PLANNING AND SCHEDULING HIGHWAY CONSTRUCTION USING GIS AND DYNAMIC PROGRAMMING

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ABSTRACT

Planning and Scheduling Highway Construction Using GIS and Dynamic Programming

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This study presents a model to plan, schedule and control the construction of highway projects. It automatically generates the work breakdown structure and develops precedence networks defining the construction of new and rehabilitation projects. Geographic information systems (GIS) is employed to automate data acquisition and analyse spatial data. Digital terrain models are generated to represent the original ground topography and underlying soil strata. Variances in swell and shrinkage factors of different soil types are considered in computing cut and fill quantities. The optimum earthmoving plan is automatically developed, accounting for the presence of transverse obstructions.

A two-state-variable, N-stage dynamic programming procedure, in conjunction with a set of heuristic rules, are employed to optimize either: 1) construction duration; 2) total construction cost; or 3) their combined impact for cost-plus-time bidding, also known as “A+B” bidding. The model is capable of generating schedules to meet a specified budget or duration restraints, and can select the optimum expediting technique to reduce project duration. Resource-driven scheduling is employed to ensure work continuity for crews. Both repetitive and

non-repetitive activities are incorporated in the optimization procedure. The proposed model incorporates both typical (equal quantity of work in all units) and non-typical (varying quantities along highway length) repetitive activities in the optimization procedure. The proposed model accounts for the impact of practical factors, such as transverse obstructions, on crew assignment and project duration and cost. The impact of inclement weather on crew productivity is accounted for, as well as the beneficial effects of the learning curve. A relational database model is developed to store: 1) local weather conditions; 2) swell and shrinkage factors for various soil types; and 3) the available resource pool. The model supports tracking and controlling project progress utilising the earned value concept. A flexible and practical methodology is proposed to forecast project time and cost at completion, enabling the assignment of a higher weight to recent crew performance.

A prototype software based on the model is developed, coded in Visual C++ (version 6.0), employing object oriented programming. ArcView® version 3.1 is employed as the GIS engine, and the 3-D data analysis is carried out employing ArcView® 3D Analyst. Microsoft Access® is employed as the database management system. The model operates in Windows environment, providing a friendly graphical user interface. It is capable of generating graphical and tabular reports and at various degrees of detail to suit the requirements of project members.

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NOMENCLATURE

α_{ck} = performance indicator of crew (c) to work on section (k) based on its capacity

β_{ck} = performance indicator of crew (c) to work on section (k) based on its performance

γ_{ck} = rank of crew (c) to work on section (k) based on balancing progress with immediately preceding activity(ies)

η_{ck} = composite performance indicator of crew (c) to work on section (k)

C_c = daily cost of crew (c)

CD = calendar date corresponding to workday

$Cdemob_i$ = demobilization cost of equipment (i)

$Cmob_i$ = mobilization cost of equipment (i)

$CT_{i/j\text{-}k}$ = cost of transporting equipment (i) from segment (j) to segment (k)

D_k = duration of woks at segment (k),

$u_{k/1}$ & $u_{k/L}$ = numbers of first and last units of section (k), respectively

DAC = direct activity cost

dc_i = direct daily cost of equipment (i)

DCEC = daily equipment cost of crew c

DCLC = daily labour cost of crew c

DFC = daily float cost (operating or rental)

Dur_j = duration of works on unit (j)

$E_{i,k}$ = top elevation of stratum "i" at point "k"

EF_j = actual finish of work on unit (j)

ES_j = actual start of work on unit (j)

G_k = ground elevation at point "k"

IAQ_c = quantity initially assigned to crew (c)

IDC = indirect daily project cost

L = distance between end sections

L_k = length of segment (k)

$M_{i,j}$ = element [i][j] of the mobilization matrix

$MaxAss_c$ = max quantity of work that can be allotted to crew (c)

$MC_{c/j\text{-}k}$ = mobilization cost of crew (c) from segment (j) to segment (k)

