF}(j)$ respectively. It is also assumed that the earthwork quantities to be moved from borrow pits (B_p) to fill sections (F_i) are denoted by $X_B(p, i)$, whereas (X_{ij}) , $X_B(p, i)$ and $X_{LF}(j)$ represent the decision variables of a linear optimisation equation for earthwork allocation (see Table D-1). The matrix table in a cut-fill assignment identifies the direction of earthwork movement between cut and fill sections more clearly with possible optimised quantities.

Moreover, it is assumed that the unit cost of haulage from a cut section (j) to a fill section (i) is given by $C(i, j)$, and from a cut section (j) to a landfill section (k) is given by $C_{LF}(k, j)$. Similarly, the unit cost of haulage for a unit quantity of earthwork from a borrow pit (p) to fill sections (F_i) is given by $C_B(p, i)$. The unit cost between different possible cut and fill sections was determined using the “RoadSim” simulator and it was considered as a decision coefficient in the optimisation equation.

Table D-1 shows earthwork quantities allocation between cut-fill sections

Matrix table of cut and fill sections including borrows and landfills						
Sources\Destinations	Fill-1 (F₁)	Fill-2 (F₂)	-	Fill-i (F_i)	Land Fill (LF)	Total (Qty)
Cut1 (C ₁)	X ₁₁	X ₁₂	-	-	X _{LF1}	XC ₁
Cut2 (C ₂)	X ₂₁	X ₂₂	-	-	X _{LF2}	XC ₂
-	-	-	-	-	-	-
-	-	-	-	-	-	-
Cut-J (C _j)	-	-	-	-	X _{LFk}	-
Borw-1 (B ₁)	X _{B11}	X _{B21}	-	-	-	-
Borw-2 (B ₂)	X _{B21}	X _{B22}	-	-	-	-
Total Quantity	XF ₁	XF ₂	XF ₃	-	-	-

Derivation of a linear optimisation equation

A mathematical equation of an objective function was developed for a road section showing two cutting and two filling sections in addition to two borrow pits and a landfill site as shown in Figure D-2. Following are the key assumptions made for the derivation.

Total volume of the cutting sections = XF_i ; where $i = 1, 2, 3, \dots, n$

Total volume of the filling sections = XC_j ; where $j = 1, 2, 3, \dots, n$

Similarly, for borrow pits and landfill having capacity of B_p and LF_k :

Total borrow pits volume = B_p ; whereas $B = 1, 2, 3, \dots, n$

Total landfill volume = LF_k ; whereas $LF = 1, 2, 3, \dots, n$

The objective function that minimises the total cost of embankment, excavation and haul is formulated as below:

$$Z = \sum_i \sum_j C(i, j) X(i, j) + \sum_i \sum_k C_{LF}(k, i) X_{LF}(k) + \sum_p \sum_j C_B(p, j) X_b(p, j) \quad (1)$$

The decision variables are $X(i, j)$, $X_{LF}(i, k)$, and $X_B(p, j)$ which are subjected to following five constraints:

- 1) Total quantities moved from cut sections to fill sections and landfill sites should be equal to total quantity available at cut section i , is T_i

$$\sum_j X(i, j) + \sum_k X_d(i, k) = T_i; \text{ where } i = 1, 2, 3, \dots, N_c \quad (2)$$

- 2) Total quantities moved from cut sections and borrow pits to fill sections should be equal to total quantity available at fill section j , is equal to F_j and S_{ij} is denoted for swelling factors of excavated quantities of cut and borrow pits.

$$\sum_j S_{ij} X(i, j) + \sum_j S_{pj} X_b(p, j) = F_j; \text{ where } j = 1, 2, 3, \dots, N_f \quad (3)$$

- 3) Total quantities moved to landfill k from all cut sections should be equal to or less than the landfill capacity D_k

$$\sum_k S_{ik} X_d(i, k) \leq D_k; \text{ where } k = 1, 2, 3, \dots, N_d \quad (4)$$

- 4) Total quantities moved from all borrow pits p to all fill sections should be equal to or less than the borrow pits capacity B_p ,

$$\sum_j X_b(p, j) \leq B_p; p = 1, 2, 3, \dots, N_b \quad (5)$$

- 5) Total quantities used from borrow pit p , x_p , should be equal to the sum of the quantities moved from these borrow pits to all fill sections,

$$X_p = \sum_j X_b(p, j) \quad (6)$$

- 6) Non-negativity restrictions

$$X(i, j), X_d(i, k), X_b(p, j) \text{ and } X_p \geq 0 \quad (7)$$

The unit cost of earthwork is a function of equipment productivity, haulage distance, working conditions and soil characteristics, which are the key factors that affect earthworks productivity and the unit cost of haulage throughout a road construction. The unit cost was calculated using the productivity and unit cost simulator of the “RoadSim”. The hourly cost of all types of construction equipment was calculated considering a life cycle cost, and stored in the “RoadSim” database (Castro, 2005). The unit cost of the earthwork was calculated by multiplying the unit hour cost of equipment

with the total time required for earthworks of a selected section using the productivity model of the simulator. The typical unit cost table is shown in Table D-2.

Table D-2 shows the unit cost of earthworks between cut-fill sections

Unit Cost of Earthworks (per m3)					
	Fill-1 (F ₁)	Fill-2 (F ₂)	-	Fill-i (F _i)	Land Fill (k)
Cut1 (C ₁)	C ₁₁	C ₂₁	-	C _{i1}	C _{LF1}
Cut2 (C ₂)	C ₁₂	C ₂₂	-	-	C _{LF2}
-	-	-	-	-	-
Cut-J (C _j)	C _{1j}	C _{2j}	-	C _{ij}	C _{LFk}
Borw-1 (B ₁)	C _{B11}	C _{B12}	-	C _{B1i}	
Borw-2 (B ₂)	C _{B21}	C _{B22}	-	C _{B2i}	

The algorithm was developed using VBA programming. The VBA was used to integrate Excel solver with the automatically generated cut/fill matrix table and a unit cost table. The total cost of the earthwork produced by the module includes the haulage cost of the cut to fill section, the cost of borrow quantities to fill sections, and any extra quantities needed to deposit in a landfill site from cut sections. The algorithm produces a matrix table that shows the optimised quantities of cut-fill sections using the unit cost data shown in Tables D-1 and D-2. The algorithm was integrated within the Excel solver. The algorithm determines the minimum earthwork cost using equation 1 above. The equation uses the optimum quantities shown in Table D-1 and the unit cost data shown in Table D-2 to calculate the minimum cost of earthwork in a cut-fill assignment.

The optimisation module outputs, i.e. optimum quantities and the movement direction, are represented in a matrix table of a road section. The table provides information on the movement of the earthwork quantities from one cut section to another fill section, borrow to fill, or cut to landfill. The impact on the earthwork cost was analysed by changing the direction of the haul of earthwork between the cut and fill sections in a cut-fill assignment. The next section demonstrates the functionality of the optimisation module.

Demonstration for earthwork optimisation function

A typical road section with a number of cut and fill sections was selected from a road project to demonstrate the optimisation functionality. The road section includes 4- cuts and 5-fill sections as shown in Figure D-3.

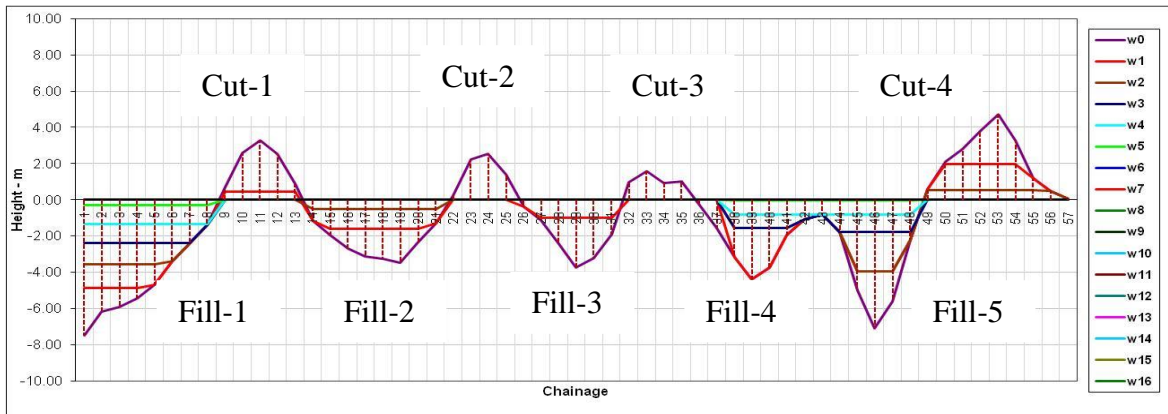


Figure D-3 Typical road profile including 4- cut and 5- fill sections

A mass haul diagram corresponding to the selected road section was developed (see Figure D-4). An access point algorithm was also developed using the mass haul diagram characteristics to identify the numbers of cut and fill sections of a selected road section with corresponding economical working length and respective earthworks quantities of each cut-fill sections (see Chapter 5).

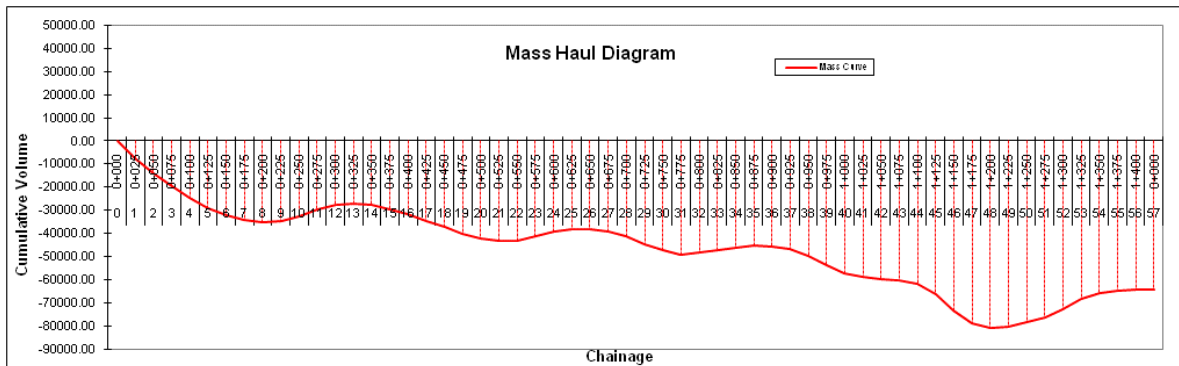


Figure D-4 Snapshot of a mass haul diagram generated by the model

The access point algorithm identified the station number with access points, working length and the volumes of each cut and fill section as shown in Figure D-5. A snapshot

of the interface of the optimisation module is also shown in Figure D-5. The module demonstrates the optimisation function of the prototype model for cut-fill assignments.

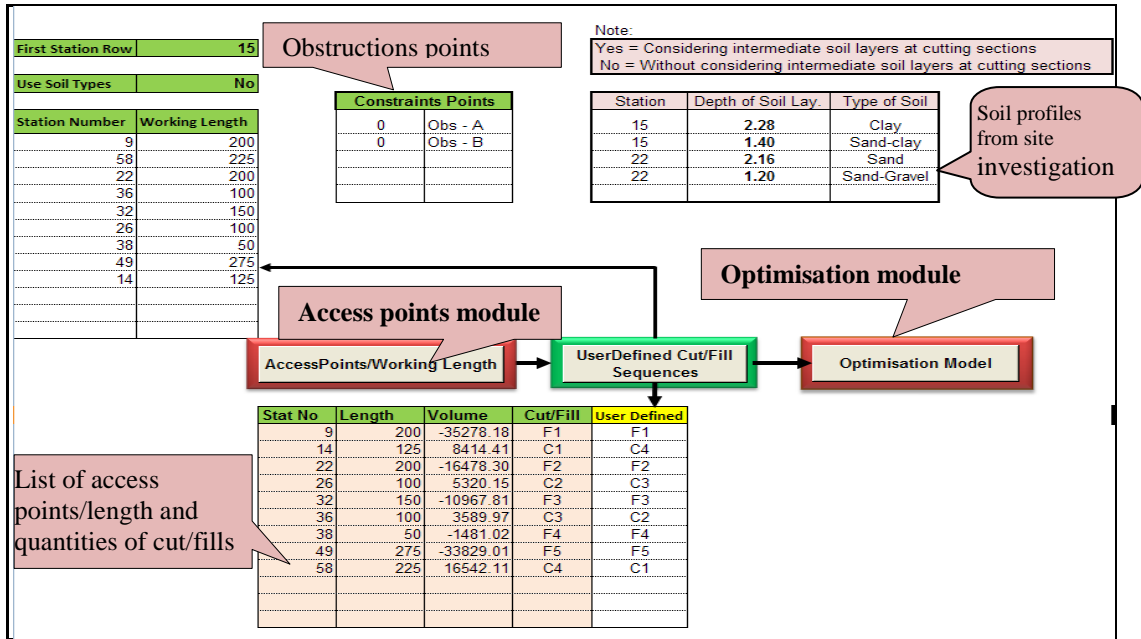


Figure D-5 Snapshot of interface with optimisation and access point module

The unit cost coefficient is a function of the equipment type, haulage distance, soil characteristics and working conditions. An average haulage distance of cut-fill sections of a road section (Figure D-3) was selected for the calculation of the unit cost of the earthworks. Option 2 of the “RoadSim” productivity module (Motor-scraper – cut/hauling) operation was selected for the movement of earthwork in the selected road section (see Figure D-6).

Figure D-6 Snapshot of productivity and cost calculation sub-module (Castro, 2005)

The average haulage distance between the cut and fill sections, or the fill from borrows or cut to landfill sites, was considered. Other variables were assumed constant for a road section. The unit cost of the earthwork for each cut-fill section was calculated using a unit cost sub-module of the “RoadSim” simulator. The calculated unit cost is listed and presented in Table 5.3.

Table 5.3 Unit cost table for the earthworks allocation of a road section

Unit Cost of Earthworks (£ per m3)						
	Destinations					
	Fill-1	Fill-2	Fill-3	Fill-4	Fill-5	Land- Fill
Cut1	0.82	0.81	2.19	3.19	4.00	4.00
Cut2	2.38	0.75	0.88	1.63	2.44	4.05
Cut3	3.63	2.00	0.63	0.38	1.19	4.10
Cut4	6.06	4.44	3.06	2.06	1.25	4.15
Borw-1	7.10	7.40	7.50	7.60	7.90	
Borw-2	9.10	9.50	9.60	9.80	9.90	

The algorithm produced a matrix table (see Table D-4) as the output of the optimisation module. This provides information on the optimised quantities and movement direction of earthwork between cut-fill sections, fill from borrow or cut to landfills, if required (see Table D-4 below).

Table D-4 Shows optimum earthwork quantities and direction of allocation

Number of cut and fill sections including borrows and landfills									
	Fill-1	Fill-2	Fill-3	Fill-4	Fill-5	Land Fill	Total Qty	Available Qty	
Cut1	-	8,414	-	-	-	-	8,414	8,414	
Cut2	-	5,320	-	-	-	-	5,320	5,320	
Cut3	-	-	-	3,590	-	-	3,590	3,590	
Cut4	-	-	-	-	16,542	-	16,542	16,542	
Borw-1	35,278	2,744	10,968	11,130	4,048	-	64,168	64,168	
Borw-2	-	-	-	-	-	-	0	0	
Total Qty	35,278	16,478	10,968	14,720	20,590	0			
Required Qty	35,278	16,478	10,968	14,720	20,590	0			
Total cost Earthworks	502,454.79								

The output of the earthwork optimisation module is shown a tabular form (see Table D-4). A graphical representation of the tabular information is developed and presented in Figure D-7 below.

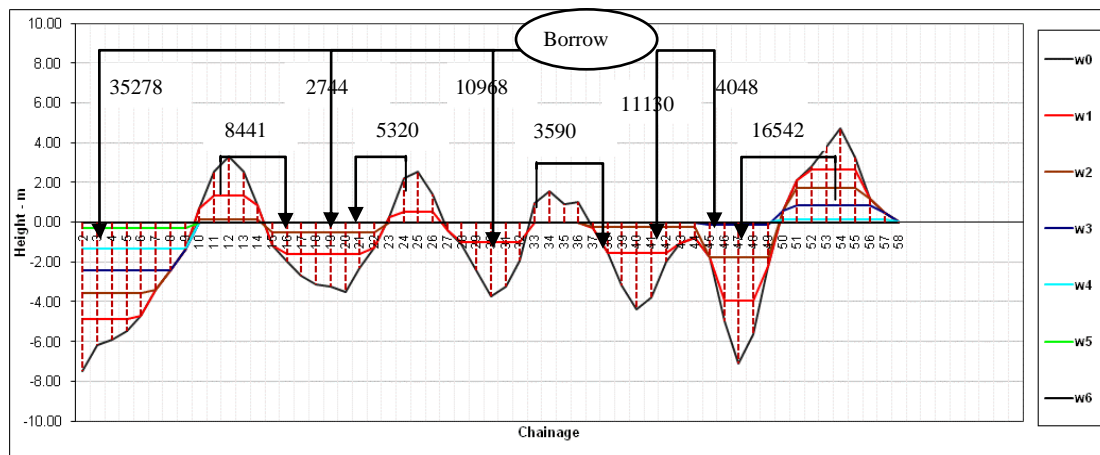


Figure D-7: Visual view of earthworks quantities and direction of allocation

Figure D-7 provides the visual information of earthwork allocation quantities and the direction of allocation for a cut-fill assignment. The optimisation result provides two key pieces of earthwork planning information in a cut-fill assignment of a road section:

- Optimised quantities of earthworks
- Movement directions between cut-fill sections

The visual representation of the earthwork allocation quantities and directions between cut-fill sections is a key output of the optimisation module. This is expected to assist construction managers in resource planning and in optimising the selection of a suitable set of equipment for earthwork operations. The output is also expected to aid the mobilisation of heavy construction equipment and exact quantities of materials at a required location, and, when necessary, throughout earthwork operations. The next section discusses the sensitivity reports produced by the earthwork optimisation module.

Sensitivity reports generated by the earthwork optimisation

The earthwork optimisation module also produces a sensitivity report. This report provides the information relating to a unit cost coefficient that can be reduced, without affecting the cost of the earthwork allocation in a cut-fill assignment. Cost reduction information on each option of cut-fill, borrow to fill, or cut to landfill section is provided by the sensitivity report. The report also provides the maximum allowable increase or decrease of unit cost between all possible cut-fill sections (see Table D-5). The optimisation module produces a constraint table showing the maximum limit of quantities for the cutting and filling sections (see Table D-6 below).

Table D-5 Sensitivity report of unit cost reduction for a cut-fill assignment

Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
Cut1 Fill-1	-	0.30	0.82	1E+30	0.3025
Cut1 Fill-2	8,414.41	-	0.81	0.3025	1E+30
Cut1 Fill-3	-	1.27	2.19	1E+30	1.275
Cut1 Fill-4	-	2.17	3.19	1E+30	2.175
Cut1 Fill-5	-	2.69	4.00	1E+30	2.688
Cut1 Land Fill	-	10.59	4.00	1E+30	10.588
Cut2 Fill-1	-	1.93	2.38	1E+30	1.925
Cut2 Fill-2	5,320.15	-	0.75	0.025	1E+30
Cut2 Fill-3	-	0.03	0.88	1E+30	0.025
Cut2 Fill-4	-	0.67	1.62	1E+30	0.675
Cut2 Fill-5	-	1.19	2.44	1E+30	1.188
Cut2 Land Fill	-	10.70	4.05	1E+30	10.700
Cut3 Fill-1	-	3.75	3.63	1E+30	3.750
Cut3 Fill-2	-	1.83	2.00	1E+30	1.825
Cut3 Fill-3	-	0.35	0.62	1E+30	0.3500
Cut3 Fill-4	3,589.97	-	0.38	0.350	1E+30

Cut3 Fill-5	-	0.51	1.19	1E+30	0.512
Cut3 Land Fill	-	11.33	4.10	1E+30	11.325
Cut4 Fill-1	-	5.61	6.06	1E+30	5.613
Cut4 Fill-2	-	3.69	4.44	1E+30	3.687
Cut4 Fill-3	-	2.21	3.06	1E+30	2.213
Cut4 Fill-4	-	1.11	2.06	1E+30	1.113
Cut4 Fill-5	16,542.11	-	1.25	1.1125	1E+30
Cut4 Land Fill	-	10.80	4.15	1E+30	10.8000
Borw-1 Fill-1	35,278.18	-	7.10	0.302	1E+30
Borw-1 Fill-2	2,743.74	-	7.40	1.825	0.02500
Borw-1 Fill-3	10,967.81	-	7.50	0.025	1E+30
Borw-1 Fill-4	11,130.17	-	7.60	0.675	0.3500
Borw-1 Fill-5	4,047.77	-	7.90	0.512	1.1125
Borw-1 Land Fill	-	-	0.00	10.588	0
Borw-2 Fill-1	-	2.00	9.10	1E+30	2.000
Borw-2 Fill-2	-	2.10	9.50	1E+30	2.100
Borw-2 Fill-3	-	2.10	9.60	1E+30	2.100
Borw-2 Fill-4	-	2.20	9.80	1E+30	2.200
Borw-2 Fill-5	-	2.00	9.90	1E+30	2.000

Table D-6 Shows the quantities of cut and fill sections with available constraints.

Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
Total Fill-1	35,278	7.10	35278.18	0	35278.18
Total Fill-2	16,478	7.40	16478.30	0	2743.74
Total Fill-3	10,968	7.50	10967.81	0	10967.81
Total Fill-4	14,720	7.60	14720.14	0	11130.17
Total Fill-5	20,590	7.90	20589.88	0	4047.77
Total Land Fill	0	0.00	0.00	0	0
Cut1 Total	8,414	-6.59	8414.41	2743.74	0
Cut2 Total	5,320	-6.65	5320.15	2743.74	0
Cut3 Total	3,590	-7.22	3589.97	11130.17	0
Cut4 Total	16,542	-6.65	16542.11	4047.77	0
Borw-1 Total	64,168	0.00	64167.68	1E+30	0
Borw-2 Total	0	0	0	0	0

Appendix- E

Snapshot of Earthwork Operations and Site visits

Following are a few examples of typical earthwork operations with heavy construction equipment; see Figures E-1, E-2, E-3 and E-4 below.



Figure E-1: Bulldozer excavating and spreading earthwork



Figure E-2: Compacting roller



Figure E-3: Earthwork backfilling, loading and compacting operations



Figure E-4: Earthwork excavation and loading operation



Figure E-5: Earthwork compaction on shoulder of bypass road in Middlesbrough



Figure E-6: Site visit of earthwork construction for a bypass road in Middlesbrough

Appendix- F Evaluation Questionnaire Form

(Response: 1)

This evaluation questionnaire form has been designed to assist in the evaluation of prototype model functionality, including the time-location plan and space congestion plan. Open questions have been used to collect general opinions and views from construction professionals regarding the prototype functions. Please give your views wherever possible.

Evaluator Details
What is your name? <i>Hayden Green</i>
What is your work position? <i>Project Manager, Balfour Beatty Civil Engineering Ltd.</i>
Briefly, what are your professional responsibilities? <i>Control and planning of construction projects (Roads: £3-15 million)</i>
A. Benefits of earthwork modelling, time-location plan and space congestion in earthwork planning and simulation
1) What do you think of the overall prototype model and time-location plan as a strategic decision support planning system?
<i>The prototype model is very useful in presenting visually the implication of different equipment. Thus very useful in support of initial strategic decisions at planning.</i>
2) In which way could the system add value and enhance the construction planning process?
<i>The system may be able to add value in the contractor planning to enable planners to optimise the use of plant. In the UK, most contractors will have a limited number of excavators and dump trucks etc. They will not have a large fleet to call up and so must use what equipment they have.</i>
3) How do you find the system as a communication tool among the project team?
<i>Visually the system is very good as a communication to all. However, the planner/input data may be more complicated to set up initially.</i>

4) How the actual information of location and time would benefit the planners and construction managers to manage the resources and site constraints?
<i>This information is useful, but is limited in the UK as contractors may not have a large fleet to call upon in order to change equipment as work progresses on weekly basis.</i>
5) Could you elaborate on the space congestion identification system assist to the planning and mobilisation of construction equipment along the construction site? How realistic is it?
<i>In the UK, most contractors will rely on the foreman to control the size and number of equipment at any given point in time. The size of earthwork construction projects in the UK tends to be small and readily controllable by 1 or 2 foremen; therefore, the planning and mobilisation output is of limited use to the UK earthwork market.</i>
6) Could you elaborate on any cost saving or any potential benefits from the system?
<i>The cost saving/benefits demonstration are applicable to contractors with a large fleet of equipment. There are only one or two such earthworks contractors in the UK, i.e. Blackwell and Colton. The potential benefits of this system are more suitable or applicable to other part of the world or European markets.</i>
7) Are there any barriers from using prototype model (people, technology)?
<i>The system would need operators who are familiar with computers and who use computers regularly. In the UK most foremen who control fleet/plant are not computer trained and don't like using computers. Other members of staff would have to input data, make changes and then pass the results to the foreman. The visual output is very good and would help to show the foreman why decisions have been made, which would be very useful.</i>

Thank you for your time

Return Address: Email: r.k.shah@tees.ac.uk

Centre for Construction Innovation and Research (CCIR) / School of Science and Engineering, Teesside University, Tees Valley, Middlesbrough, UK, TS1 3BA

Evaluation Questionnaire Form (Response - 2)

This evaluation questionnaire form has been designed to assist in the evaluation of prototype model functionality including the time-location plan and space congestion plan. Open questions have been used to collect general opinions and views from construction professionals regarding the prototype functions. Please give your views wherever possible.

<i>Evaluator Details</i>
What is your name? <i>Jess Yates</i>
What is your work position? <i>Contracts Manager, C A Blackwell (Contracts) Limited</i>
Briefly, what are your professional responsibilities? <i>Tender Planning and Costing</i>
A. Benefits of Earthwork modelling, time-location plan and space congestion in earthwork planning and simulation:
1) What do you think of the overall prototype and time-location plan as a strategic decision support planning system?
<i>I think that the overall prototype and time-location plan will be extremely useful as a strategic support planning system on complex linear projects with multiple cuttings and embankments (e.g. road projects and rail projects), to optimise the earthworks movements.</i>
2) In which way could the system add value and enhance the construction planning process?
<i>In particular, it should provide greater accuracy in establishing the cut/fill balance points on these linear projects and where the surpluses or deficits of material will occur such that measures can then be planned to either accommodate the surplus or make good the deficit.</i>
3) Do you find the system to be useful as a communication tool amongst the project team?
<i>I think that as a communication tool amongst the project teams provides a useful and graphic way of explaining the planned earthworks movements.</i>

4) How will the actual information of location and time benefit planners and construction managers in managing resources and site constraints?
<i>It should allow the resources to be managed more efficiently so as to try and eliminate either high peaks or low troughs in resource demand so as to provide a more even and well-balanced plant requirement.</i>
5) Could you comment on the space congestion identification system in relation to how it assists in the planning and mobilisation of construction equipment along the construction site? How realistic is it?
<i>Space congestion identification has significant implications from a health and safety point of view and this system will allow greater focus to be placed on how best to manage these congested areas in order to mitigate the risks that are associated with space congestion in such areas.</i>
6) Could you elaborate on any cost saving or any potential benefits from the system?
<i>The efficient movement of material will also be the most cost-effective movement of that material. The most important aim on linear projects is to eliminate the “cross-hauling” of material, i.e. the inefficient movement of material beyond the cut/fill balance point such that at a later date material has to be “cross-hauled” an even greater distance in the opposite direction.</i>
7) Are there any barriers that may prevent the use of the prototype model system (people, technology)?
<i>I think it’s a question of finding the right project for this prototype model which as mentioned earlier will be of particular use on any linear projects. If the High Speed 2 Rail projects get the go ahead or major road projects then I can see this system having great benefit in the management of their materials.</i>

Thank you for your time.

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Appendix-G

Verification of the developed mathematical equation

This section presents the verification process of a mathematical equation. The equation which has been derived in this study for the generation of weekly progress quantities and location-based schedules is shown below:

$$V_r = [\{\sum_{i=1}^{i=n} (V_i) - P\}/n] \quad (7)$$

Whereas,

n = number of stations selected by an algorithm for a layer along a cut/fill section,

V_r = the remaining volume after progress at a layer and each station,

V_i = sectional volume of earthwork at each station, $i = 1, 2, 3, \dots, n$

r = number of construction layers at each station of a cut/fill section, $r = 1, 2, 3, \dots, t$

$p = (p_c/p_f)$ represents productivity of earthwork activity according to cut/fill section.

For the verification of equation number 7, a 1.0 km section from a road construction project in Portugal was selected. A longitudinal profile of the selected road section shows the depth of both cutting and filling sections at each station at an interval of 25 m (Figure G-1). The cross-section of the road was considered as a trapezoidal shape with side slopes (1.5: 1) and road width (30m) for the demonstration of the section volume calculation. Then the sectional volume at each station of earthwork was calculated using the “average end-area” method (see Table G-1).

According to Warren (1996), a mass profile of earthwork of a road section was developed by calculating the sectional volume at each station along the road section (see Figure G-2). Figure G-2 includes a cut and two fill sections with a total of 41 stations (chainage points) at an equal interval of 25 m. The stations from 1 to 11 and from 26 to 42 represent fill sections, whereas the stations from 12 to 25 represent a cut section of the road section. The sectional volume of earthwork between stations 1 and 2 is represented at station 2. Similarly, the sectional volume of cut and fill sections are represented at each station along the road section (see Figure G-2). The mass profile was

used for the derivation of a basic mathematical equation. This derivation process is discussed in the next section.

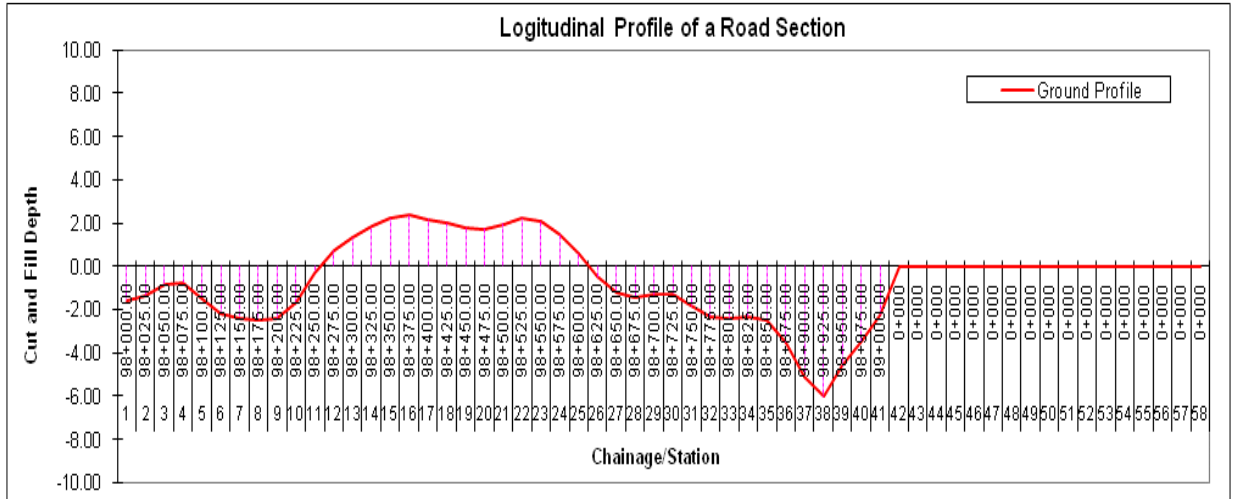


Figure G-1 Longitudinal profiles of a road section selected from a road project

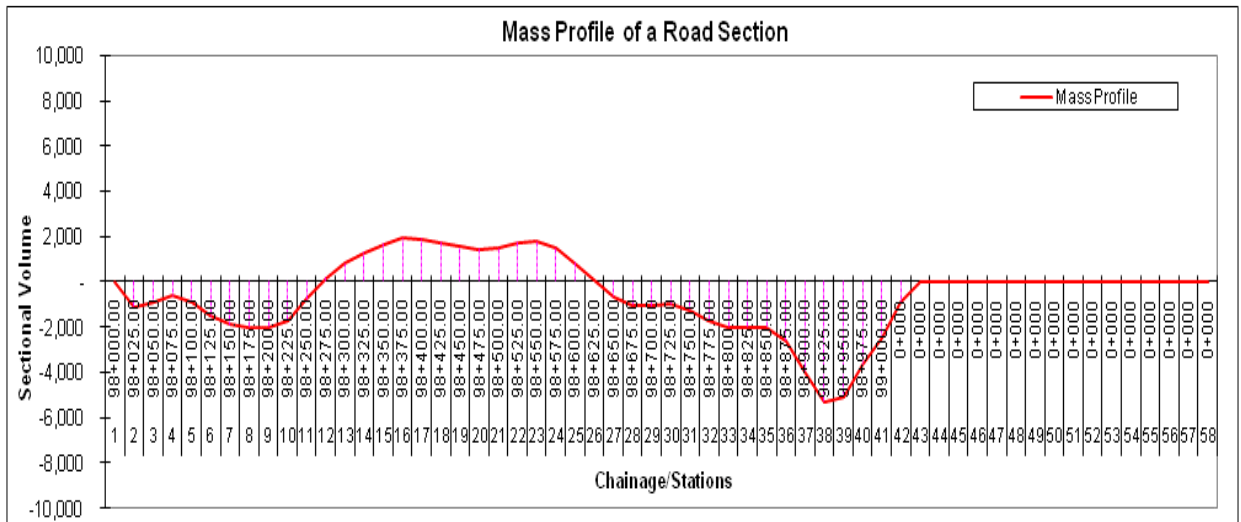


Figure G-2 Mass profile of earthwork of a road section shown in Figure G-1

Table G-1 Sectional volume calculation at each station of a road shown in Figure G-1

S N	Activity	Interval (L)	Existing G. L.	Design Level	Side Slope (s)	Depth of Fill/Cut (-/+)	Width of Road (B)	Sectional Area	Average Sectional Area	Sectional Volume
1	98+000.00	25	461.94	463.50	1.50	-1.56	30.00	-50.45	0.00	-
2	98+025.00	25	462.07	463.40	1.50	-1.33	30.00	-42.55	-46.50	- 62.55
3	98+050.00	25	462.57	463.43	1.50	-0.86	30.00	-26.91	-34.73	- 868.28
4	98+075.00	25	462.83	463.58	1.50	-0.75	30.00	-23.34	-25.13	- 628.16
5	98+100.00	25	462.35	463.86	1.50	-1.51	30.00	-48.72	-36.03	- 900.80
6	98+125.00	25	462.11	464.26	1.50	-2.15	30.00	-71.43	-60.08	-1,501.92
7	98+150.00	25	462.40	464.79	1.50	-2.39	30.00	-80.27	-75.85	-1,896.27
8	98+175.00	25	462.99	465.44	1.50	-2.45	30.00	-82.50	-81.39	-2,034.65
9	98+200.00	25	463.78	466.22	1.50	-2.44	30.00	-82.13	-82.32	- ,057.93
10	98+225.00	25	465.39	467.04	1.50	-1.65	30.00	-53.58	-67.86	-1,696.43
11	98+250.00	25	467.59	467.87	1.50	-0.28	30.00	-8.52	-31.05	- 776.27
12	98+275.00	25	469.41	468.69	1.50	0.72	30.00	22.38	6.93	173.25
13	98+300.00	25	470.85	469.52	1.50	1.33	30.00	42.55	32.47	811.64
14	98+325.00	25	472.19	470.35	1.50	1.84	30.00	60.28	51.42	1,285.40
15	98+350.00	25	473.38	471.17	1.50	2.21	30.00	73.63	66.95	1,673.81
16	98+375.00	25	474.35	472.00	1.50	2.35	30.00	78.78	76.20	1,905.12
17	98+400.00	25	475.01	472.83	1.50	2.18	30.00	72.53	75.66	1,891.40
18	98+425.00	25	475.62	473.65	1.50	1.97	30.00	64.92	68.72	1,718.12
19	98+450.00	25	476.27	474.47	1.50	1.80	30.00	58.86	61.89	1,547.27
20	98+475.00	25	476.92	475.21	1.50	1.71	30.00	55.69	57.27	1,431.83
21	98+500.00	25	477.78	475.84	1.50	1.94	30.00	63.85	59.77	1,494.14
22	98+525.00	25	478.59	476.36	1.50	2.23	30.00	74.36	69.10	1,727.56
23	98+550.00	25	478.88	476.79	1.50	2.09	30.00	69.25	71.81	1,795.14
24	98+575.00	25	478.60	477.11	1.50	1.49	30.00	48.03	58.64	1,466.03
25	98+600.00	25	477.90	477.32	1.50	0.58	30.00	17.90	32.97	824.18
26	98+625.00	25	476.94	477.43	1.50	-0.49	30.00	-15.06	1.42	35.56
27	98+650.00	25	476.25	477.44	1.50	-1.19	30.00	-37.82	-26.44	- 661.05
28	98+675.00	25	475.94	477.34	1.50	-1.40	30.00	-44.94	-41.38	-1,034.55
29	98+700.00	25	475.85	477.14	1.50	-1.29	30.00	-41.20	-43.07	-1,076.70
30	98+725.00	25	475.62	476.87	1.50	-1.25	30.00	-39.84	-40.52	-1,013.00
31	98+750.00	25	474.79	476.61	1.50	-1.82	30.00	-59.57	-49.71	-1,242.65
32	98+775.00	25	474.06	476.41	1.50	-2.35	30.00	-78.78	-69.18	-1,729.40
33	98+800.00	25	473.88	476.32	1.50	-2.44	30.00	-82.13	-80.46	-2,011.43
34	98+825.00	25	474.02	476.33	1.50	-2.31	30.00	-77.30	-79.72	-1,992.93
35	98+850.00	25	473.97	476.44	1.50	-2.47	30.00	-83.25	-80.28	-2,006.94
36	98+875.00	25	473.14	476.66	1.50	-3.52	30.00	-124.19	-103.72	-2,592.96

37	98+900.00	25	471.91	476.99	1.50	-5.08	30.00	-191.11	-157.65	-3,941.19
38	98+925.00	25	471.38	477.41	1.50	-6.03	30.00	-235.44	-213.28	-5,331.89
39	98+950.00	25	473.35	477.95	1.50	-4.60	30.00	-169.74	-202.59	-5,064.77
40	98+975.00	25	475.09	478.58	1.50	-3.49	30.00	-122.97	-146.36	-3,658.88
41	99+000.00	25	477.09	479.32	1.50	-2.23	30.00	-74.36	-98.66	-2,466.62
42	0+000	25	0.00	0.00	1.50	0.00	30.00	0.00	-37.18	- 929.49

Illustration for equation 7 is shown below:

$$V_r = [\{\sum_{i=1}^{i=n} (V_i) - P\}/n] \quad (7)$$

The equation 7 was underpinned within the algorithm developed for the prototype model, which assists to generate automatically the weekly progress quantities and working locations information of earthwork operations along a road section. The weekly progress quantities of earthworks generated by the model along a road section are shown in Table 2, whereas the weekly information of locations generated by the model is presented in Table 3 below.

Considering figure G-2, the weekly progress quantities of earthworks are calculated for week 1 along the selected cut and fill section of a road. A cut section from stations 12-21 (250m) and a fill section from stations 1 to 11 (250m) were designated for the illustration for the calculation of weekly progress quantities (Figure G-3). The selected number of stations where progress occurred at each week is determined by the algorithm (see Figures 4.5a and 4.5b in Chapter 4). The weekly productivity of cutting and filling operations were determined using the “RoadSim” simulator, where a number of factors such as different sets of equipment, soil characteristics and site working conditions were considered for both cutting and filling operations in a road construction project (Figure 8.3 in Chapter 8).

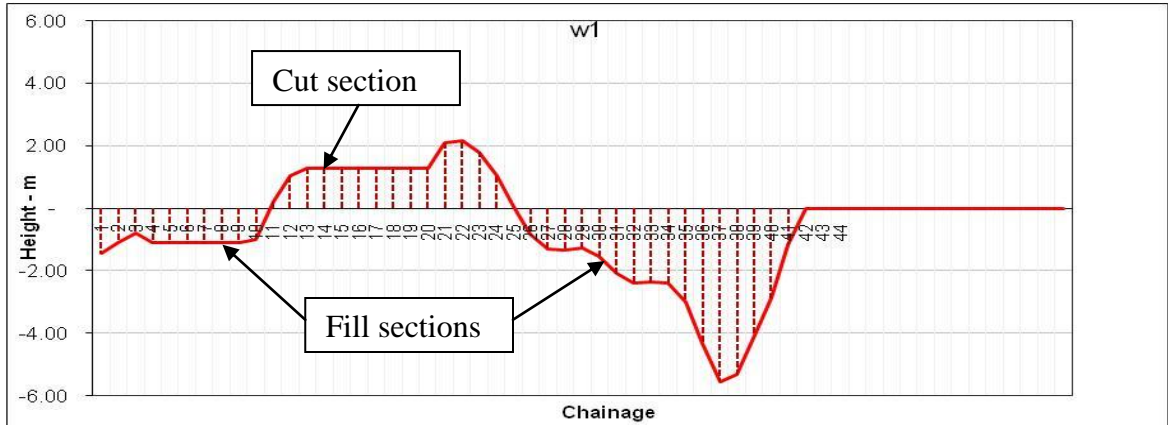


Figure G-3 Weekly progress profiles at the end of week 1 of the road section

For the fill section from stations 1-11 (see Figure G-3)

a) Earthwork progress of fill section from stations 5 to 10 at week 1 (Table G-2),

The total number of the selected stations from 5 to 10 (n) = 6.

Weekly productivity of the filling operation was determined using “RoadSim” and assuming a suitable set of equipment and site conditions. Hence, the filling productivity (P) = 4847.00 m³/wk.

V_i represents the sectional volume from stations 5 to 10.

$$\text{Total volume } (V_{5-10}) = V_5 + V_6 + V_7 + V_8 + V_9 + V_{10}$$

$$\text{Total volume of earthwork from stations 5 to 10 } (V_{5-10}) = 10088.00 \text{ m}^3$$

$$\begin{aligned} \text{The remaining volume at the end of week 1 } (V_r) &= [(10088.00 - 4847.00) / 6] \\ &= 873.50 \text{ m}^3 \end{aligned}$$

b) Progress at week 2 of the fill section from station 2-11 (see Table G-2),

The total number of selected stations from 2 to 11 in the cut section (n) = 10

$$\text{The total sectional volume of earthwork from stations 2 to 11 } (V_{2-11}) = 8676.26 \text{ m}^3$$

Weekly productivity of filling determined by “RoadSim” (P) = 4847.00 m³/wk

Hence, the remaining volume at each station after progressing at week 2,

$$V_r = [8676.26 - 4847.00] / 10 = 382.93 \text{ m}^3$$

- c) **Progress at week 3 of the fill section from station 2-11 (see Table G-2),**
 Since the total remaining volume at all stations of the fill section is less than the weekly productivity, the earthwork progress will be completed at week 3. Hence, the total weekly progress quantity at week 3 from stations 2 to 11 (V_{2-11}) = 3829.30 m³ which is less than the weekly productivity (4847.00 m³/wk).

For the cut section from 12-21 (see Figure G-3)

- a) **Earthwork progress of cut section from stations 14-21 at week 1 (Table G-2),**

A total number of the selected stations from 14 to 21 (n) = 8.

Weekly productivity of cutting determined by RoadSim (P) = 4847.00 m³/wk

Total volume (V_{14-21}) = $V_{14} + V_{15} + V_{16} + V_{17} + V_{18} + V_{19} + V_{20} + V_{21}$

Using the values of each station, total volume (V_{14-21}) = 12947.09 m³

The remaining volume (V_r) = $[(12947.09 - 4847.00) / 8] = 1012.51 \text{ m}^3$

- b) **Earthwork progress at week 2 from station 13-21 (Table G-2),**

Total number of selected stations from 13 to 21 in the cut section (n) = 9

Remaining volume of earthwork from stations 13 to 21 $V_{(13-21)} = 8911.73 \text{ m}^3$

Weekly productivity of cutting determined by “RoadSim” (P) = 4847.00 m³/wk

Hence, the remaining volume at each station after progressing at week 2,

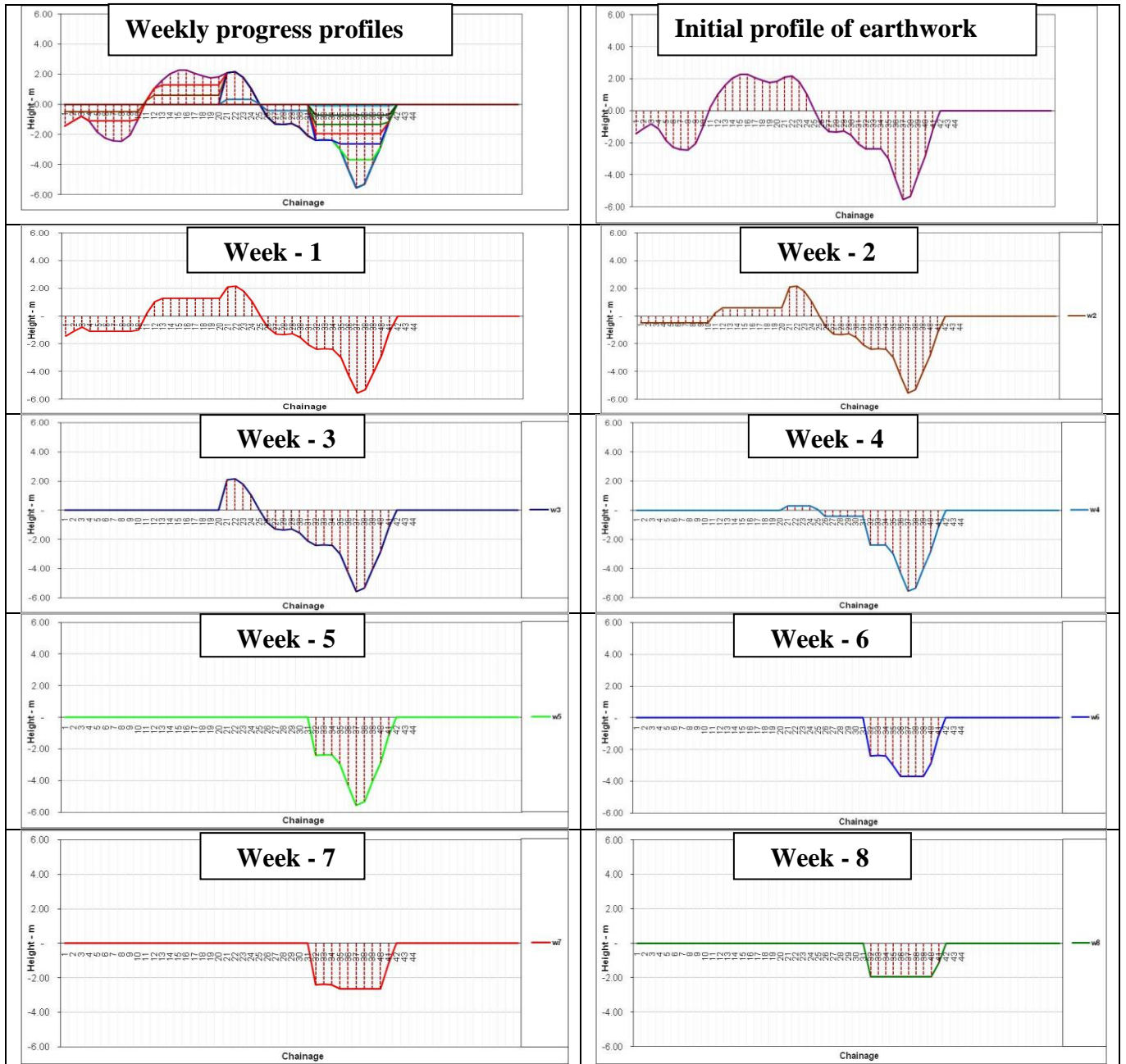
$V_r = [8911.73 - 4847.00] / 9 = 451.64 \text{ m}^3$

- c) **Earthwork Progress at week 3 from stations 12-21 (Table G-2),**

Since the total remaining volume at all stations of the fill section is less than weekly productivity, the earthwork progress will be completed at week 3. Hence, the total weekly progress quantity at week 3 (V_{12-11}) = 4237.98 m³ which is less than weekly productivity (4847.00 m³/wk).

Similarly, the weekly progress quantities at all remaining stations along the road section are calculated. The weekly progressed quantities of cut-fill section are presented in Table G-2 below. The weekly progress profiles of the road section produced by the prototype model using one set of construction equipment for earthwork operations are

shown in Figure G-4 below, to show how the earthwork profiles change in respect to time.



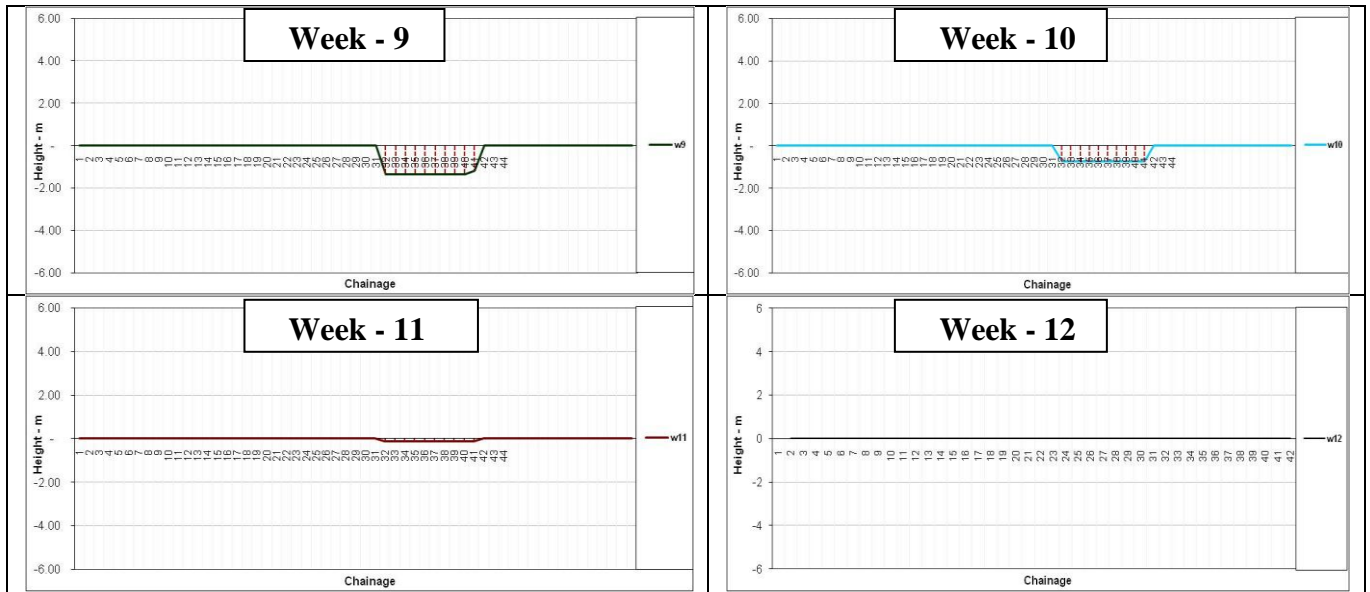


Figure G-4 Weekly progress profiles generated by the prototype model of a road section

Moreover, the allocation of cut-fill quantities and the movement direction was first determined by the optimisation module (Chapter 5) before generating a time-location plan. A demonstration of the optimisation module was performed with a road section (Chapter 8). The results of optimised cut-fill quantities and the allocation directions are presented in Figure G-5 below.

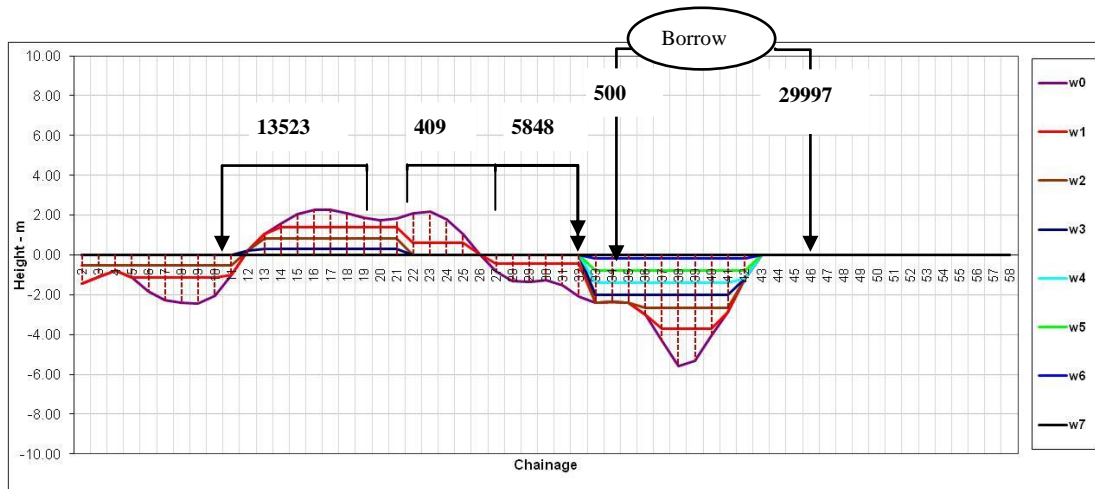


Figure G-5 Graphical views of optimised cut-fill quantities and the movement direction

Table G-2 Weekly progress quantities of earthwork generated by a prototype model developed during the course of study

Cut/Fill section	S. N	Chainage Points	Chainage Interval	Sectional Volume	Week-1	Week-2	Week-3	Week-4	Week-5	Week-6	Week-7	Total Weekly Qty (m3)
					Progress Qty.	Progress Qty.	Progress Qty.	Progress Qty.	Progress Qty.	Progress Qty.		
Fill section - 1	1	98+000.00	0	0	0							
	2	98+025.00	25	-1162.55	0.00	-779.62	-382.93					
	3	98+050.00	25	-868.28	0.00	-485.36	-382.93					
	4	98+075.00	25	-628.16	0.00	-245.24	-382.93					
	5	98+100.00	25	-900.80	-27.30	-490.57	-382.93					
	6	98+125.00	25	-1501.92	-628.42	-490.57	-382.93					
	7	98+150.00	25	-1896.27	-1022.77	-490.57	-382.93					
	8	98+175.00	25	-2034.65	-1161.15	-490.57	-382.93					
	9	98+200.00	25	-2057.93	-1184.43	-490.57	-382.93					
	10	98+225.00	25	-1696.43	-822.93	-490.57	-382.93					
	11	98+250.00	25	-776.27	0.00	-393.34	-382.93					
	Sub total	250	-13523.26	-4847.00	-4847.00	-3829.26						-13523.26
Cut Section - 1	12	98+275.00	25	173.25	0.00	0.00	173.25					
	13	98+300.00	25	811.64	0.00	360.00	451.64					
	14	98+325.00	25	1285.40	272.88	560.88	451.64					
	15	98+350.00	25	1673.81	661.29	560.88	451.64					
	16	98+375.00	25	1905.12	892.61	560.88	451.64					
	17	98+400.00	25	1891.40	878.89	560.88	451.64					
	18	98+425.00	25	1718.12	705.61	560.88	451.64					
	19	98+450.00	25	1547.27	534.75	560.88	451.64					
	20	98+475.00	25	1431.83	419.31	560.88	451.64					
	21	98+500.00	25	1494.14	481.63	560.88	451.64					
	Sub total	250	13931.98	4847.00	4847.00	4237.98						13931.98
	22	98+525.00	25	1727.56	1486.08	241.48						

Cut Section - 2	23	98+550.00	25	1795.14	1553.66	241.48						
	24	98+575.00	25	1466.03	1224.55	241.48						
	25	98+600.00	25	824.18	582.71	241.48						
	26	98+625.00	25	35.56	0.00	35.56						
		Sub total	125	5848.47	4847.00	1001.47						5848.47
Fill Section - 2	27	98+650.00	25	-661.05	-342.66	-318.39						
	28	98+675.00	25	-1034.55	-716.16	-318.39						
	29	98+700.00	25	-1076.70	-758.31	-318.39						
	30	98+725.00	25	-1013.00	-694.60	-318.39						
	31	98+750.00	25	-1242.65	-924.26	-318.39						
	32	98+775.00	25	-1729.40	-1411.01	-318.39						
		Sub total	150	-6757.36	-4847.00	-1910.36						-6757.36
Fill Section - 3	33	98+800.00	25	-2011.43	0.00	0.00	-397.36	-538.56	-499.30	-484.70	-91.51	
	34	98+825.00	25	-1992.93	0.00	0.00	-378.86	-538.56	-499.30	-484.70	-91.51	
	35	98+850.00	25	-2006.94	0.00	0.00	-392.88	-538.56	-499.30	-484.70	-91.51	
	36	98+875.00	25	-2592.96	0.00	-365.91	-612.98	-538.56	-499.30	-484.70	-91.51	
	37	98+900.00	25	-3941.19	-653.76	-1060.38	-612.98	-538.56	-499.30	-484.70	-91.51	
	38	98+925.00	25	-5331.89	-2044.46	-1060.38	-612.98	-538.56	-499.30	-484.70	-91.51	
	39	98+950.00	25	-5064.77	-1777.34	-1060.38	-612.98	-538.56	-499.30	-484.70	-91.51	
	40	98+975.00	25	-3658.88	-371.45	-1060.38	-612.98	-538.56	-499.30	-484.70	-91.51	
	41	99+000.00	25	-2466.62	0.00	-239.57	-612.98	-538.56	-499.30	-484.70	-91.51	
	42	99+025.00	25	-929.49	0.00	0.00	0.00	0.00	-353.28	-484.70	-91.51	
		Sub total	250	-29997.10	-4847.00	-4847.00	-4847.00	-4847.00	-4847.00	-4847.00	-915.10	-29997.10

Using the information shown in Table G-2, a location-based schedule (time-location plan) was generated by the model (see Figure G-6).