MC_c = mobilization/demobilization cost of crew (c) to/from site

MCU = material cost per unit of measurement

n = number of crews comprising a crew formation

n_{eq} = number of pieces of equipment comprising a crew

$n_{eq'}$ = number of pieces of equipment requiring a float for travel

N_{ins} = number of insurmountable obstructions

P_c = daily productivity of crew (c)

$Prod_{a_i}$ = actual productivity during period i

$Prod_p$ = planned productivity

PSD_j = possible start date of unit (j) due to precedence relations

Q_j = quantity of work in unit (j)

$Quan_{D/J}$ = quantity of work in unit J completed on day D

QW_k = quantity of work in section (k)

R = radius of horizontal curvature

RUC = daily road user cost

$t_{c/j-k}$ = time (working days) required to relocate crew (c) from segment (j) to segment (k)

$t_{s,k}$ = thickness of stratum "S" at point "k"

TAC = total activity cost

TF = total time (hrs) float is required

$Tdemob_i$ = demobilization time (hrs) required by equipment (i)

$Tmob_i$ = mobilization time (hrs) required by equipment (i)

$Tdemob_f$ = float demobilization time (hrs)

$Tmob_f$ = float mobilization time (hrs)

$v_{i,j-k}$ = travel speed (km/hr) of equip (i) corresponding to the road conditions between segments (j) and (k)

wh = number of working hours per day

WT_A = relative weight of activity A

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

Highways are a cornerstone of any nation's infrastructure. For centuries, highways have carried people, goods and ideas from one corner of the earth to another. In Québec, there are 4,860 km of highways (Québec Ministry of Transportation 2000), while in 1995, 114,900 lane-kilometres were reported (NCHRP 1999(b)) to connect the United States. These figures reveal the extensive highway network throughout North America. The term "highway" was dubbed by the Romans, who heaped up earth from parallel ditches when constructing the roadbed. This was in order to provide a drainage mechanism for the constructed roads, and resulted in roads being elevated above ground level, literally creating a high way (NGS 1992). It is the responsibility of the project team to ensure efficient utilisation of available resources and deliver a quality highway, while satisfying the scheduling objectives and minimising public inconvenience.

1.2 Repetitive Construction

Highway construction projects can be classified as repetitive projects, where crews repeat certain tasks at many locations throughout the project. Other examples of repetitive projects include high-rise buildings, multiple housing construction and pipeline construction projects. The main concern of contractors executing activities in this class of projects is maintaining crew work continuity (Johnston 1981; Arditi and Albulak 1986). Benefits gained through maintaining work continuity include:

1. Maintaining a constant workforce by reducing hiring and firing of labour.
2. Retaining skilled labour.
3. Maximizing use of the learning curve effect.
4. Minimising equipment idle time.

The applicability of network scheduling techniques, such as critical path method (CPM) and program evaluation and review technique (PERT) to scheduling repetitive projects has long been questioned (O'Brien 1975; Adeli and Karim 1997; Yamin and Harmelink 2001). The main disadvantages of applying network techniques to repetitive projects can be summarised as follows:

1. When applied, each repetitive activity is divided into a series of activities, such that the duration of each sub-activity does not exceed 10 days (Vorster *et al* 1992). Thus, the number of activities required to generate the project's precedence network can become relatively large, resulting in a complex network diagram.
2. They do not maintain work continuity for the work crews.
3. They impose a high level of detail, which masks the uncertainty and production decision realities that actually control the project.

4. Multiple-crew strategies are difficult to implement.
5. They do not provide an efficient structure for representing repetitive activities.
6. They do not provide data regarding crew progress along a project.
7. They are incapable of accounting for the learning curve effect.