Similarly, tabular information on locations and progress quantities of earthwork generated by the model on a weekly basis is presented in Table G-3 below. The detailed development processes for automatic generation of a location-based schedule were discussed in Chapters 4 and 6.

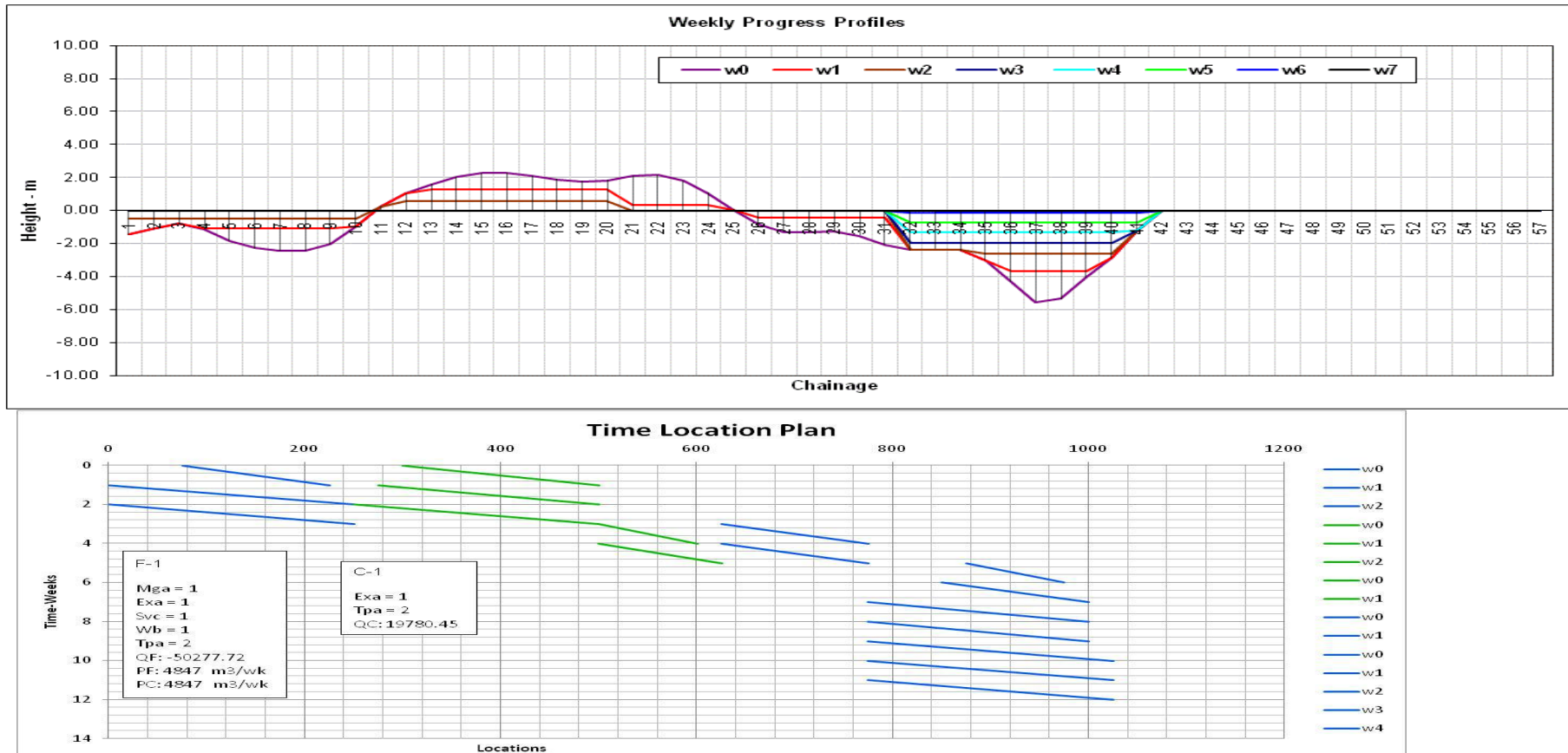


Figure G-6 A time-location plan (location-based schedule) and weekly progress profiles of a road section generated by the model

Table G-3 Tabular information on weekly performed quantities and working locations of cut and fill sections shown in Figure G-6

S.N.	Time (WK)	Section-1				Section-2				Section-3		
		Fill-Qty	Locations	Cut-Qty	Locations	Cut-Qty	Locations	Fill-Qty	Locations	Fill-Qty	Borrow-Qty	Locations
1	WK-1	4847.00	5,10 (150)	4847.00	14,21 (200)							
2	WK-2	4847.00	2,11 (250)	4847.00	13,21 (225)							
3	WK-3	3829.26	2,11 (250)	4237.98	12,21 (250)							
4	WK-4					4847.00	22,25(100)	4847.00	27, 32 (150)			
5	WK-5					1001.47	22,26(125)	1910.36	27, 32 (150)			
6	WK-6									4847.00	4847.00	37,40(100)
7	WK-7									4847.00	4847.00	36,41(150)
8	WK-8									4847.00	4847.00	33,41(225)
9	WK-9									4847.60	4847.60	33,41(225)
10	WK-10									4847.00	4847.00	33,42(250)
11	WK-11									4847.00	4847.00	33,42(250)
12	WK-12									914.50	914.50	33,42(250)
	Total	13523.26		13931.98		5848.47		6757.36		29997.10	29997.10	

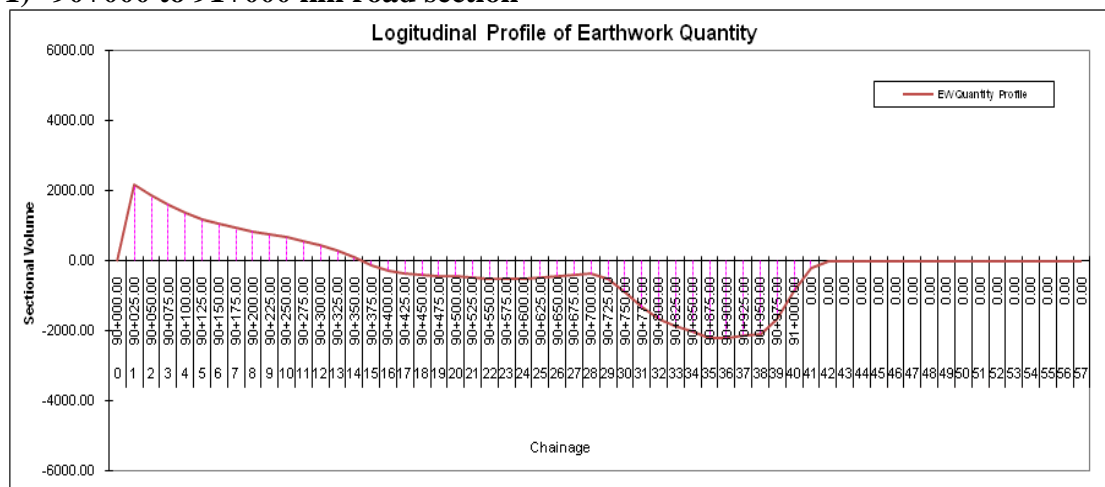
Appendix-H

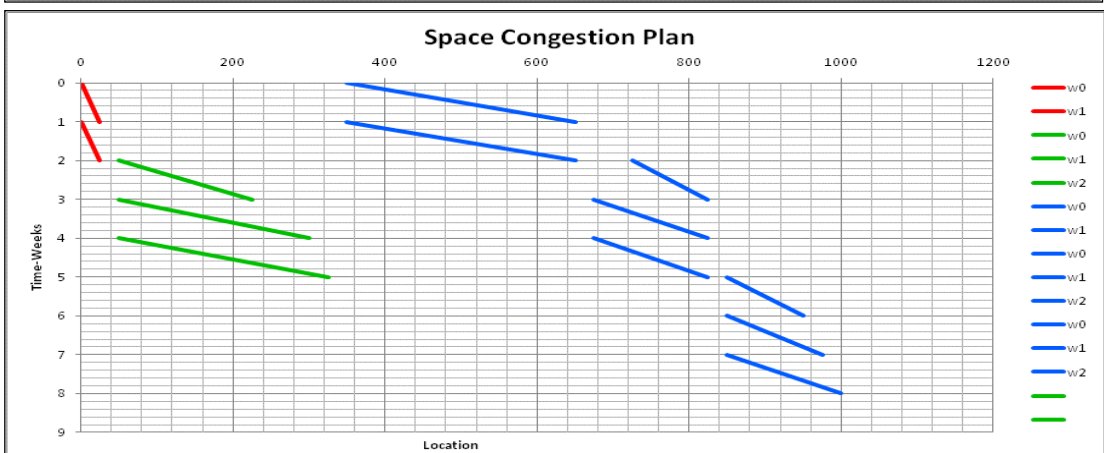
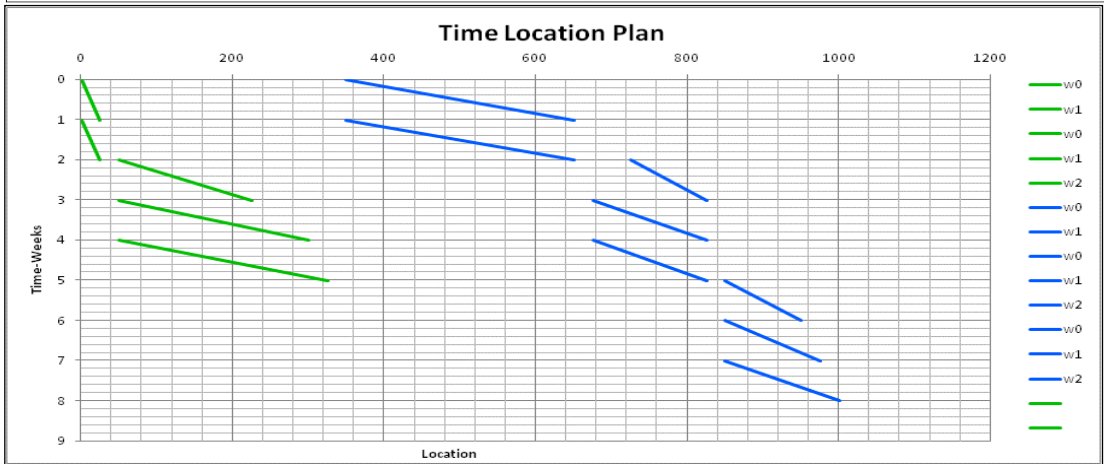
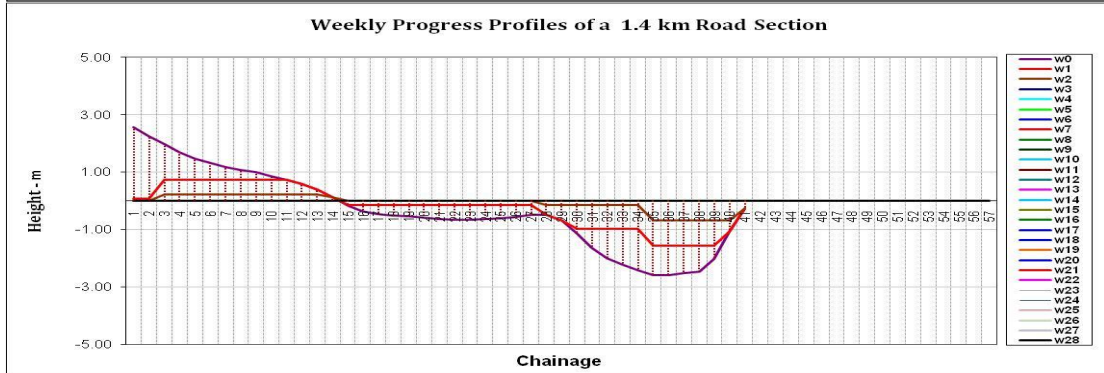
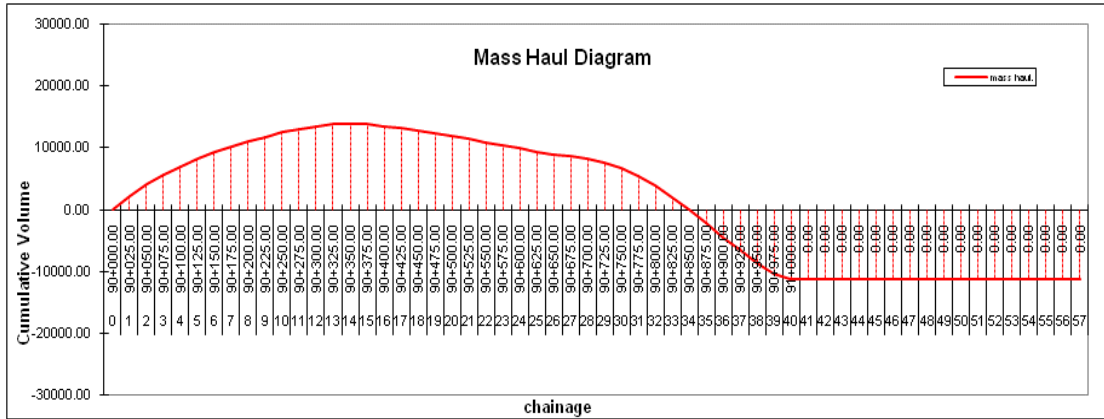
Experiments with a road profile data of 10 km section (90+000 to 100+00 km road sections)

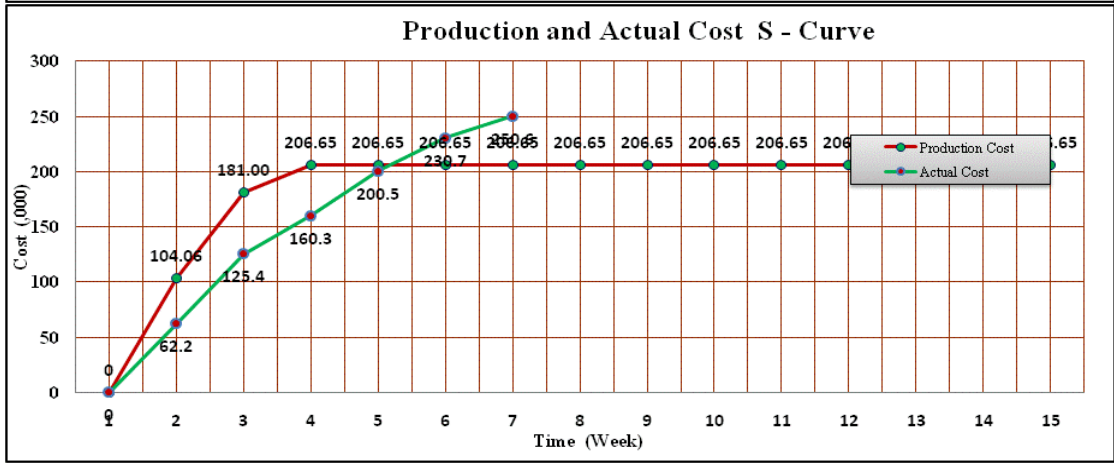
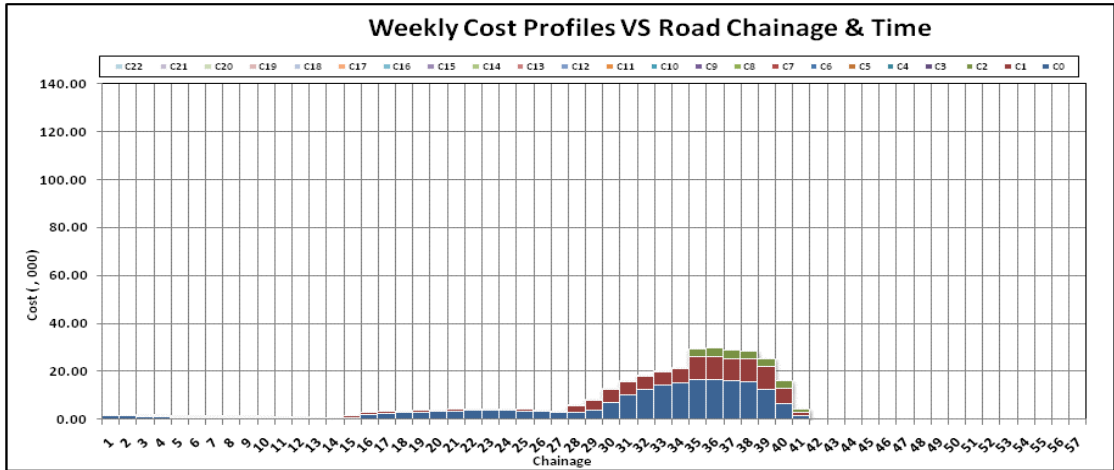
This appendix presents the experiment results of a 10 km road section. The road section was selected from the lot 5 road projects in Portugal. The road profiles were available in 10 sub-sections; therefore, each road section of the lot 5 road project was selected for the experiments. The experiments were carried out with the model functionality and the experiment results in terms of graphical outputs of each road section are presented below. The graphical outputs display the prototype model behaviours and confirm model functionality through experiments with different types of longitudinal road profiles, assuming user-defined productivity, available sets of equipment, resources and site constraints. The following are the graphical outputs (experimental results) obtained from the selected road section.

- 1) Longitudinal profiles
- 2) Mass haul diagram
- 3) Weekly progress profiles
- 4) Time location plan / location-based schedules
- 5) Time-location/space-congestion plan
- 6) Weekly cost profiles
- 7) Cost S-curve.

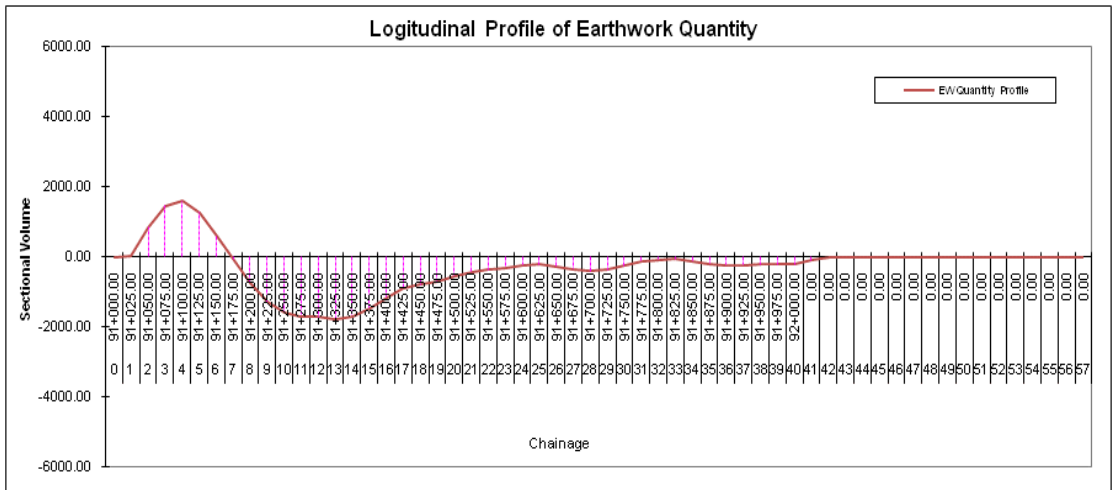
1) 90+000 to 91+000 km road section

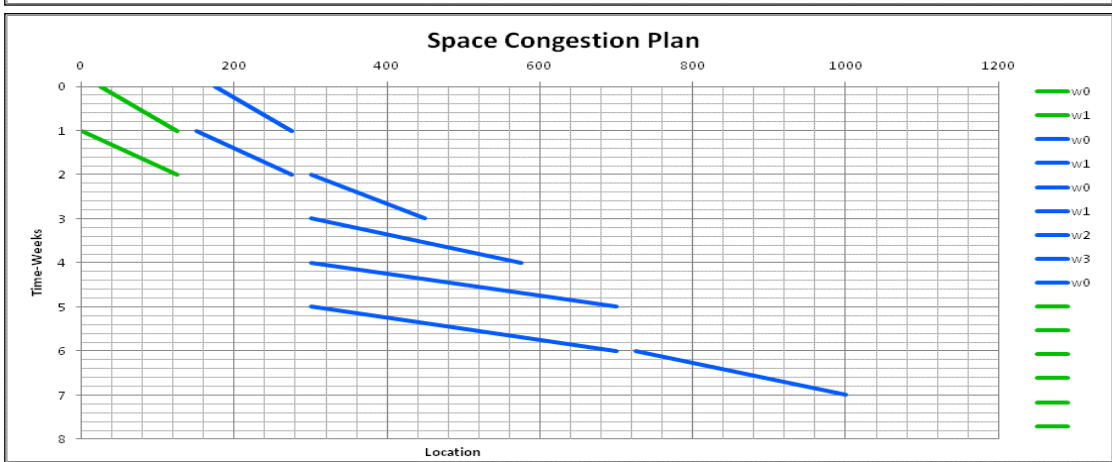
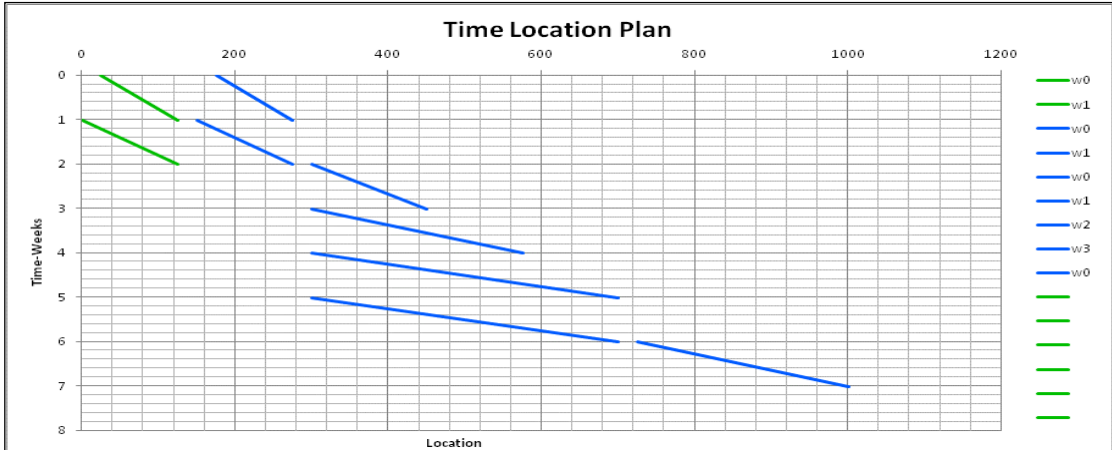
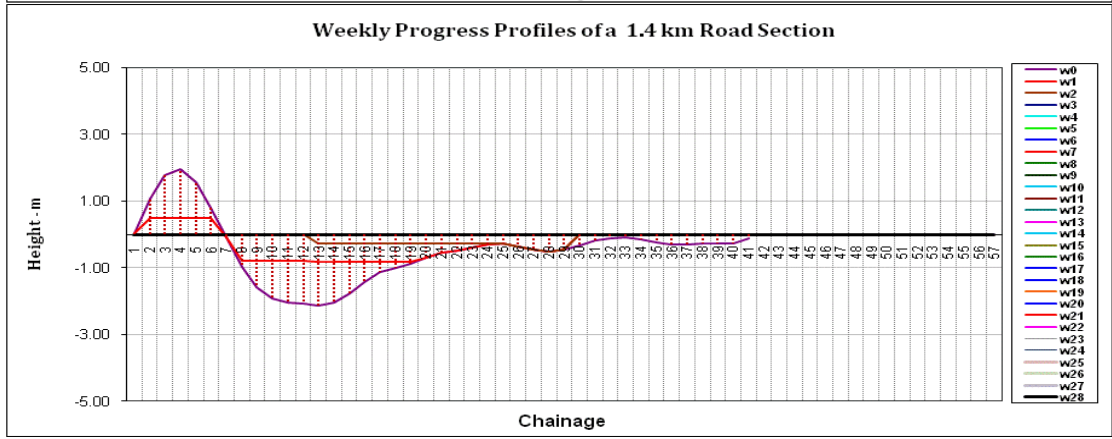
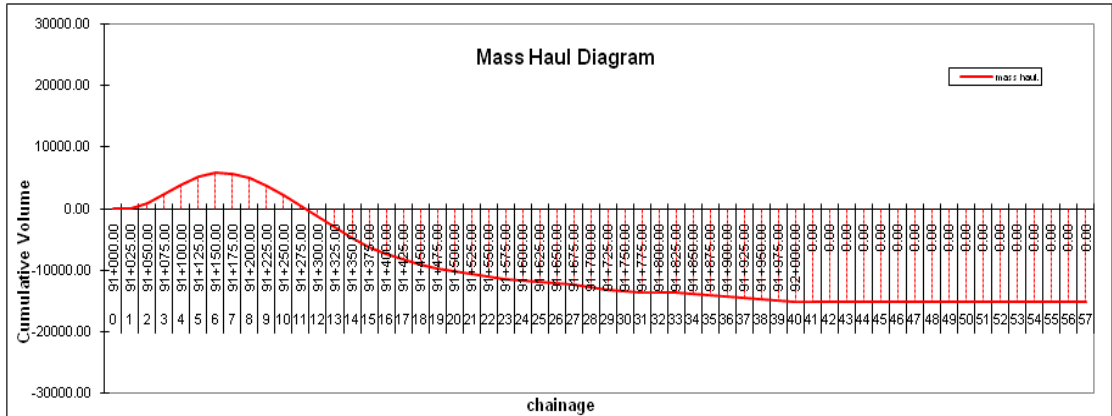