Vorster *et al* (1992) suggested dividing repetitive projects into two categories: i) projects that are repetitive due to the uniform repetition of a unit network throughout the project (non-linear projects); and ii) projects that are repetitive due to their geometric layout (linear projects). Examples of non-linear projects are multiple housing projects and high-rise construction, while highway and pipeline construction are examples of linear projects. One of the main differences between the two classes of projects is that, unlike linear projects, what constitutes a unit is physically defined in non-linear ones. In the former class of projects, when multiple crews are assigned to an activity, each crew can be assigned to non-adjacent units. For example, if two paint crews are assigned paint all floors in a high-rise building, a crew assignment scenario could be that one crew is assigned to odd-numbered floors, while the other is assigned to even-numbered ones. For non-linear repetitive projects, this is a viable solution because:

1. Relocation is part of executing a repetitive activity. In other words, crews must relocate from one unit to another (e.g. move from floor to floor, or house to house) to execute the work in all units.

2. Costs incurred when moving from unit "i" to unit "i+1" might be identical to moving from unit "i" to unit "j" (where $j \neq i \pm 1$). For example, in high-rise construction, a crew could move from the 4th floor to the 6th floor just as easily as moving to the 5th floor (press of a button in the elevator).
3. In some cases, unit number does not reflect proximity of a unit to another. For example, in a multiple housing construction project, unit 5 (house 5) could be closer to unit 7 (house 7) than unit 6 (house 6) if odd-numbered units are on one side of a street, and even-numbered units on the other.

On the contrary, assigning crews to non-adjacent units is an impractical solution for linear projects. While the relocation process discussed above is mandatory for non-linear repetitive projects, that is not the case for linear ones, where, unless a transverse obstruction exists between adjacent units, crews simply advance from one unit to the next. For example, a crew paving a highway would simply progress from km 5 (unit 5) to km 6 (unit 6) as it paves the highway. If a transverse obstruction exists between two adjacent units, upon reaching that obstruction, crews would need to demobilize, travel around the obstruction (e.g. cross via the nearest crossing) and set up at the other side of the obstruction to execute the remaining work. This relocation process is analogous to the relocation process crews have to go through between units in non-linear projects.

Figure 1.1 shows the case where two identical crews are assigned to work on a linear activity with equal quantities of work in all units (typical activity). Part (a) of the figure shows the case where the project is divided into two sections, each executed by a crew, while part (b) shows the case where crews are assigned to alternating units. The relocation time "T", shown in part (b) of the figure, is the time required for a crew to relocate from one unit to another, non-adjacent unit. It is a function of: 1) travel distance; 2) driving conditions between them (paved or off-highway conditions); and 3) crew size and mobility. The figure shows that, for linear projects, the duration required to complete a repetitive activity is shorter when the project is broken down to a number of sections, each executed by a crew ("dur_a" in figure 1.1(a)), rather than scheduling crews to alternate between units ("dur_b" in figure 1.1(b)). The total cost of executing an activity is similarly affected. Therefore, when scheduling highway projects, crews are assigned to sections of the highway.