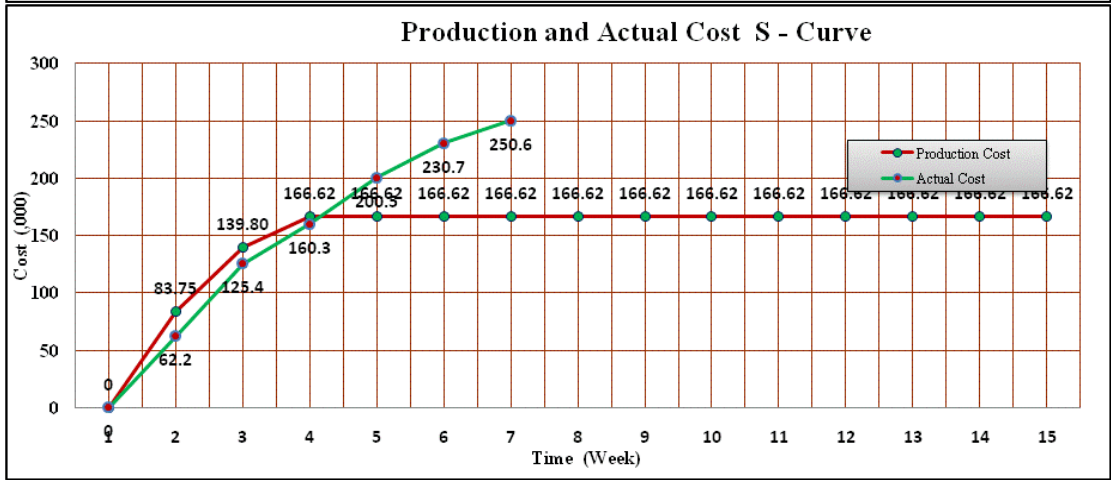
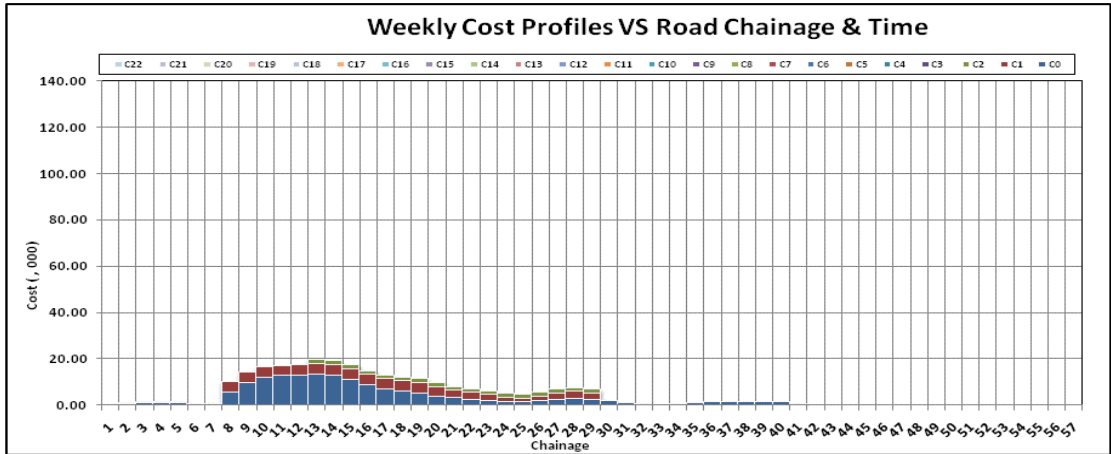




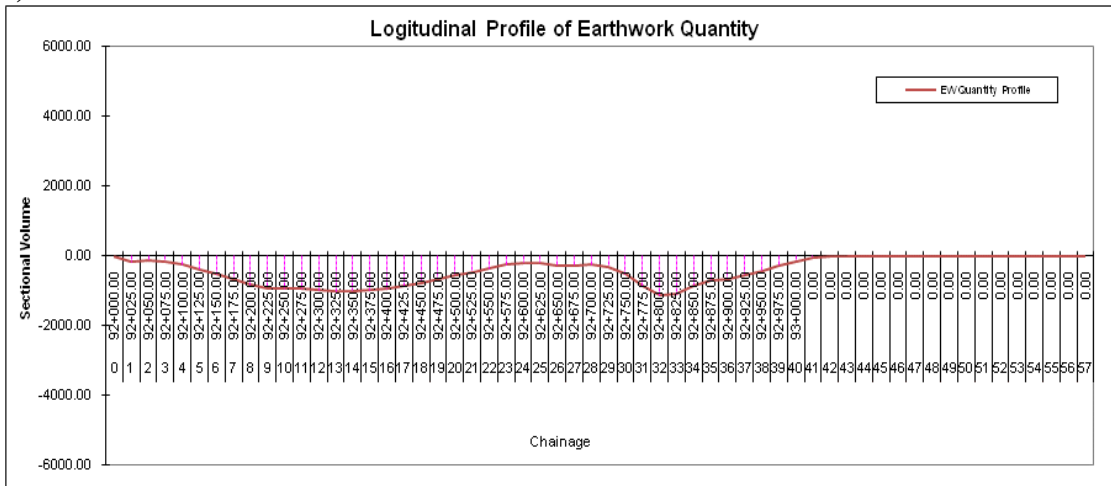
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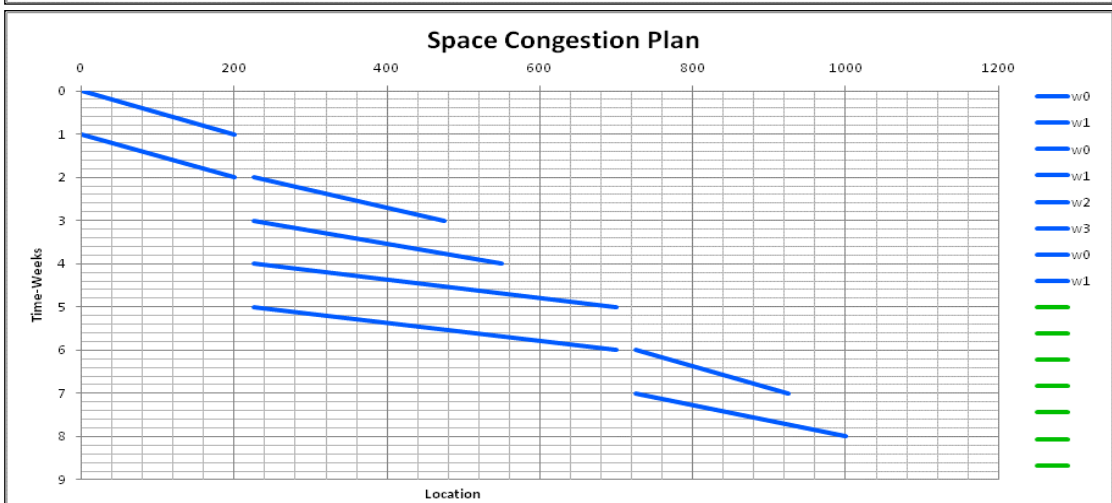
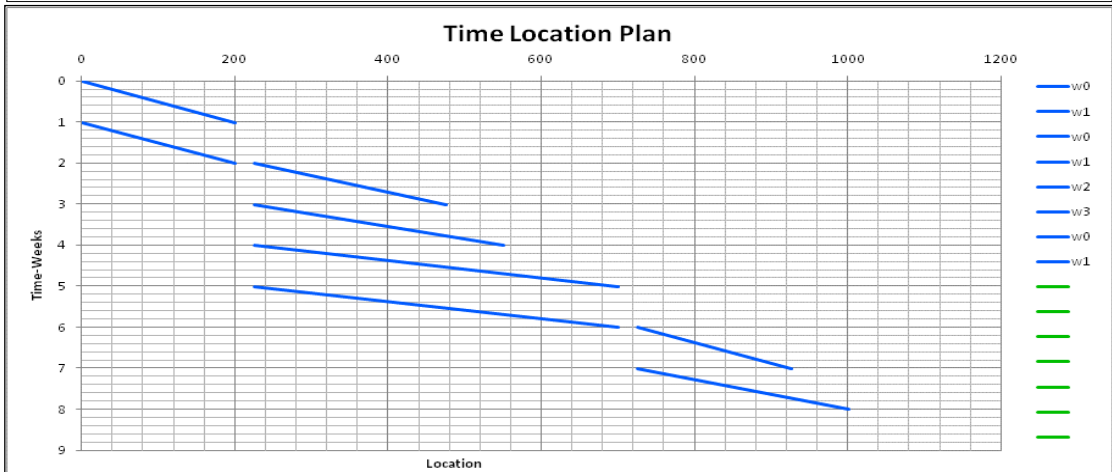
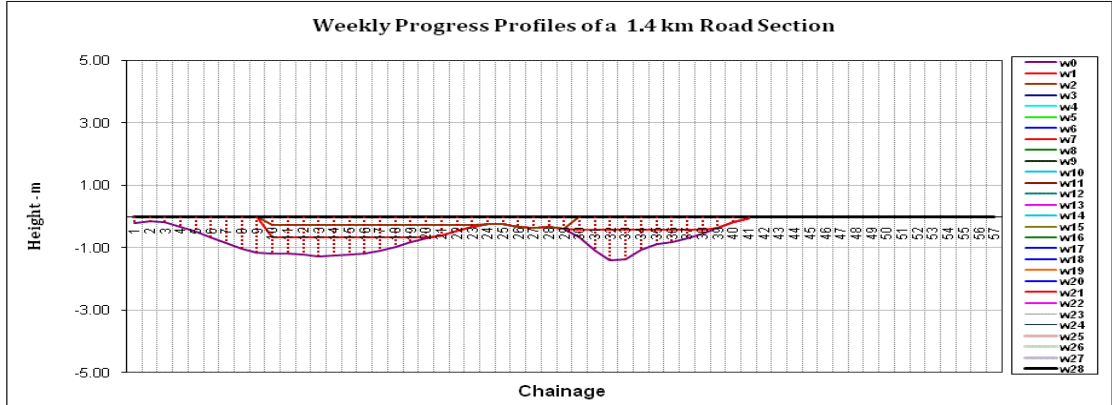
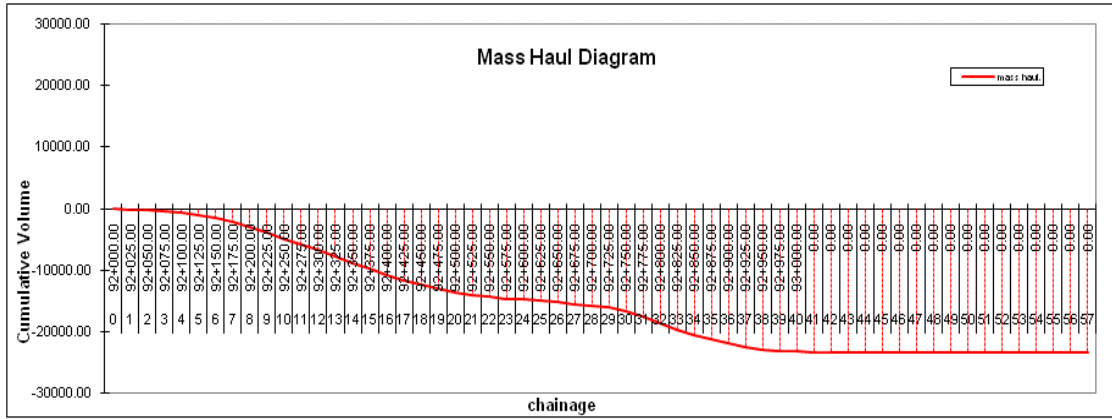


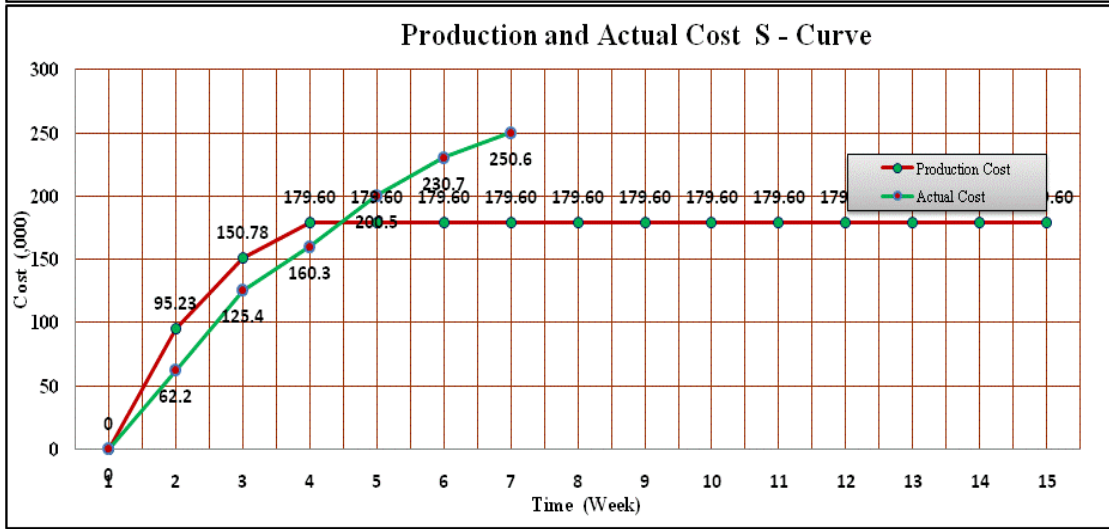
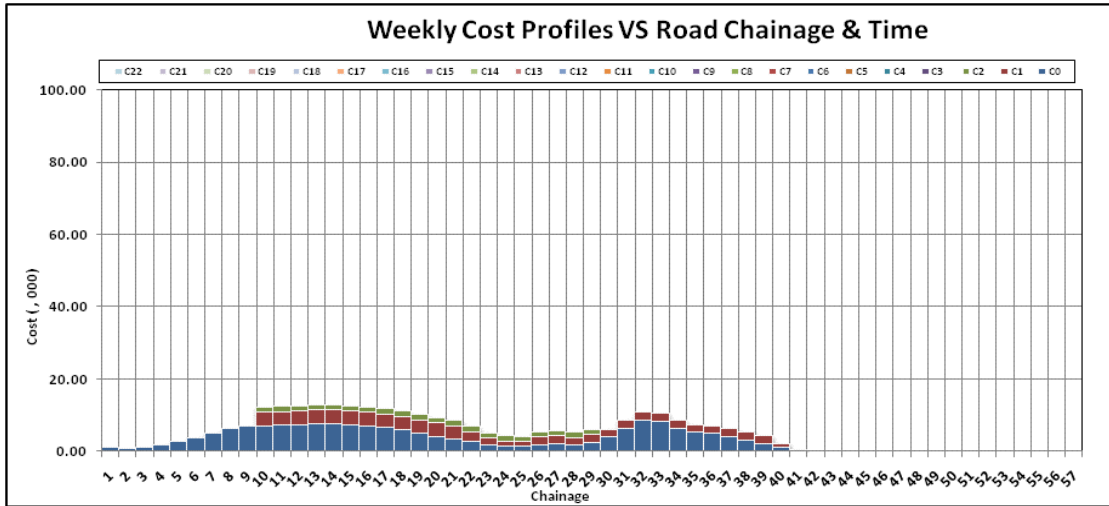




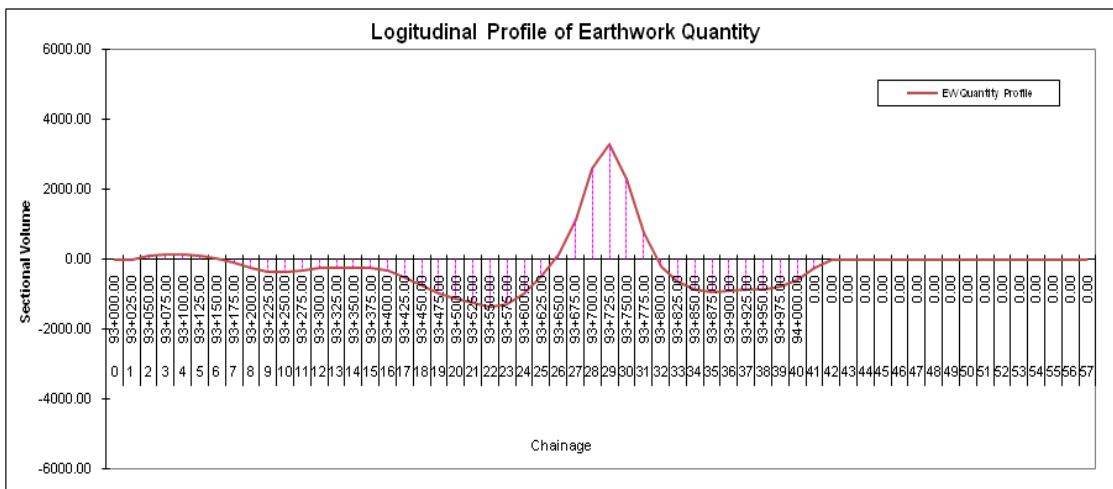
3) 92+000 to 93+000 km road section

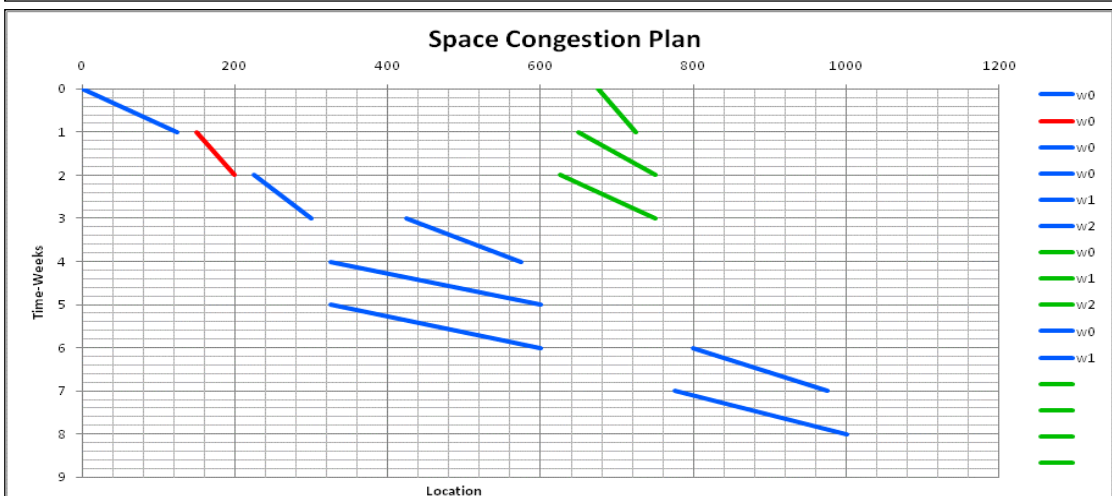
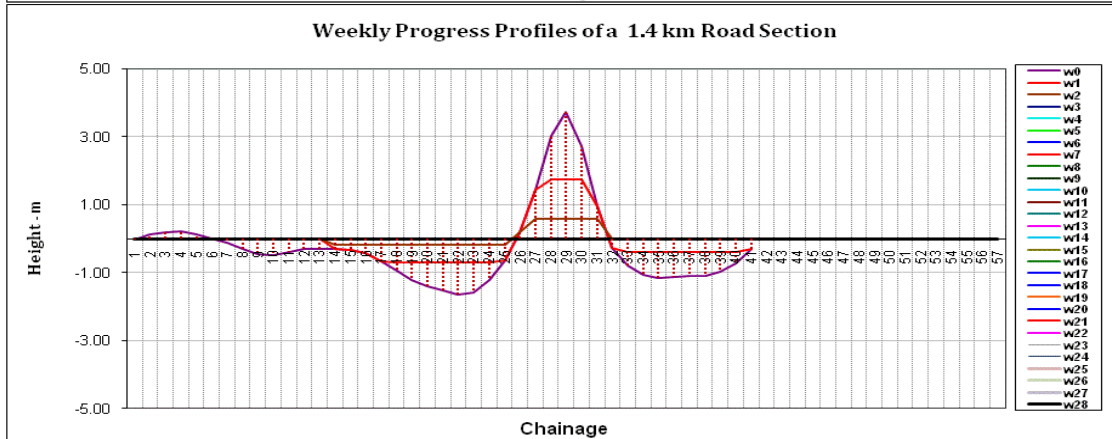
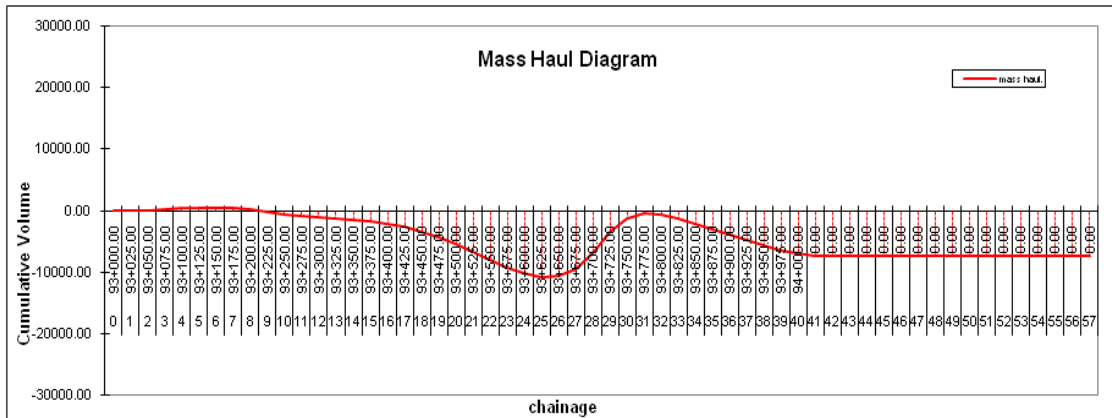