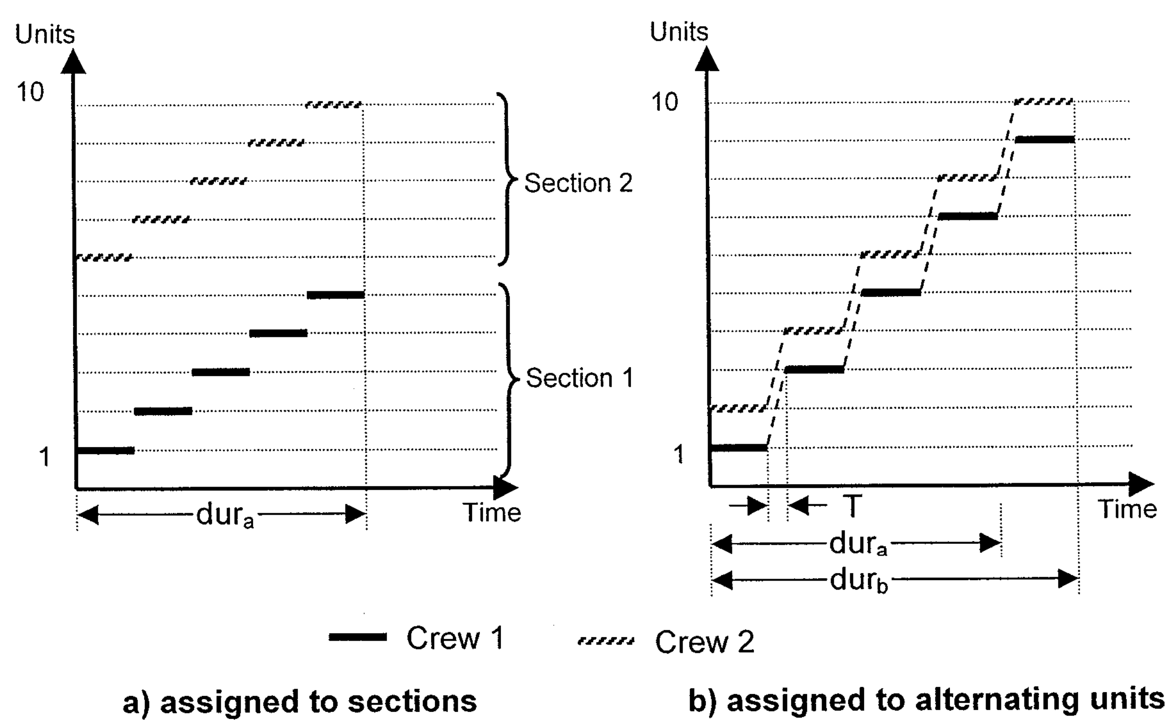


Figure 1.1: Crew assignment strategies for linear projects

1.3 Current Practice

Herbsman (1987) stressed the need for improved scheduling and monitoring methods for highway projects. Although precedence networks required to define construction of highway projects are typically simpler than those for industrial and residential construction, a recent study by Anderson *et al* (1999) revealed that highway construction firms consider poor scheduling and phasing of construction to jointly represent the second most factor impeding competent construction. A recent survey (NCHRP 2000(a)) reported that current scheduling tools lack the ability to link project resources, provide graphics or provide any flexibility in conducting "what if" analysis. A flexible tool capable of providing practical and realistic schedules is thus needed. Generally, highway construction projects can be divided into two main categories; construction of new highways, and rehabilitation of existing ones. The current practices when embarking on both types of construction are discussed below. For a review of the differences between operations involved in new pavement construction and rehabilitation, the reader is referred to NCHRP (1972) and NCHRP (1997).

1.3.1 New Highway Construction

In the scope definition phase, highway projects are typically broken down into work zones, where each zone is divided into one or more segments. The basis for this project division is based mainly on the locations of transverse obstructions, as will be discussed in Section 4.2.1. For example, Figure 1.2 shows a simplified plan of the west extension of the 407 Express Toll Route (ETR), recently constructed in Toronto, Ontario. In the scope definition stage, the project was divided into three work zones along Bronte Creek and 16 Mile Creek (see Figure 1.2), and each work zone was administered independently. Traditionally, boundaries separating work zones and segments are defined adopting any of the following approaches (or any combination thereof):

1. Strategically, for any of the following reasons:
   I. To define different phases of completion for various project segments. For example, a segment connecting two existing highways might be scheduled to open to the public before other segments.
   II. To expedite construction, by breaking the project down to more segments. This would result in more crews working concurrently on any activity, expediting construction.
   III. The presence of legislative borders. Highways crossing province borders might be divided at the border, each province supervising the construction of portions within its boundaries.
2. Physically, by transverse obstructions which impede access from one segment to the next, such as rivers or creeks. Crossing such obstructions could incur considerable costs and mobilization/demobilization times if alternate routes to the following segments are significantly long.
3. Based on the number of crews the user is willing to commit to the project, or number of separate subcontracts the user wishes to manage. If the user is

employing own crews to execute an activity (or more) of the project, then the number of committed crews plays a major role in deciding the number and size of segments.