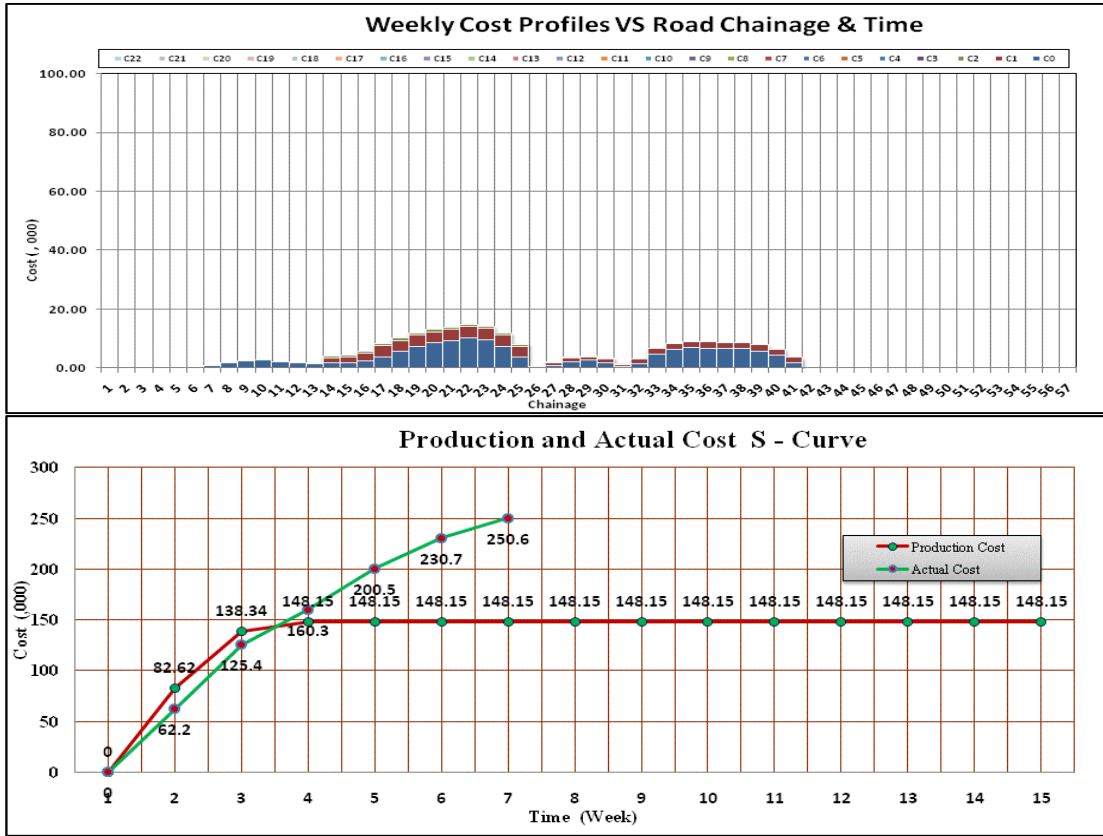




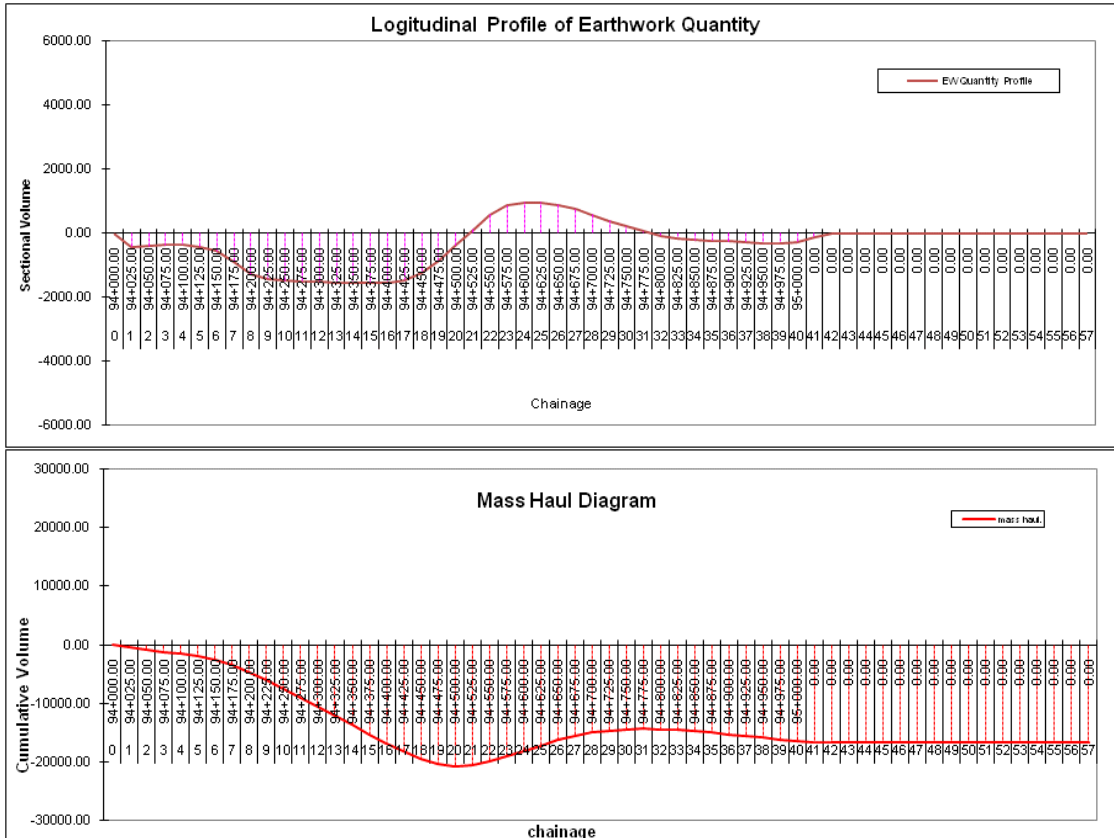
4) 93+000 to 94+000 km road section

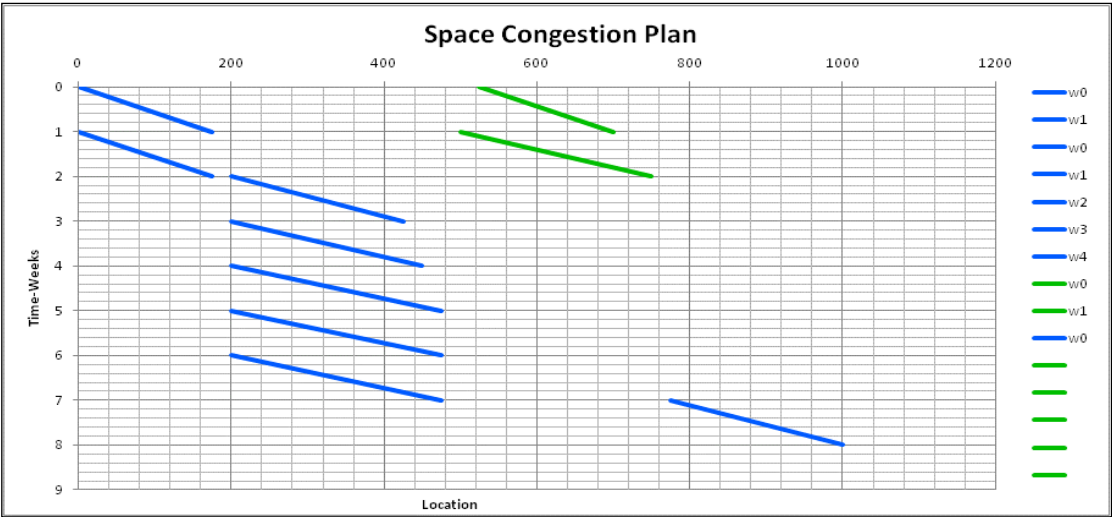
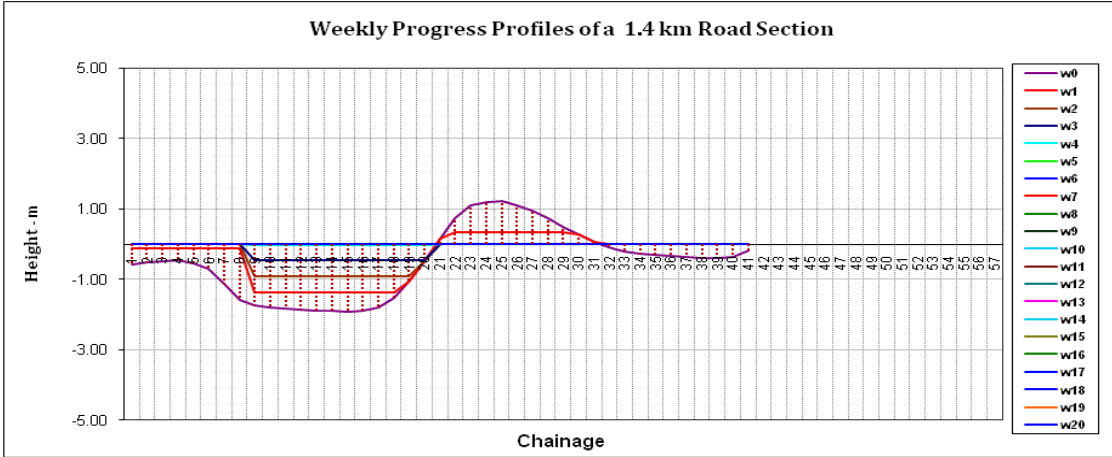


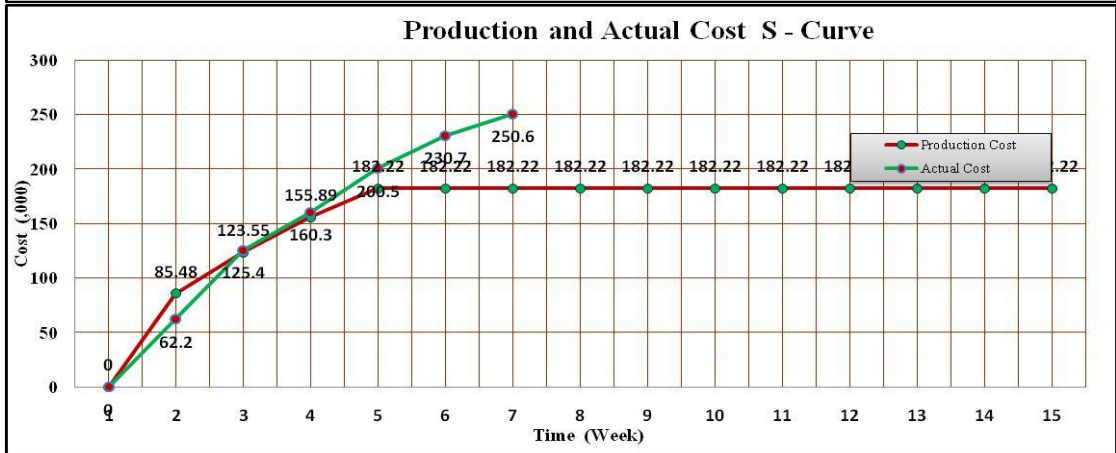
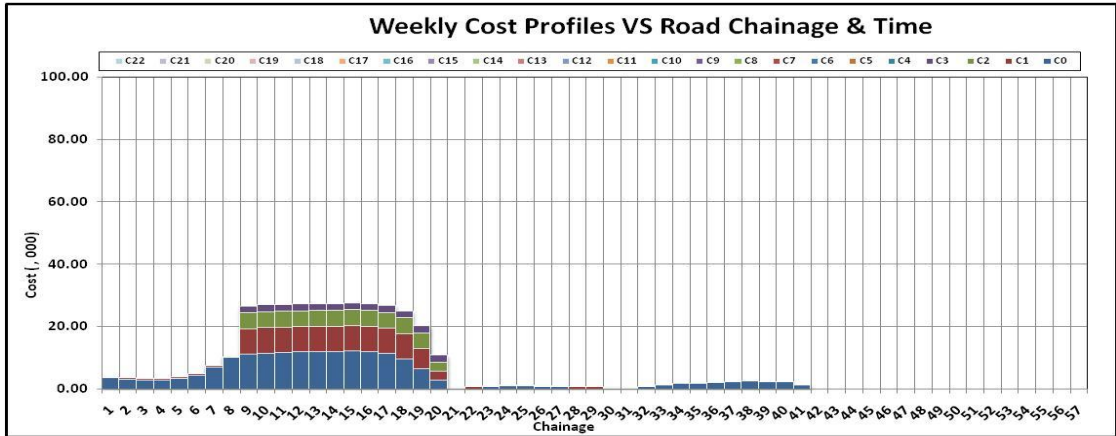




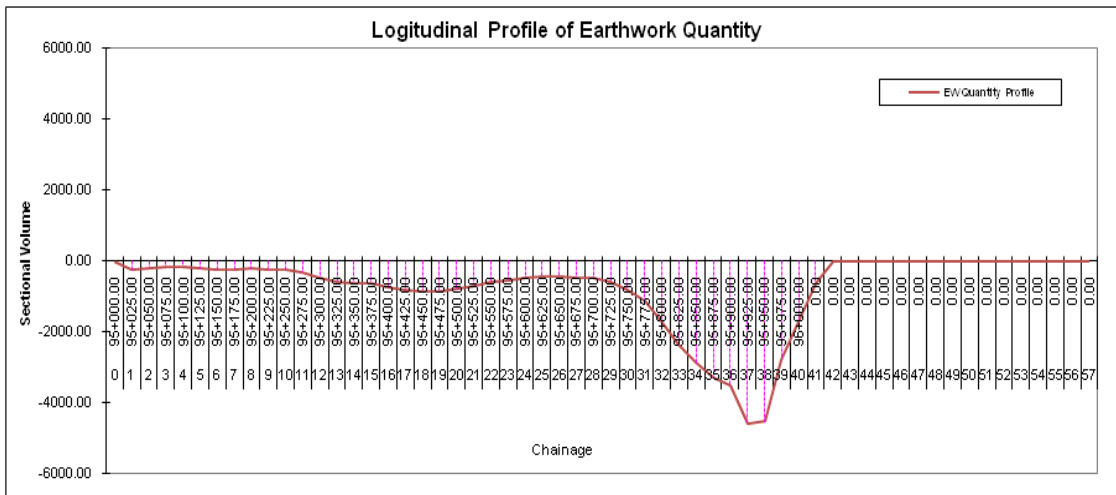
5) 94+000 to 95+000 km road section

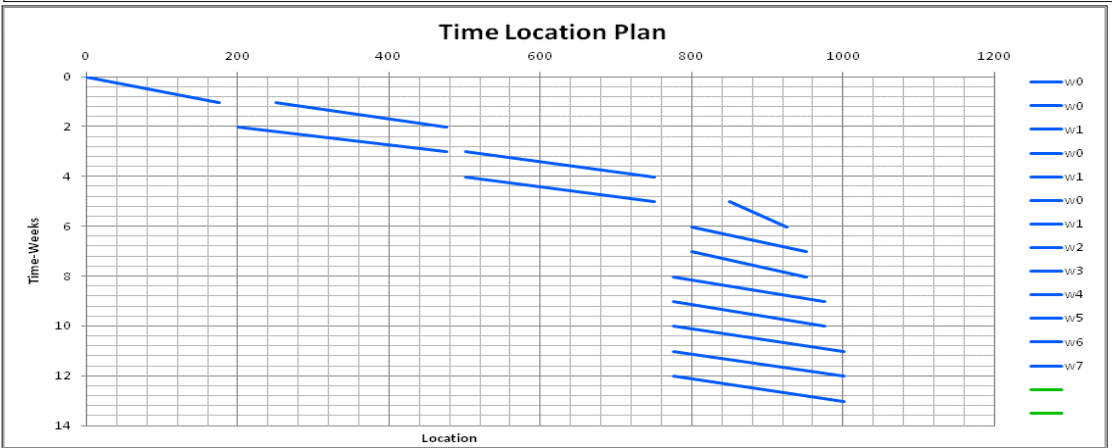
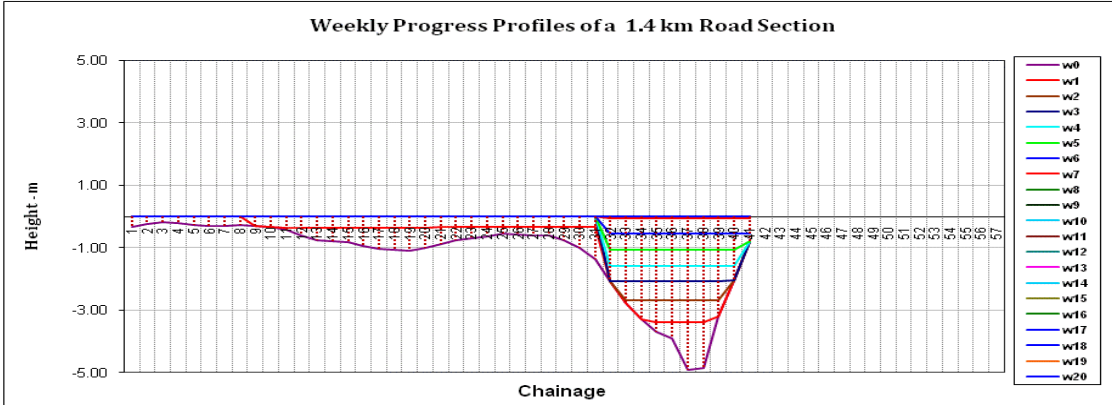
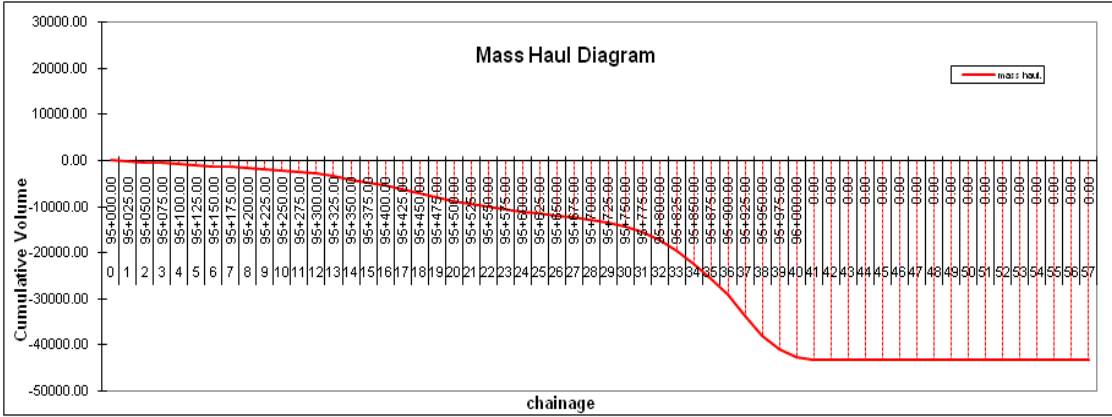


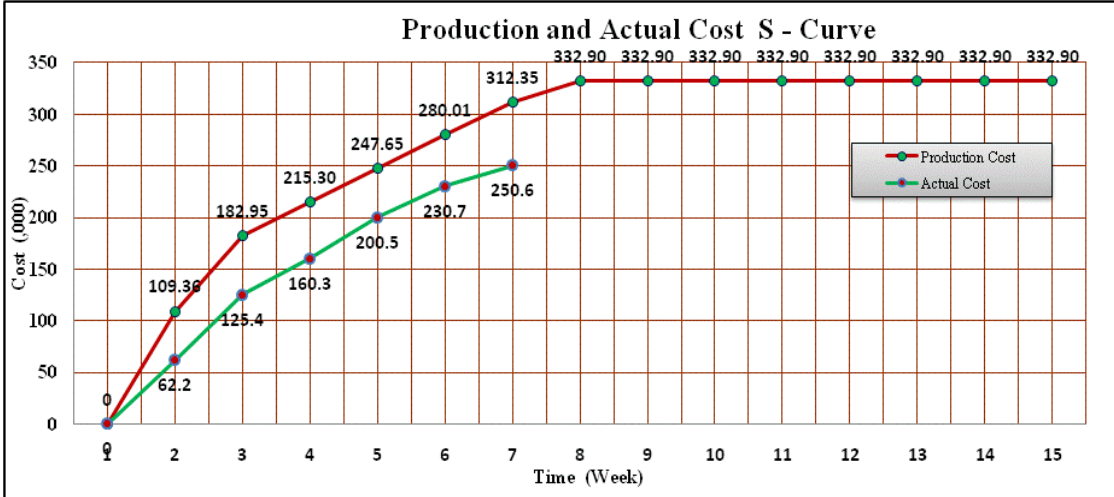
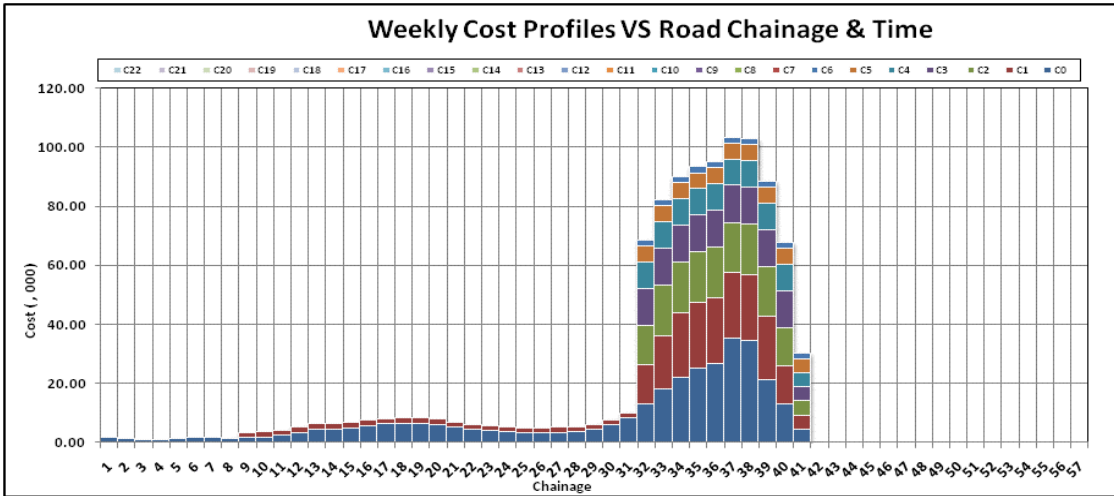
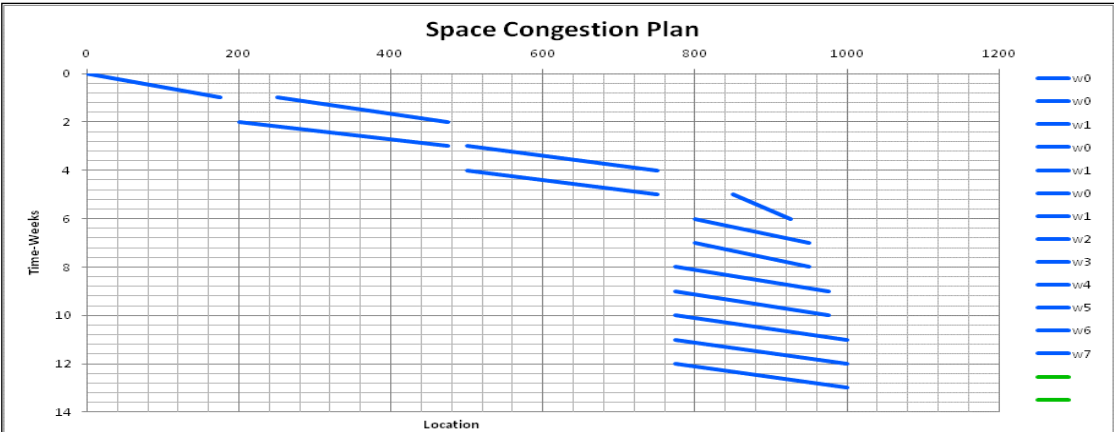




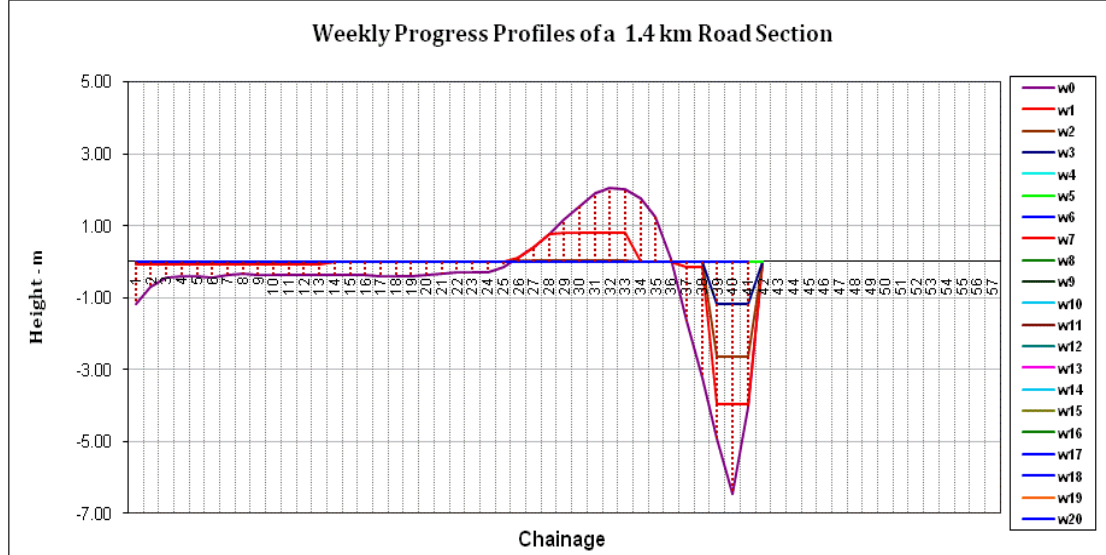
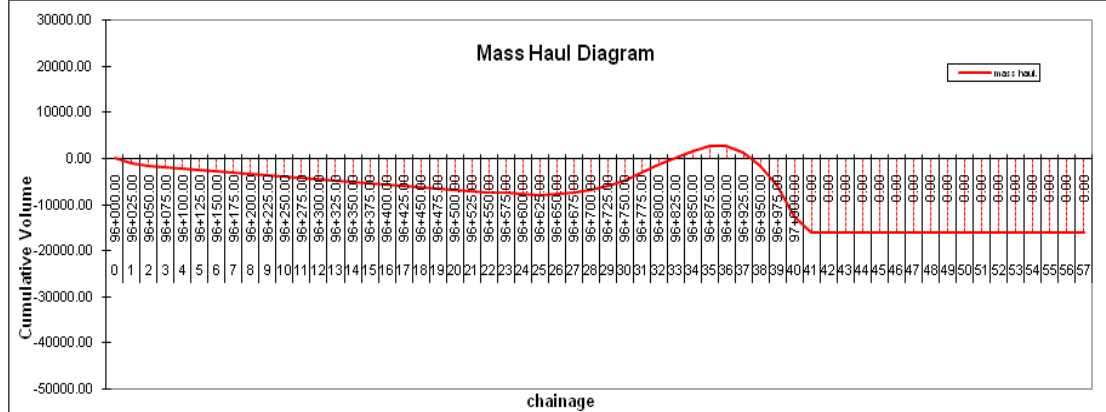
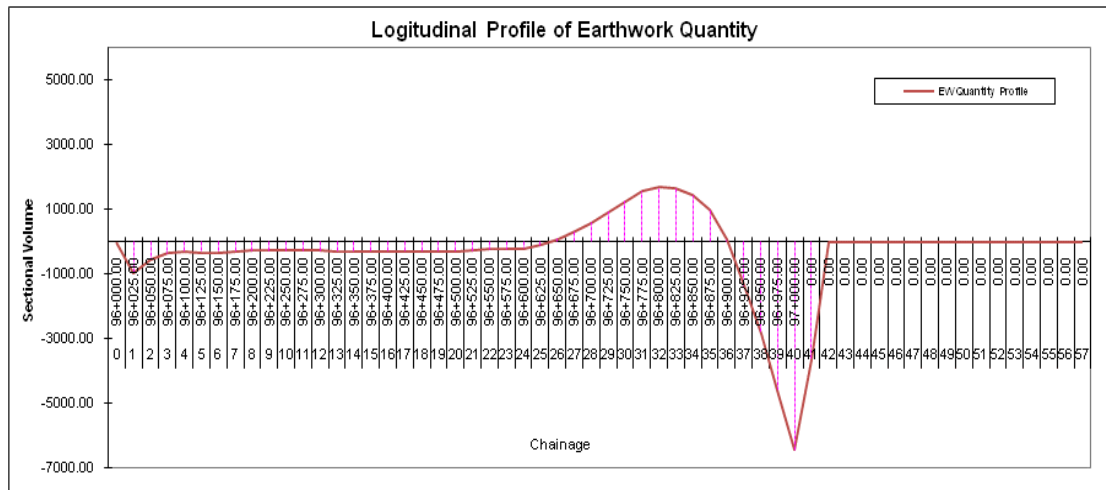
6) 95+000 to 96+000 km road section

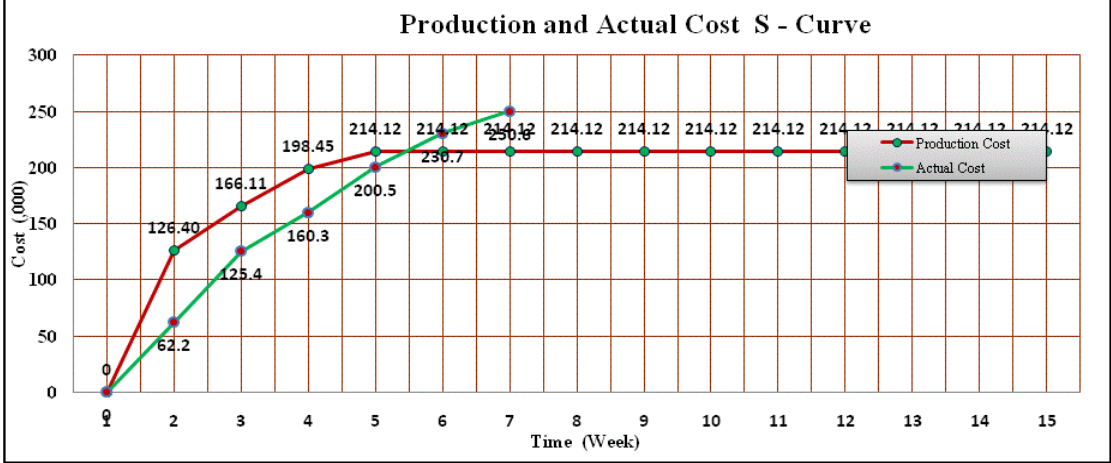
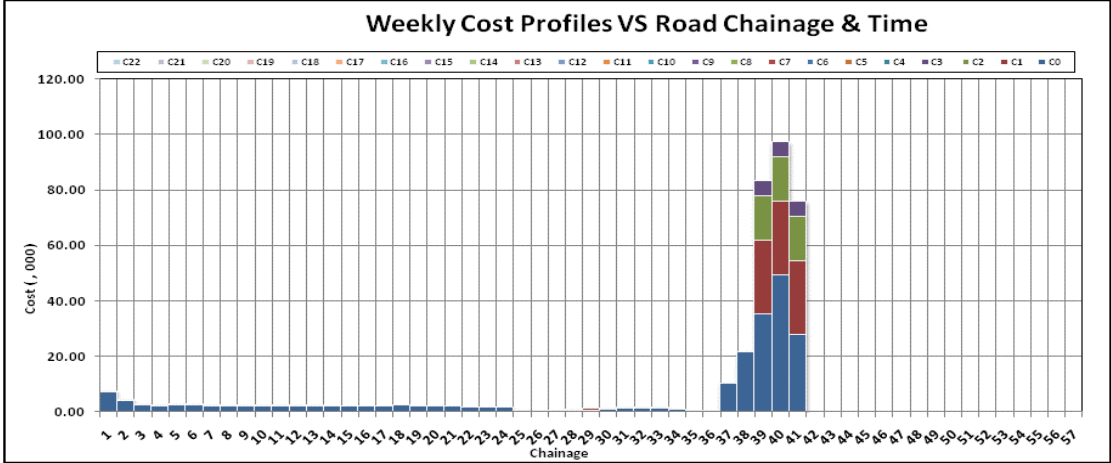
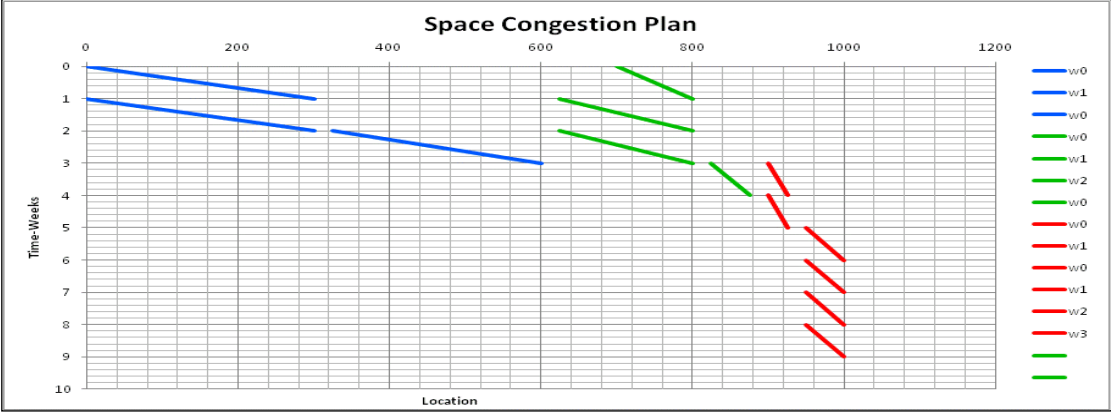
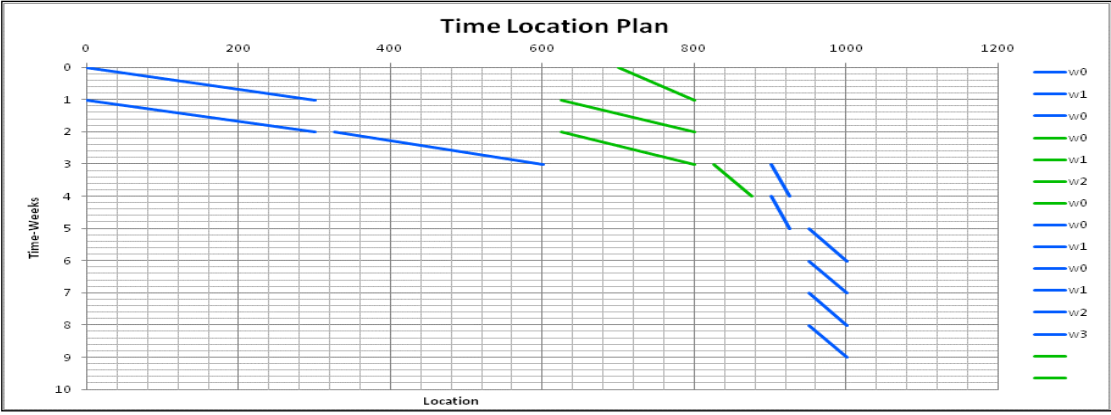