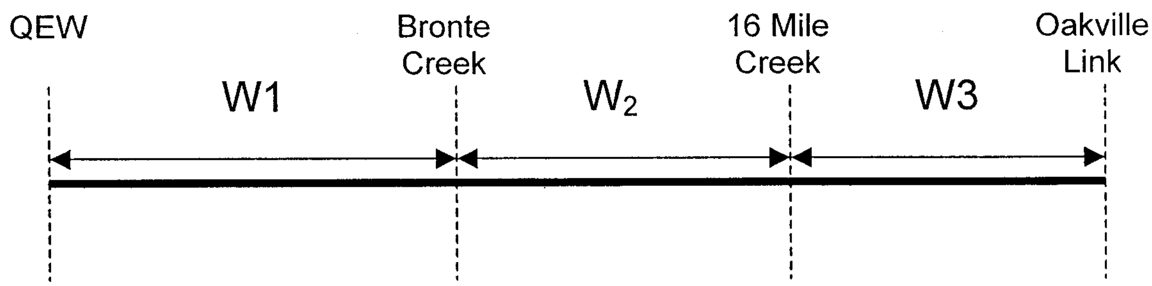


Figure 1.2: Subdivision of West extension of 407 ETR project

Upon completing highway design, cut and fill quantities are estimated to determine the scope of work involved in earthmoving operations. This is typically achieved by computing the cross-sectional area of the highway embankment at regular intervals (10-50 m) along the highway length (Siyam 1987). Sections' areas are typically determined using a planimeter, or other approximate methods. Upon determining the area of cut or fill at two successive sections, the volume of soil contained between them is estimated using the average-end-area or prismoidal formulas (Meyer and Gibson 1980). The optimum earthmoving plan is then developed, and the quantity of work involved in earthmoving operations is determined.

Activities involved in constructing a new highway are defined, along with the quantities of work involved in each. The precedence network respecting job logic is developed, and the project duration determined. In order to generate realistic schedules, each repetitive activity is divided into sub-activities, and crews are assigned to the various sections. Standard production rates, such as the ones shown in Table 1.1 (NCHRP 1995) are employed to determine the duration of work of all activities. Currently, network scheduling techniques (e.g. critical path method (CPM) and program evaluation and review technique (PERT)) are the most widely used tools to schedule highway projects (Harmelink 2001). As discussed earlier, they have a number of shortcomings when applied to repetitive projects.

Resources are then assigned to activities, and a construction schedule can be generated. If an activity is to be subcontracted, typical productivity rates and costs are employed to schedule it. Although it is in the project's best interest to maintain crew work continuity, it is not considered while generating the schedule. Rather, contractors are left with the task of attempting to minimise potential idle time for their crews, while adhering to the schedule.

Table 1.1: Sample production rates for highway operations (NCHRP 1995)

Section	Item	Contract Time
201	Clearing and grubbing	1.5 Acres/day
202	Removal of timber bridge	2 Spans/day
202	Removal of PCC pavement	400 Yd^2/day
202	Removal of concrete box culverts	1/day
202	Removal of asphaltic concrete surfacing	1 Mile/day 2 Lane miles/day
203	Excavation or embankment (figure highest quantity only)	3000 Yds^3/day (rural) 1000 Yds^3/day (urban)
203	Borrow or truck hauled embankment	500 Yds^3/day (truck hauled)
203	Mucking ditches (consider section)	1000 ft/-0.5 Mile/day
203	Mucking (very large quantity)	3500 Yds^3/day
203	Shaping roadbed	1 Mile/day
203	Shaping roadway, ditches and slopes	0.5 Mile/day
203	Shell embankment	2500 Yds^3/day
301	Base course (non-stabilized)	1500 Yds^3/day
301	Base course (Class I)	1000 Yds^3/day
302	Scarifying and compacting roadbed	1 Mile/day 2 Lane miles/day
303	In-place cement stabilized base course	6000 Yds^2/day (roadway) 4000 Yds^2/day (shoulders)
304	Lime treatment (24 Ft. width)	6000 Yds^2/day
	(20 Ft. width)	5000 Yds^2/day
305	Subgrade treatment (working table)	8000 Yds^2/day
401	Aggregate surface course	300 Yds^3/day
501	Asphaltic concrete (less than 20 tons or broken construction)	500-1000 Tons/day
501	Asphaltic Concrete (typical overlay or construction)	1000 Tons/day