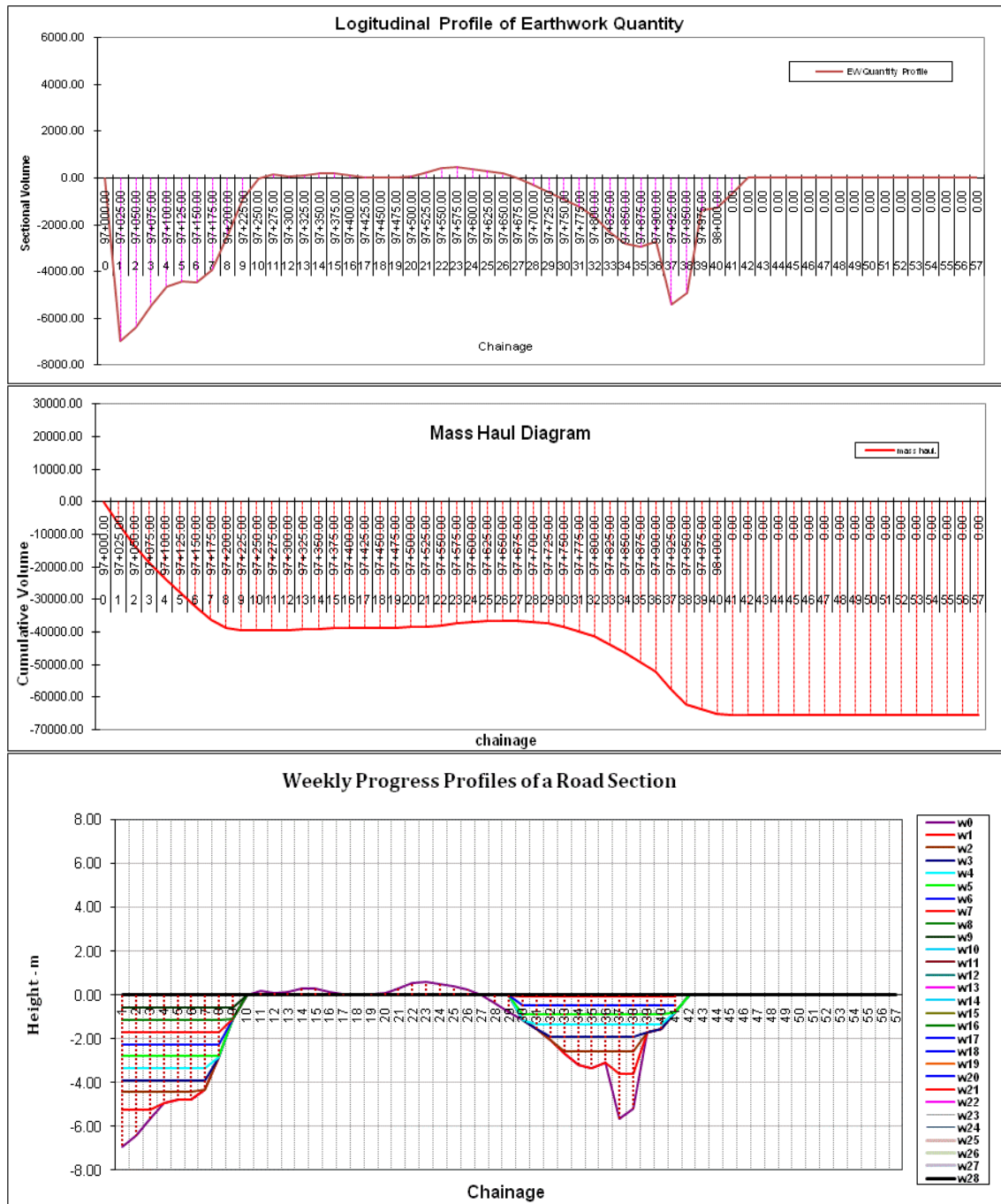


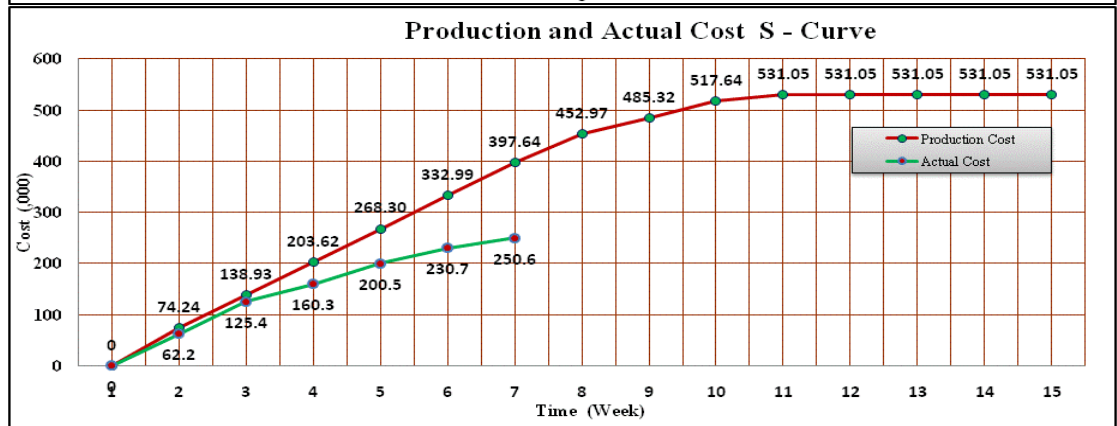
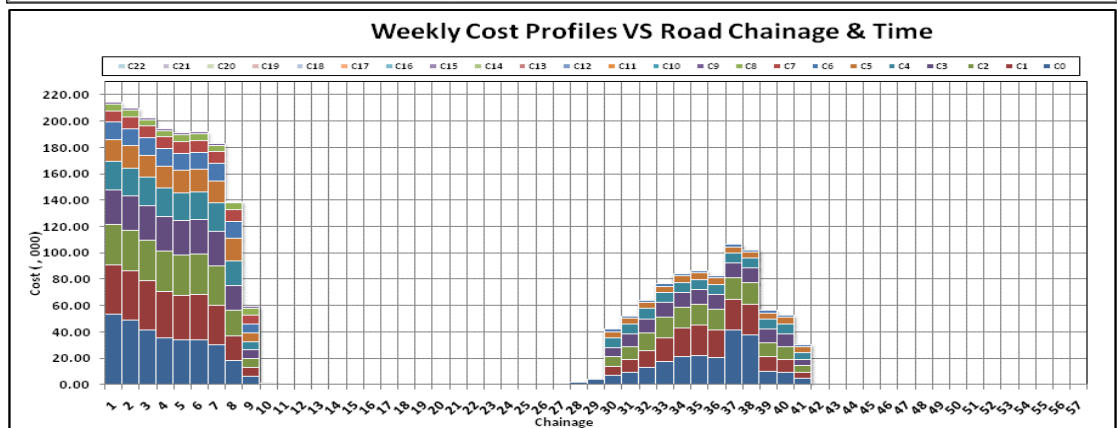
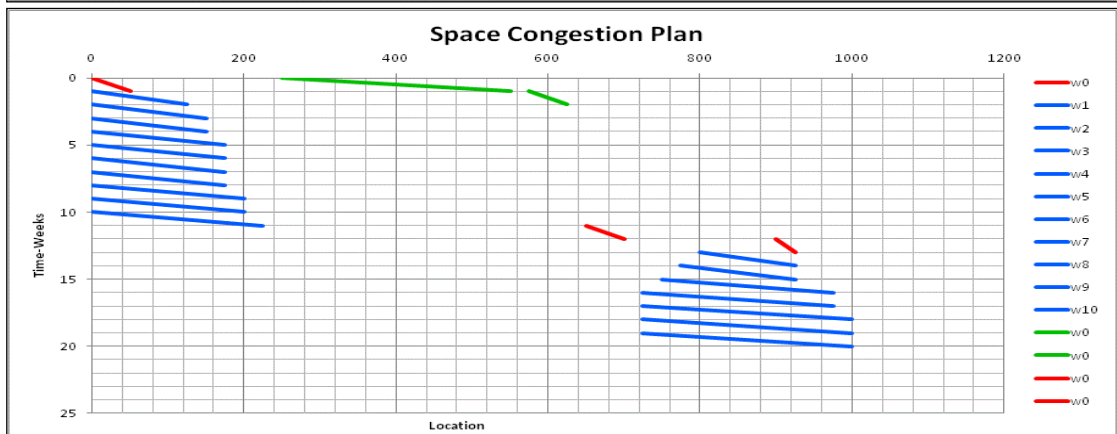
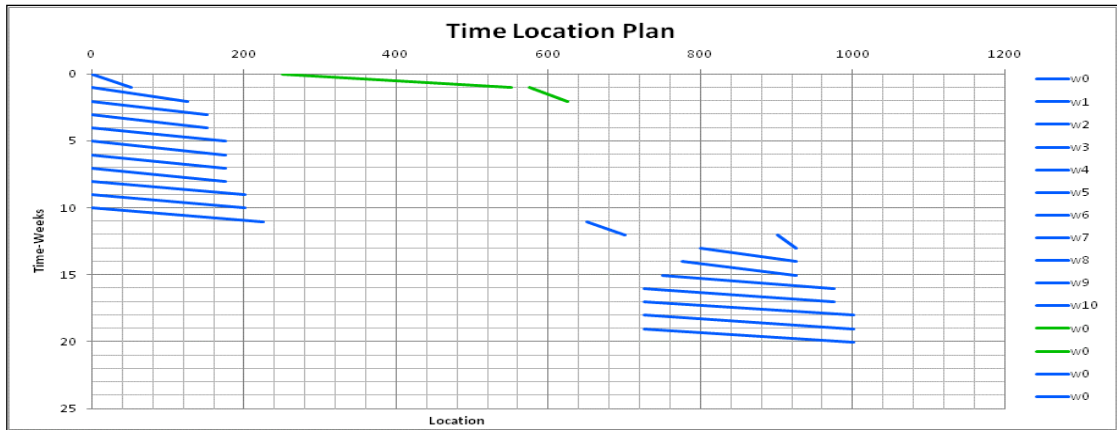
7) 96+000 to 97+000 km road section



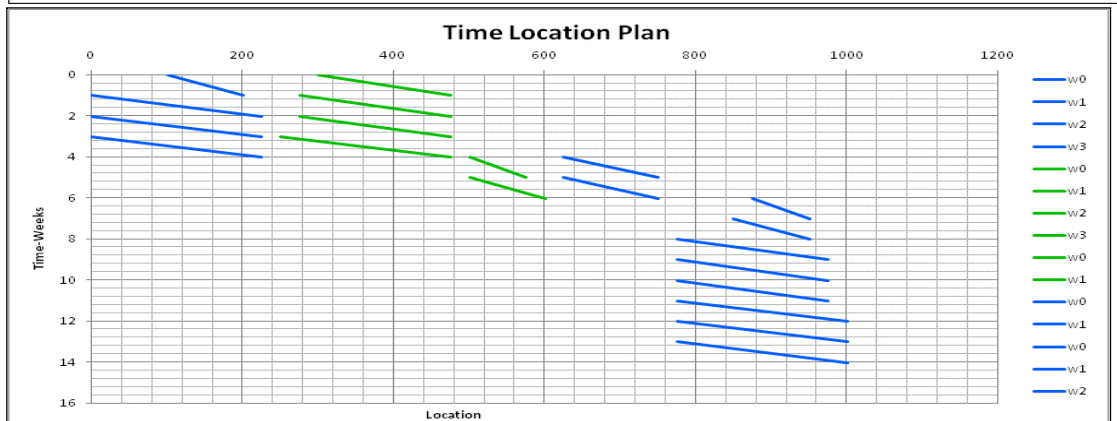
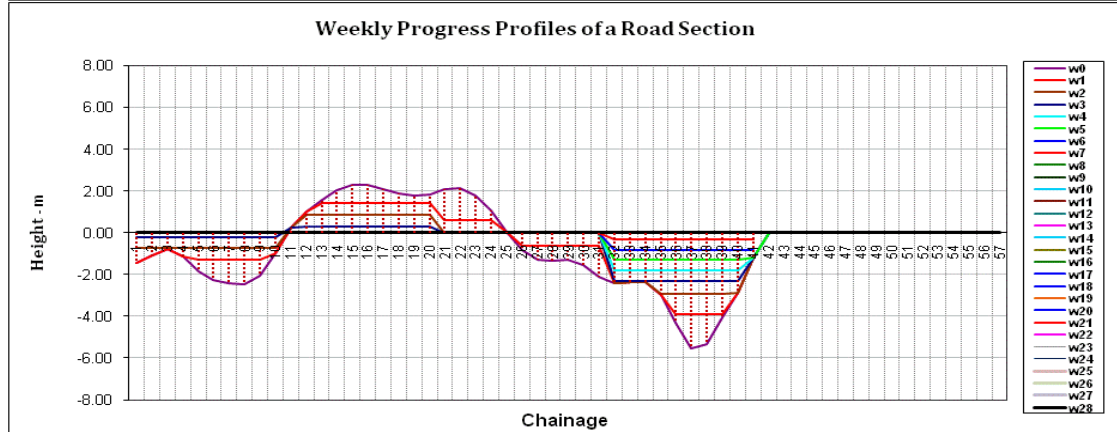
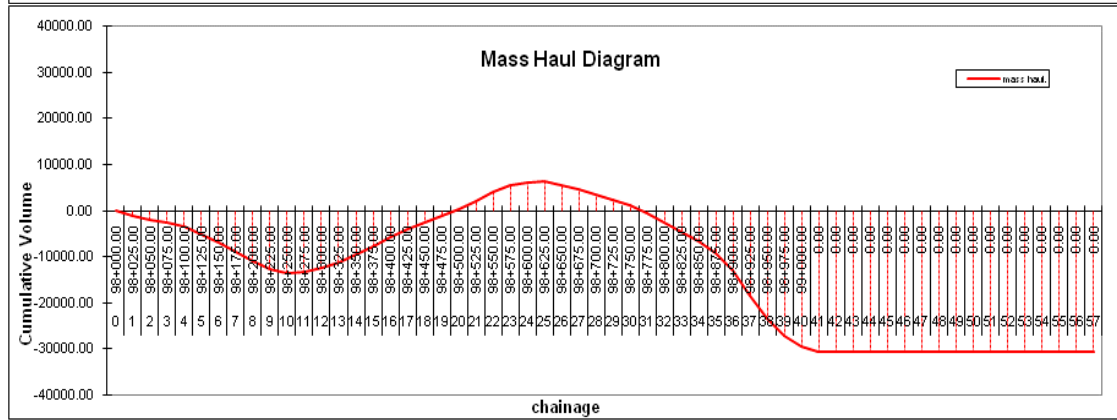
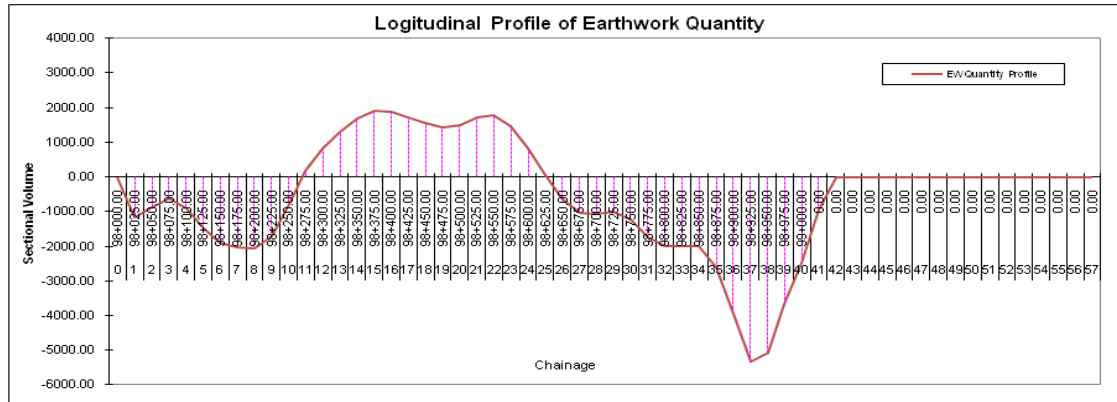


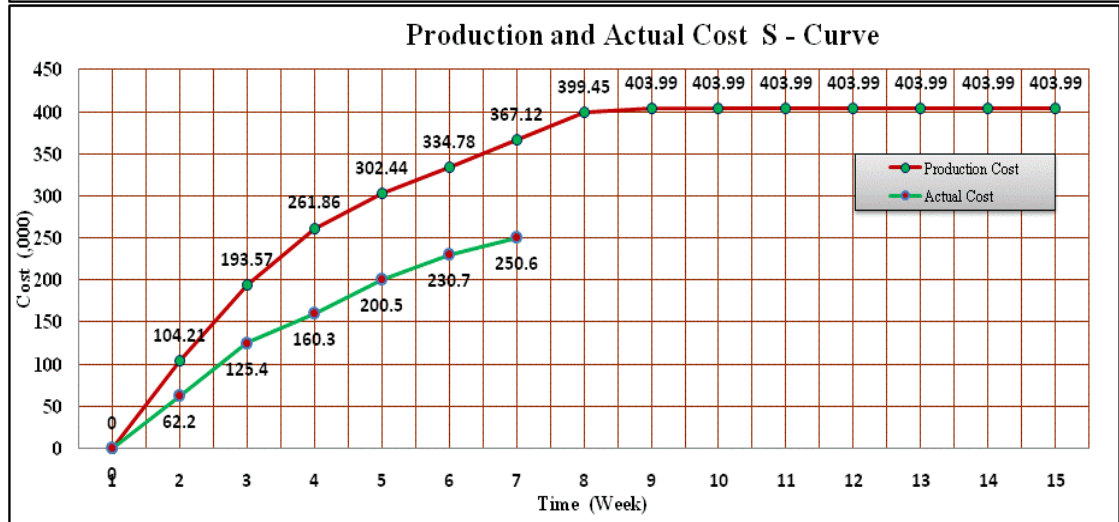
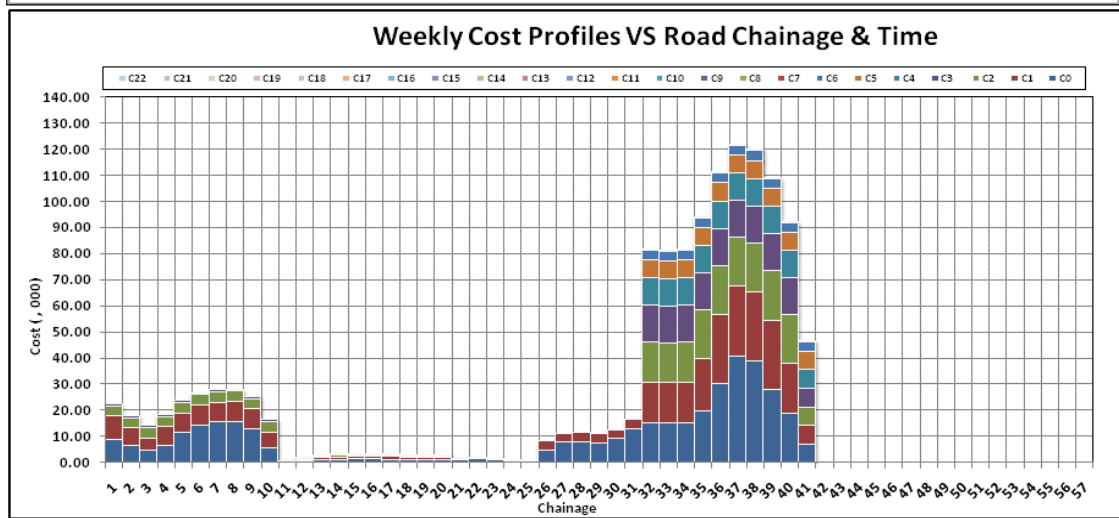
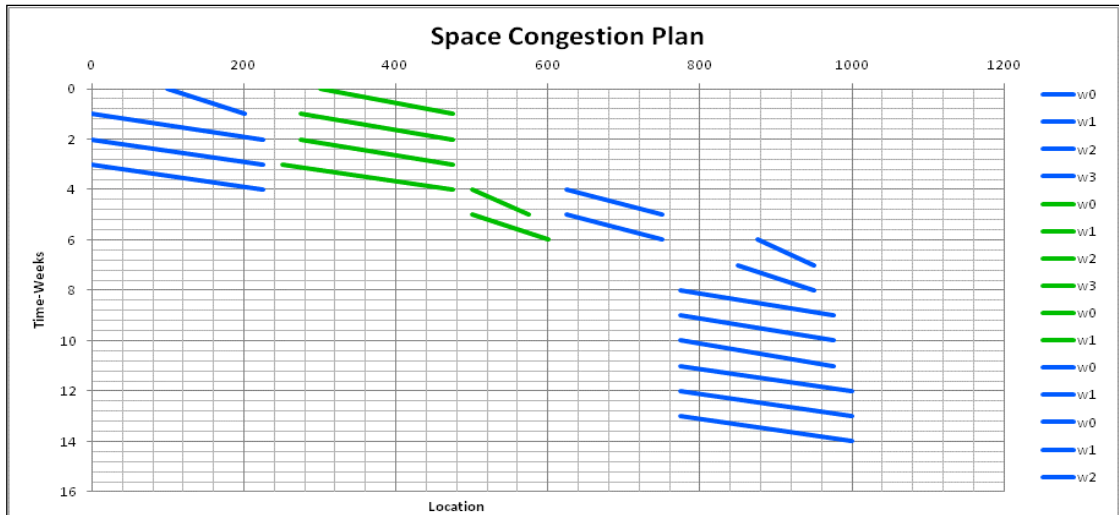
8) 97+000 to 98+000 km road section



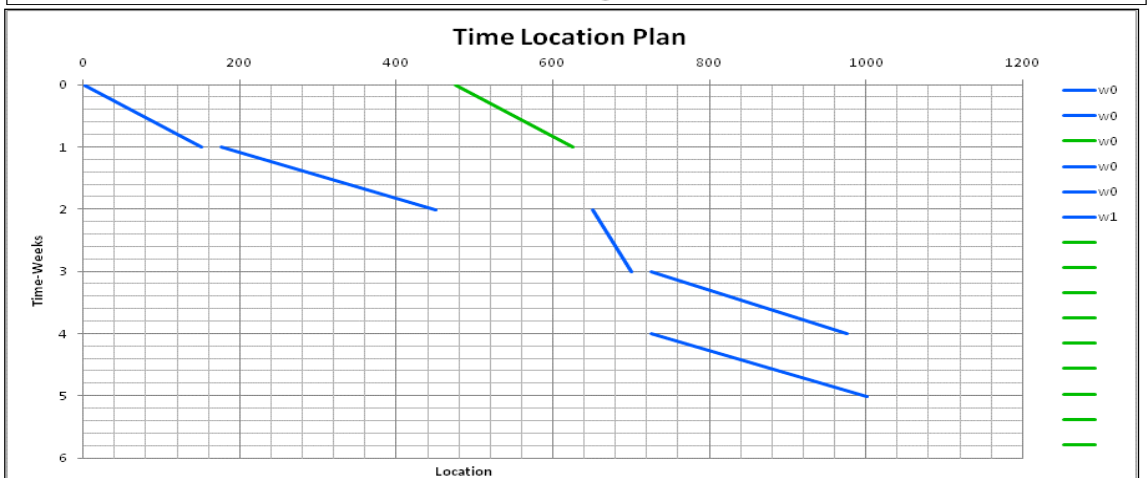
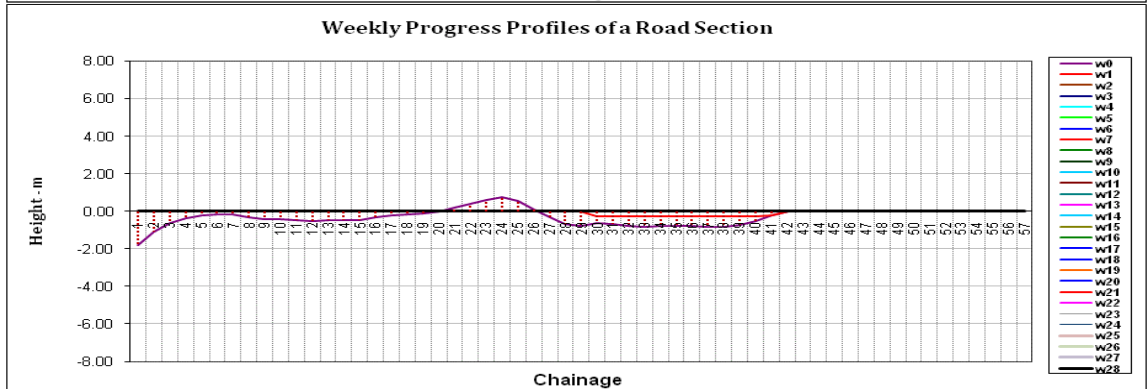
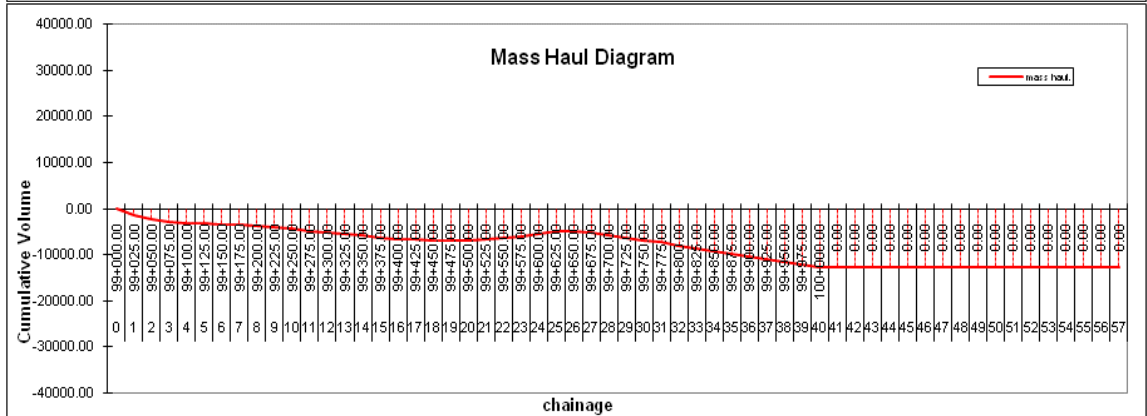
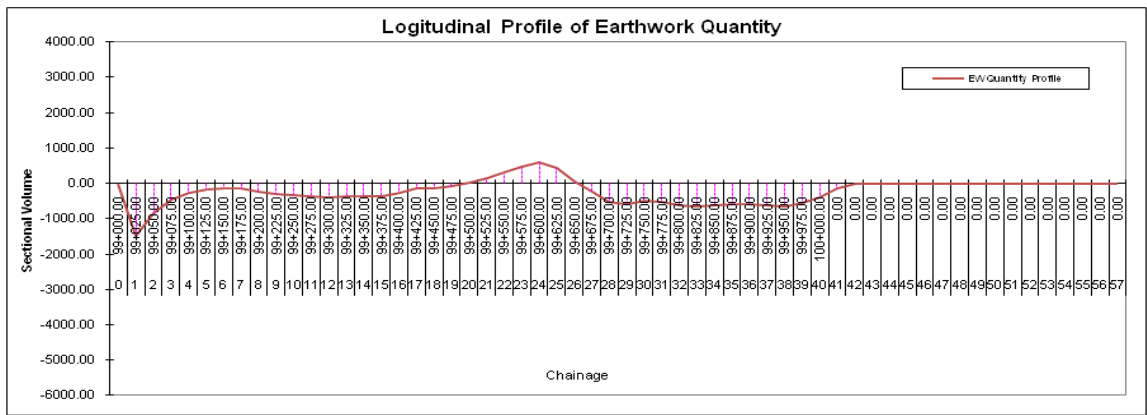


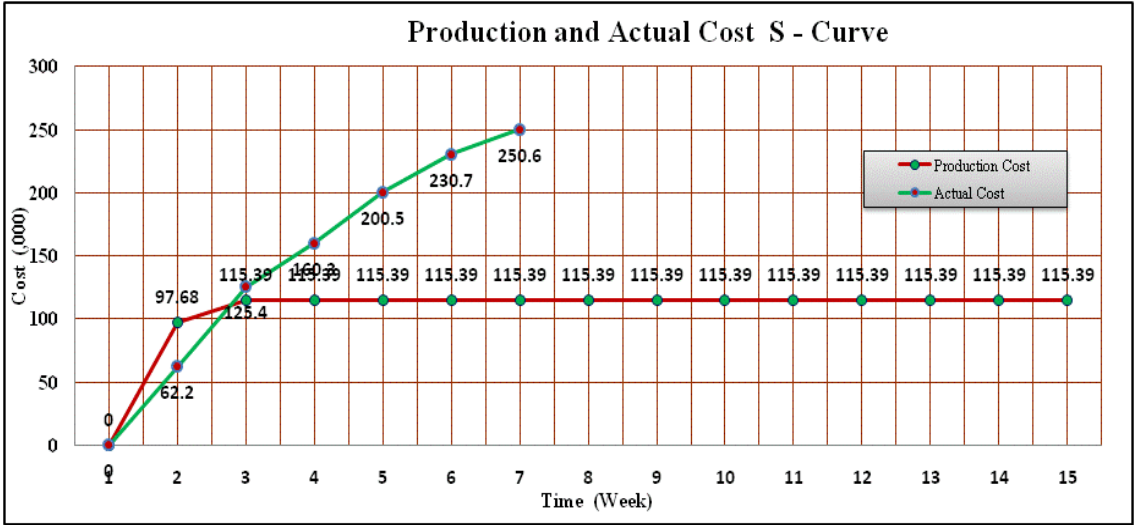
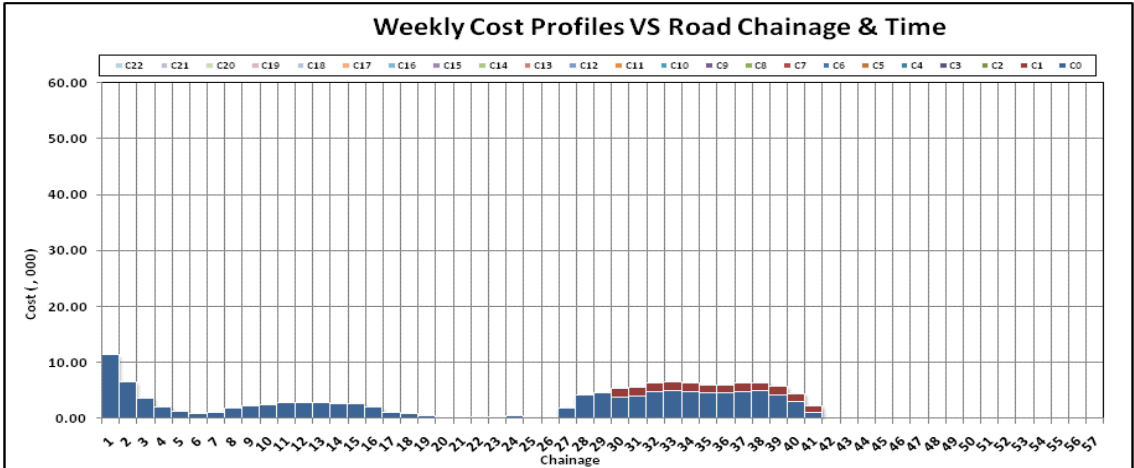
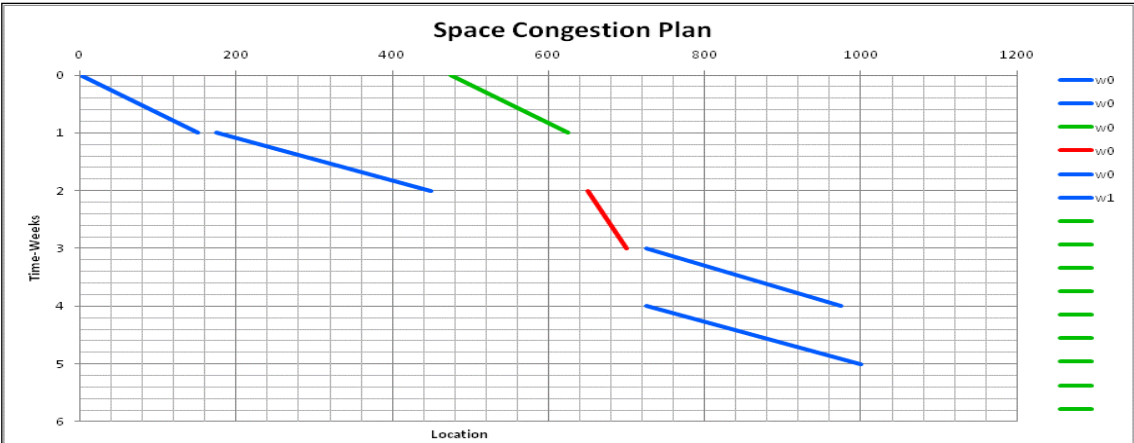
9) 98+000 to 99+000 km road section





10) 99+000 to 100+000 km road section





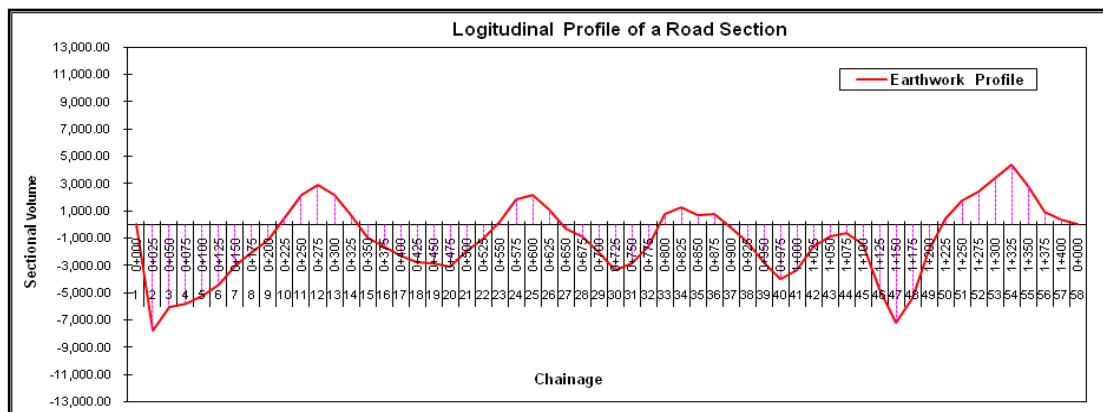
Appendix - I

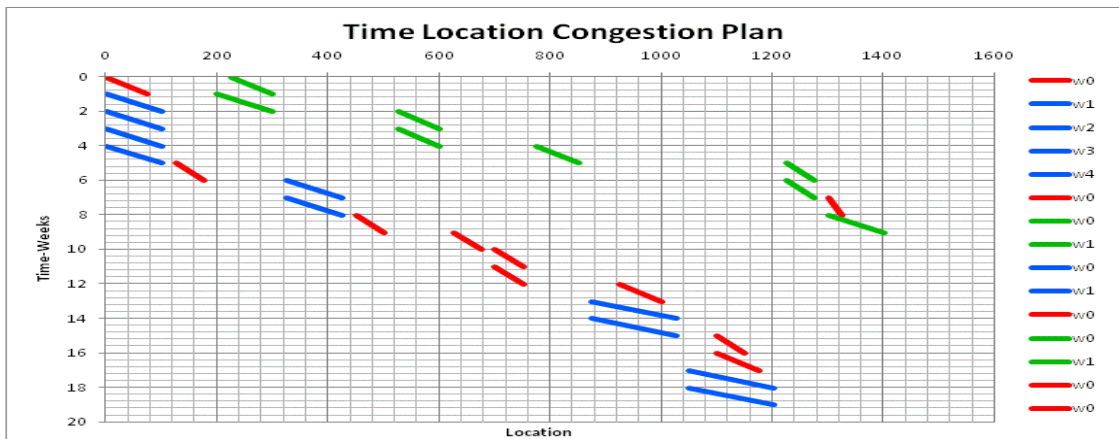
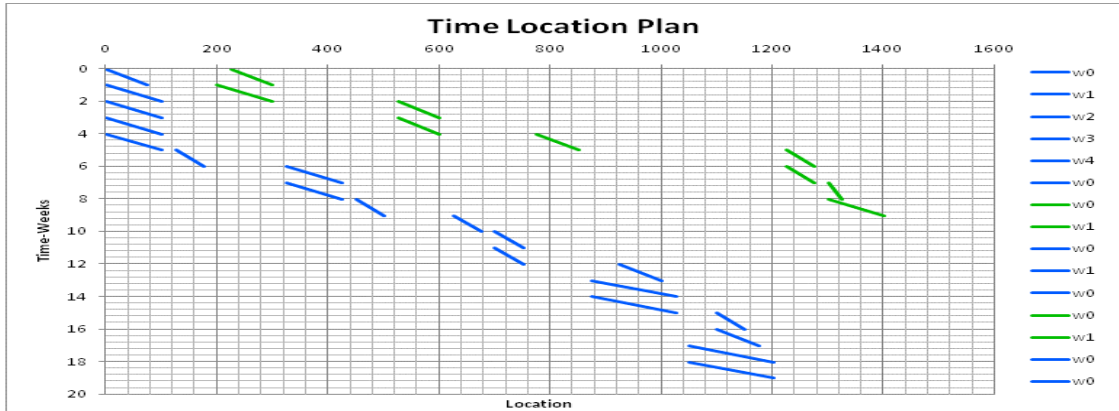
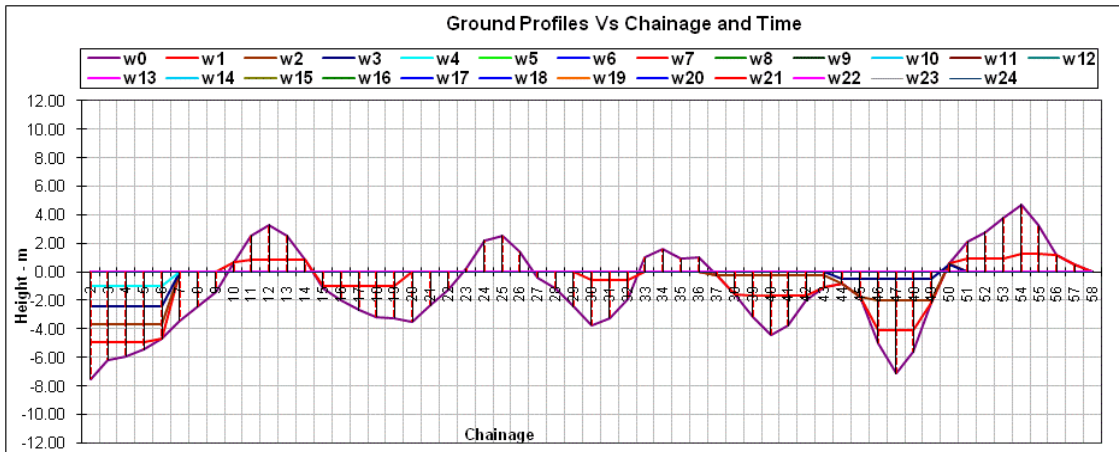
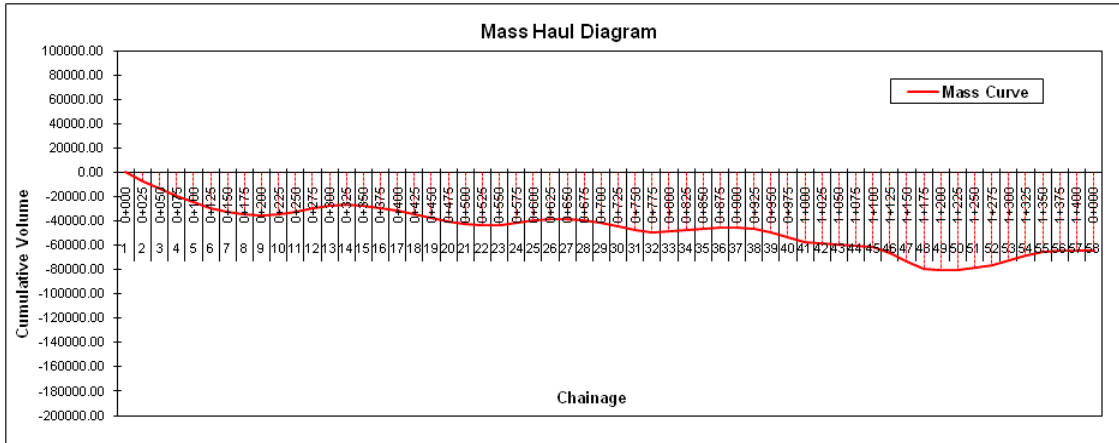
Experiments with a road section of 7 km road projects (From 0+000 to 7+000 km road section)

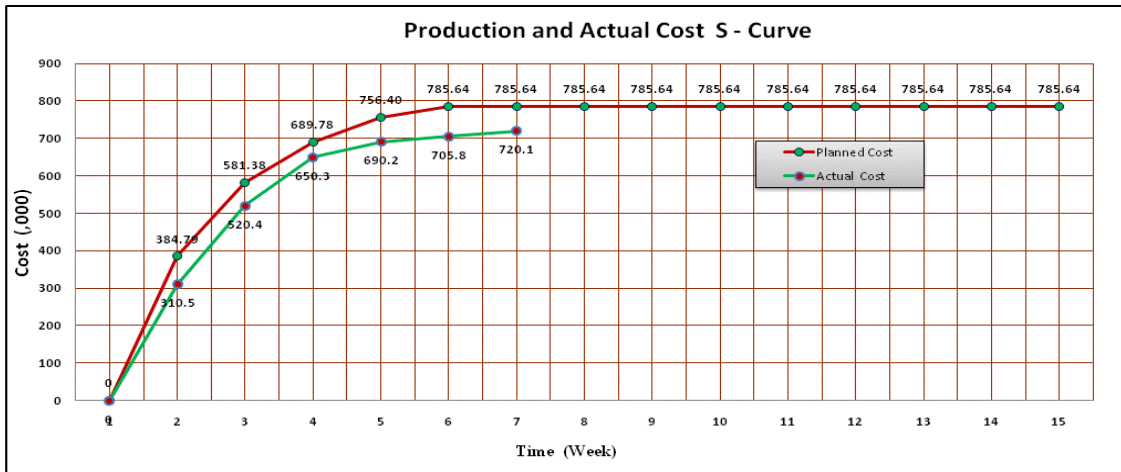
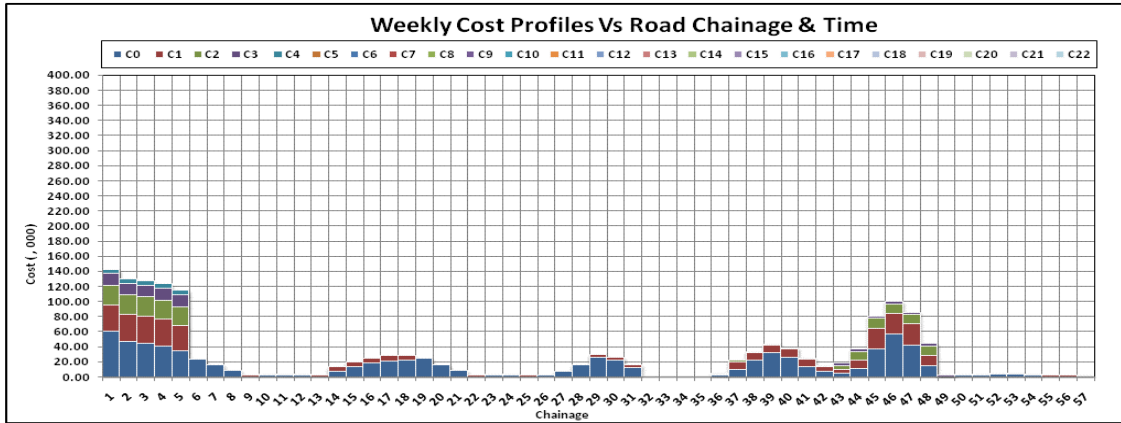
This appendix presents the experiment results of a 7 km road section. The road section was selected from the lot 6 road projects in Portugal. The road section was divided into 5 sections (each section with 1.4 km) for the experiments. The experiments were carried out with the model functions, and the results (graphical outputs) of the experiment for each road section are presented below. The graphical outputs display the prototype model behaviours and confirm model functionality under different types of road profiles in road projects, assuming user-defined productivity, and considering available sets of equipment, resource and site constraints. The following are the graphical outputs (experimental results) obtained from the selected road section.

- 8) Longitudinal profiles
- 9) Mass haul diagram
- 10) Weekly progress profiles
- 11) Time location plan / location-based schedules
- 12) Time-location / space congestion plan
- 13) Weekly cost profiles
- 14) Cost S-curve.

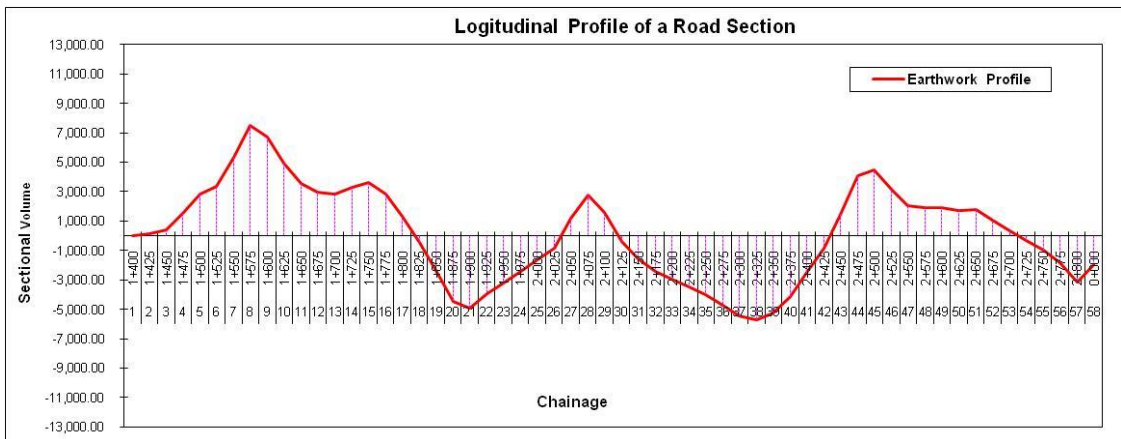
1) Road section from chainage 0+000 to 1+400 (1.4 km)

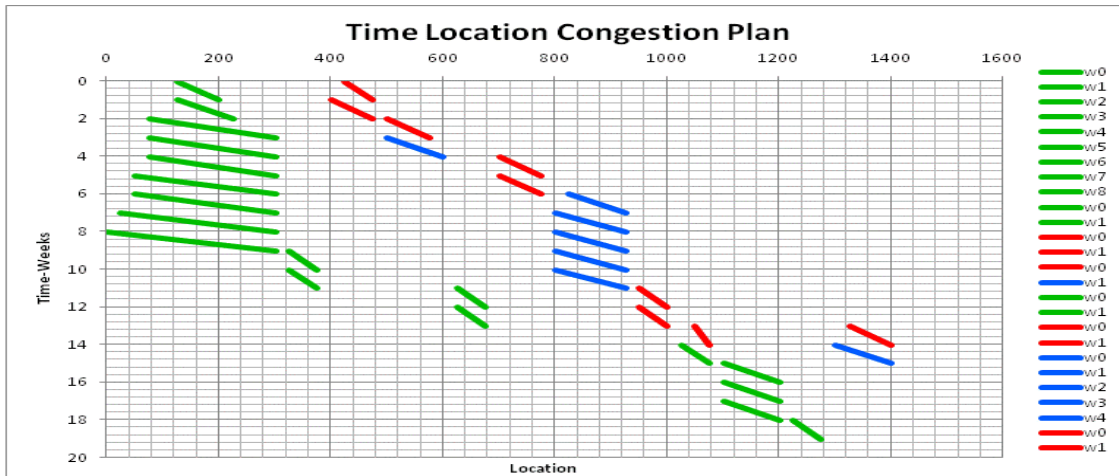
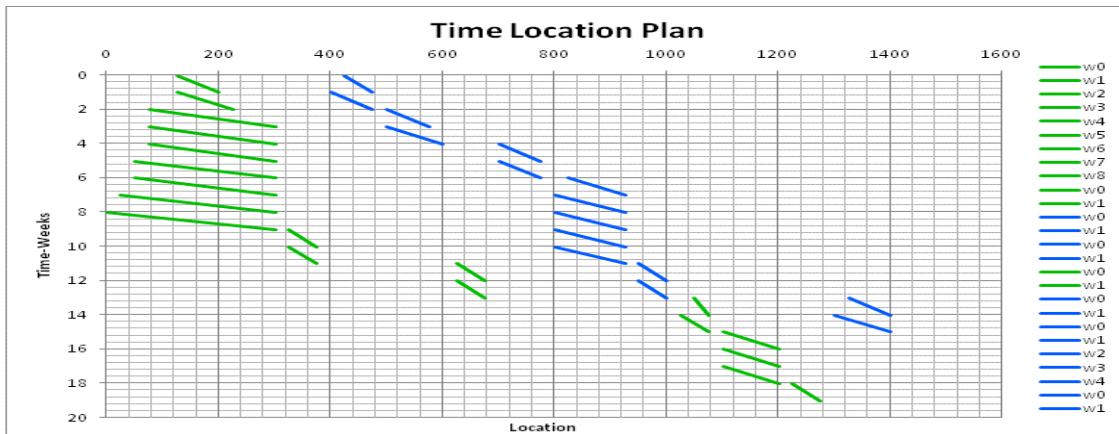
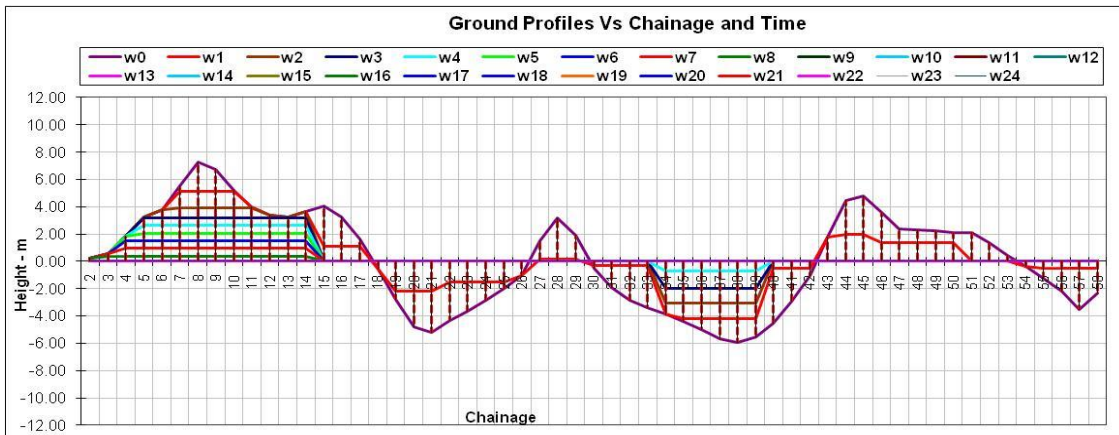
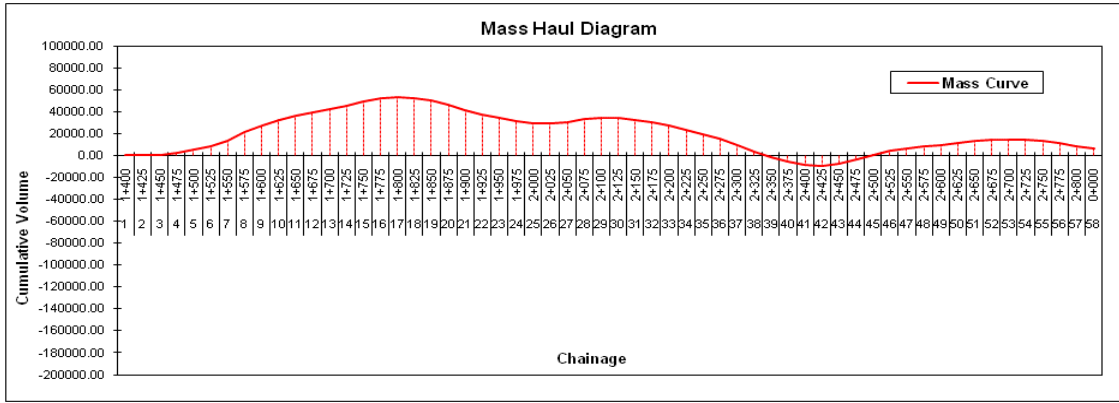


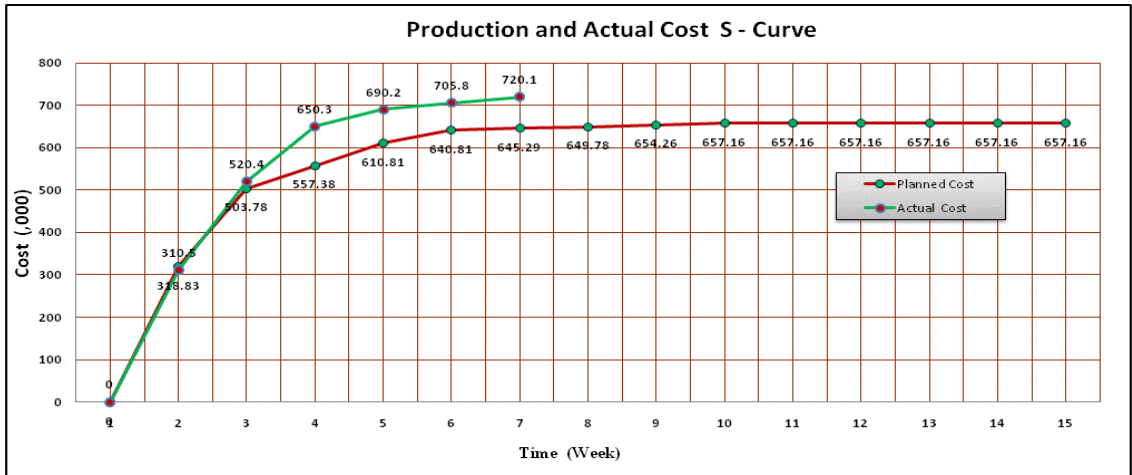
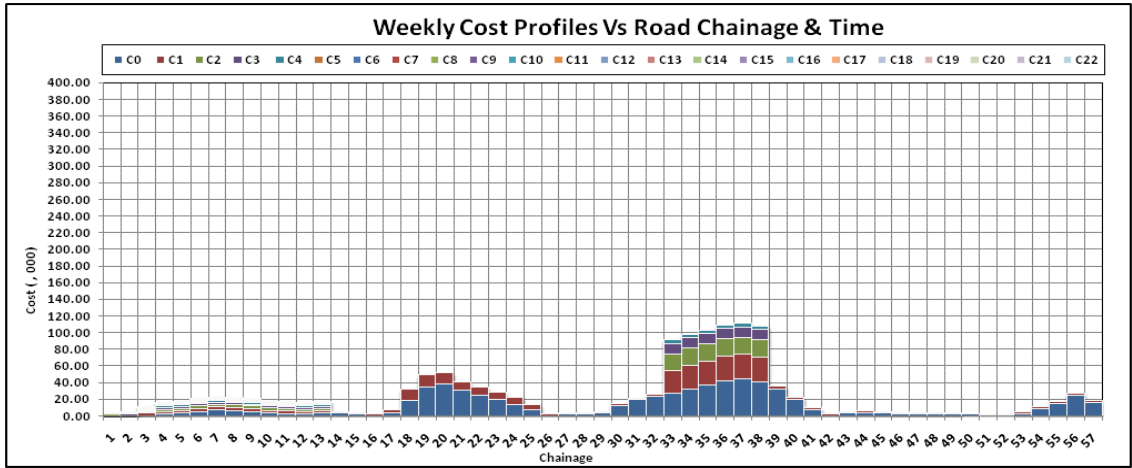




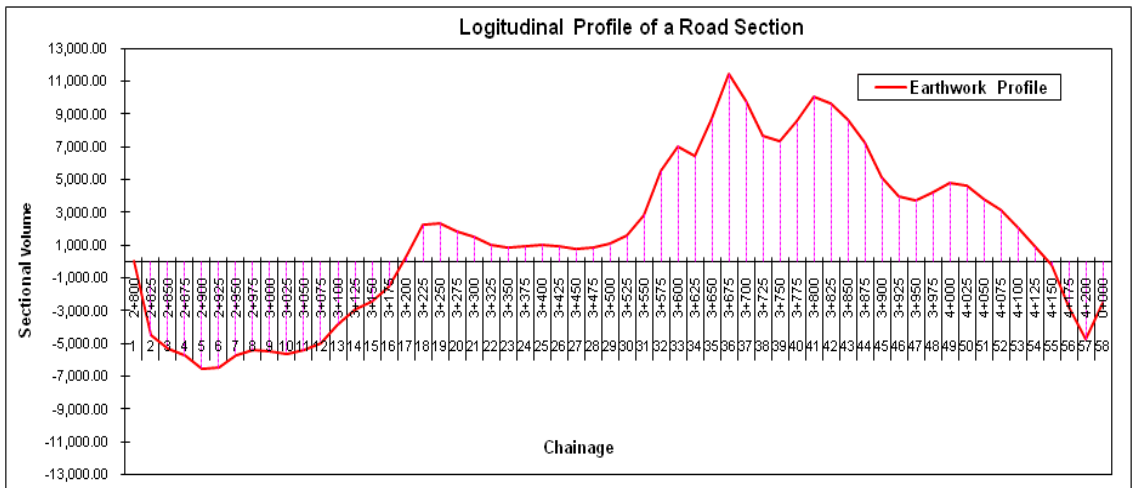
2) Station: Road Section from chainage 1+400 to 2+800 km

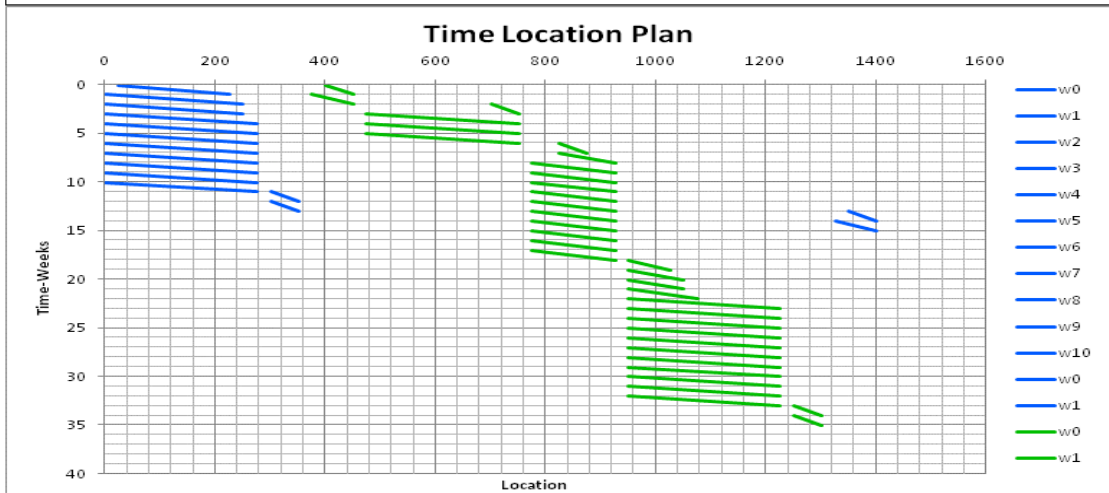
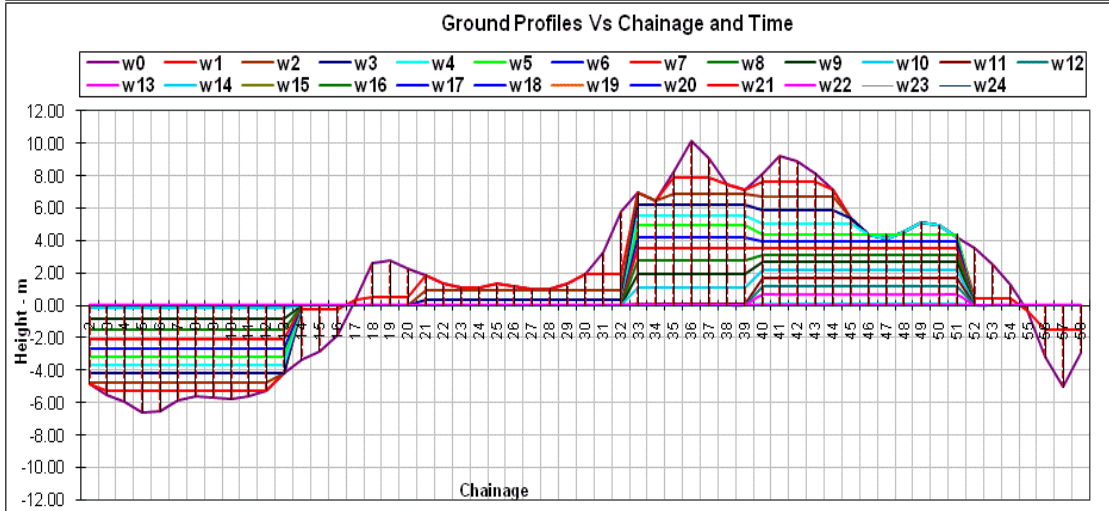
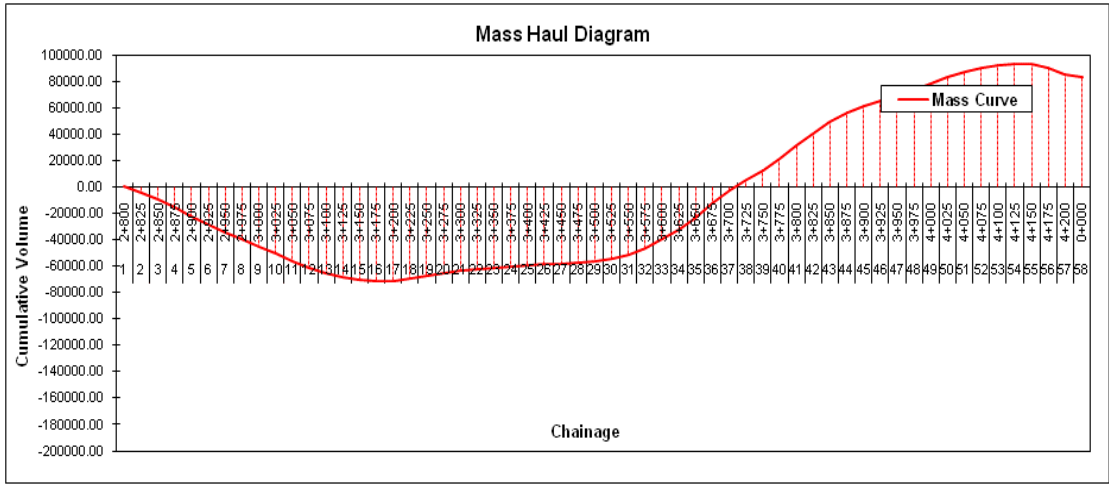


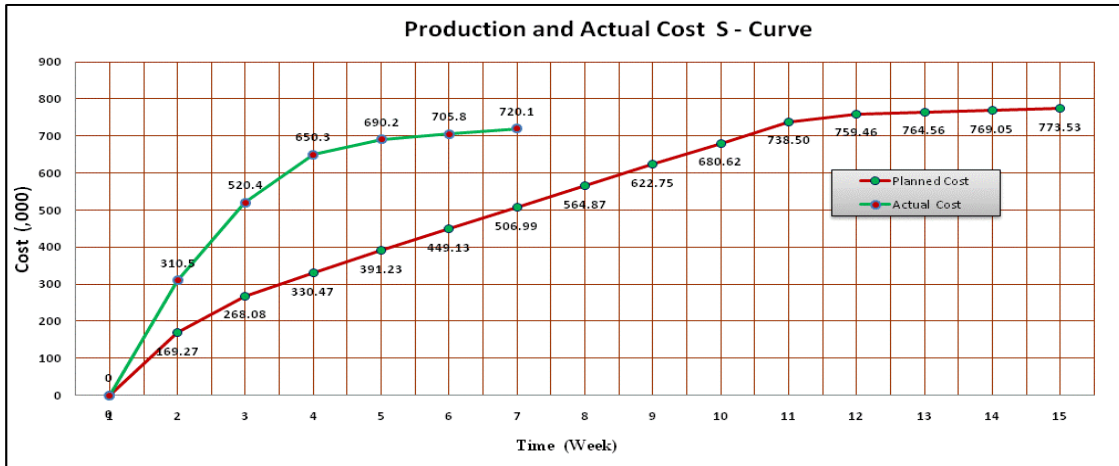
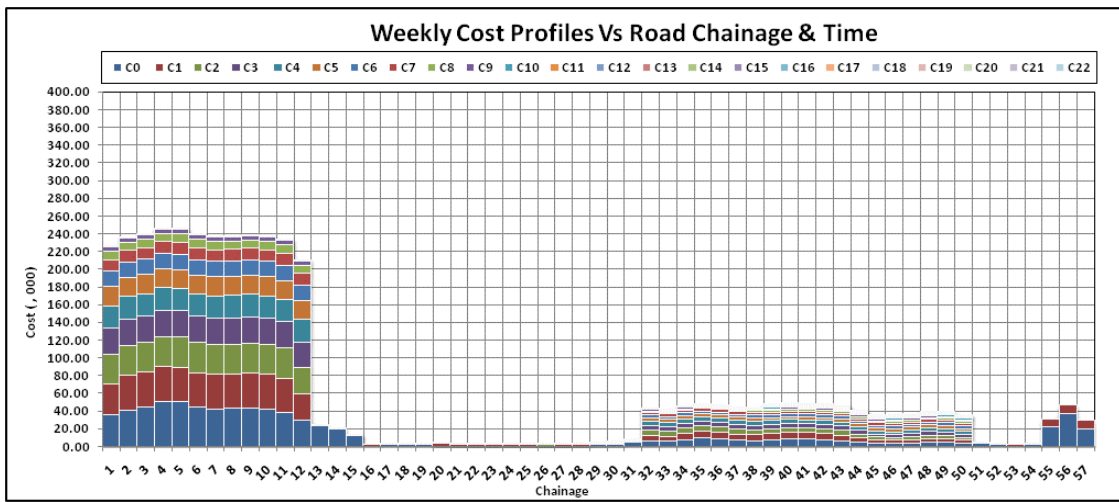
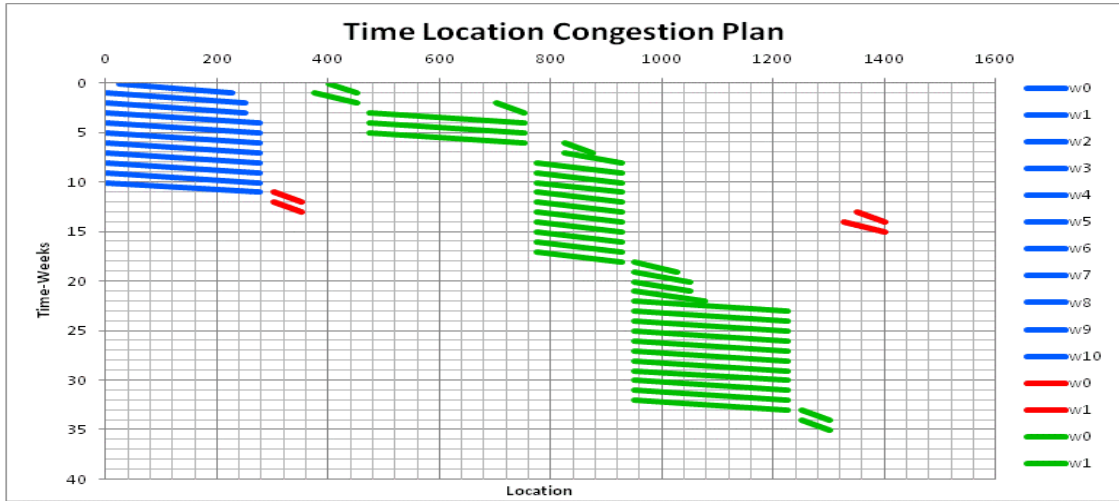




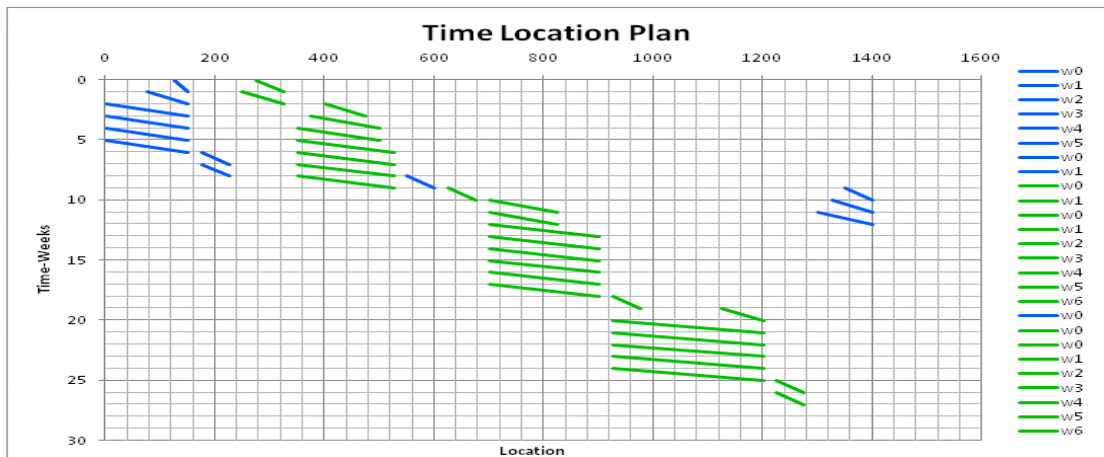
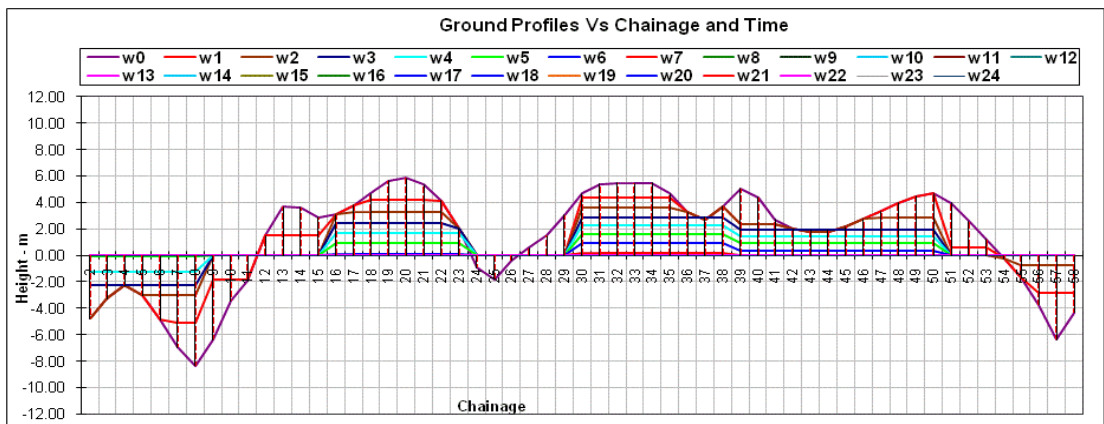
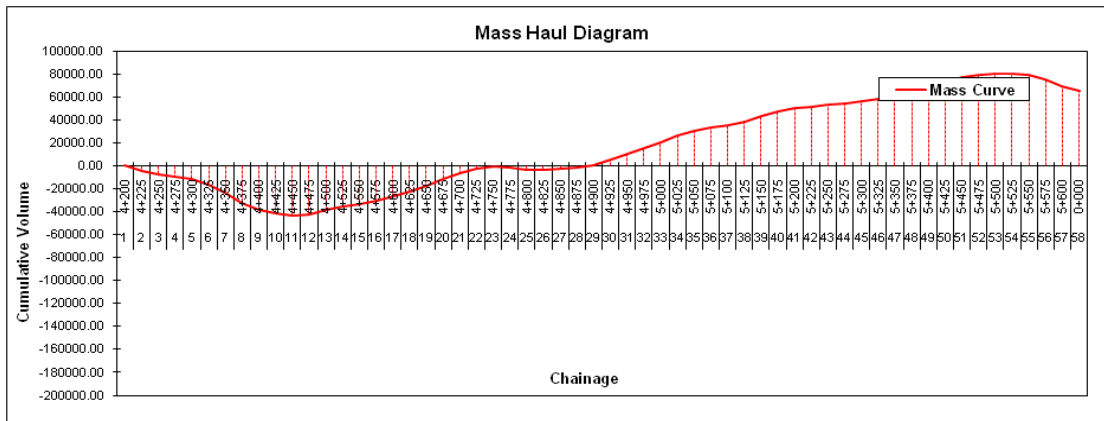
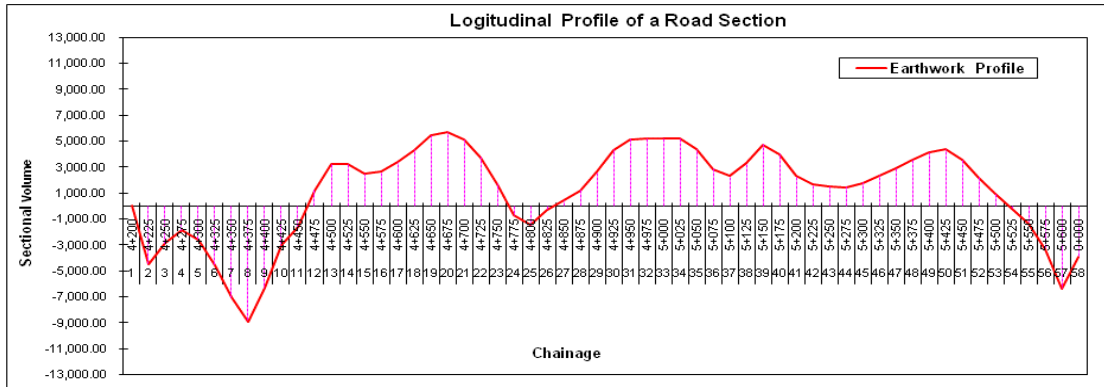
3) Road Section 2+800 to 4+200 km

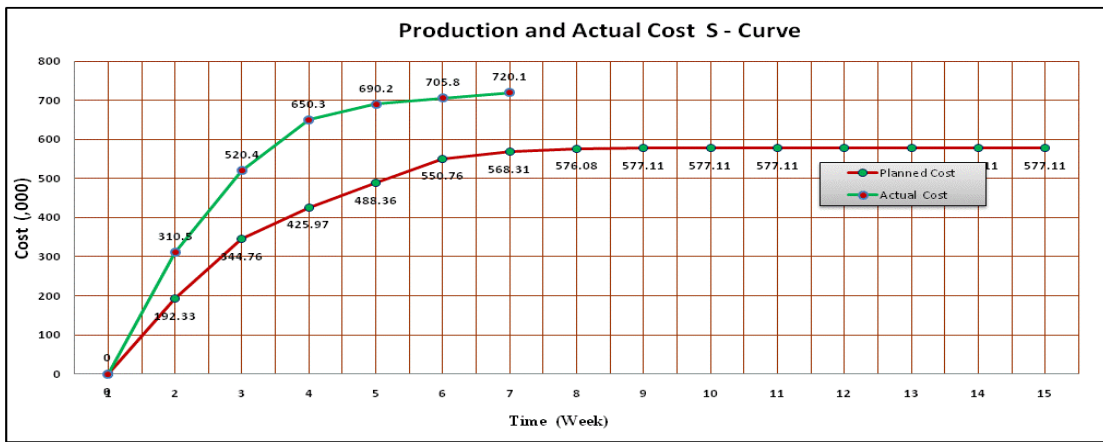
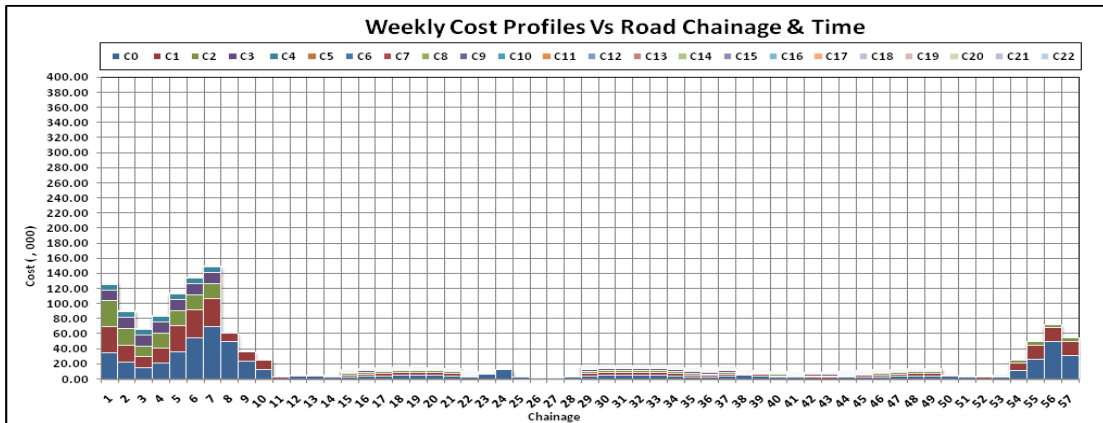
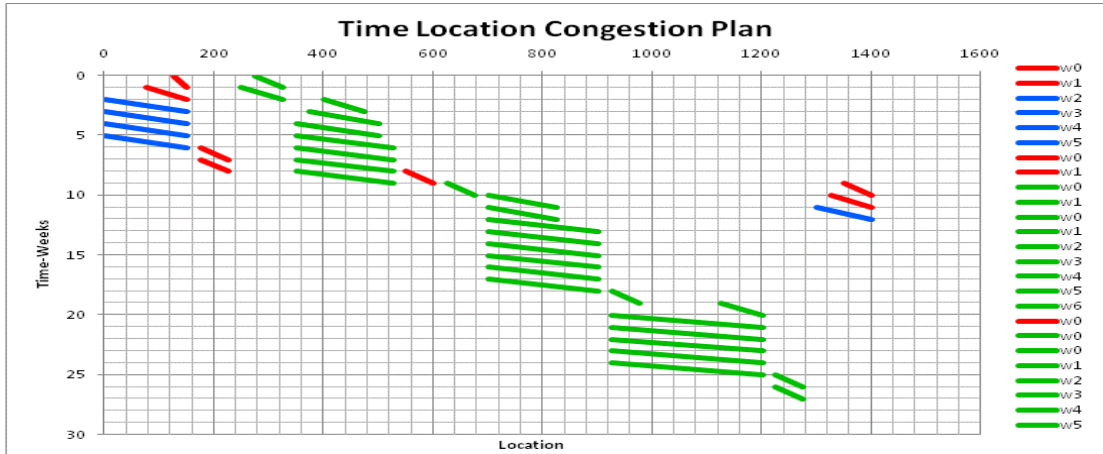






4) Road Section 4+200 to 5+600 km





5) Road Section 5+600 to 7+000 km