1.3.2 Rehabilitation of Existing Highways

Over the last decade, there have been an increasing number of 3R-type projects (rehabilitating, reconstructing and restoring) in the highway construction industry (Herbsman *et al* 1995; NCHRP 1999(b)). This trend is mirrored in Canada, where, in 2002, the Ministry of Transportation of Québec allocated $1.4 billion for 283 highway rehabilitation projects, a 73% increase over the previous year's budget (King 2002). Figure 1.3 (King 2002) shows some rehabilitation projects scheduled for the island of Montréal, and their associated cost.

Figure 1.3: Planned roadwork for Montréal area in 2002 (King 2002)

It has also been reported (Mattila 1997) that over 34% of urban interstate highways in the United States are in dire need for rehabilitation. The main reasons to rehabilitate an existing highway are (NCHRP 1974; NCHRP 1999(b)):

1. Meeting unforeseen traffic demands (addition of lanes and/or interchanges).
2. Upgrading old highways to conform to current design standards.
3. Mitigating pavement deficiencies (e.g. rutting, stripping and cracking).
4. Preserving pavement condition and preventing further deterioration.
5. Adding high-occupancy vehicle lanes, or other facilities that improve efficiency.

The cost of highway rehabilitation projects is generally classified into three main categories (NCHRP 1999(b)):

1. Direct rehabilitation costs, including engineering, construction and administration.
2. Road user costs, borne by motorists during construction (NCHRP 1999(a)).
3. Social, economic, and environmental factors, borne by the neighbouring community.

In order to minimise public inconvenience during construction, several contracting techniques have been proposed to expedite construction. These include: i) lane rental (Herbsman and Glagola 1998); ii) cost-plus-time (also known as "A+B") bidding (Herbsman *et al* 1995); iii) use of incentives/disincentives; and iv) use of flexible notice to proceed, also known as "flex-time" (NCHRP 1995). Other contracting methods, including variations of the cost-plus-time bidding method, have been successfully implemented by some US DoT's (Shr *et al* 1999; NCHRP 2000(c)). The frequency of employing these contractual techniques was recently investigated (NCHRP 2000(c)). The study concluded that applying incentives/disincentives is the most frequently used of the above techniques, followed by cost-plus-time bidding, and lane rental. In the pool investigated in the above study, the rate of success of applying of these contractual methods was as listed in Table 1.2 (modified after NCHRP 2000(c)). As the table shows, innovative contracting methods can result in minimising public inconvenience. It should be noted that of these contractual methods, only cost-plus-time bidding has a direct impact on contract time (NCHRP 1995).

Table 1.2: Impact of contracting method on reducing lane occupancy (modified after NCHRP 2000(c))

Contracting method	High impact (%)	Medium impact (%)	Low impact (%)
Lane rental	61.9	23.8	14.3
Cost-plus-time	50	36.7	13.3
Incentives/disincentives	43.9	36.6	12.2

1.4 Objectives

The main objectives of this study are:

1. Developing a practical model to plan, schedule and control highway construction while maintaining work continuity for all crews. In this regard, the model accounts for transverse obstructions, resource availability and impact of weather on crew productivity.
2. Optimizing scheduling of highway construction projects with respect to: 1) project duration; 2) total cost; 3) their combined impact for what is known as cost-plus-time, or A+B, bidding (Herbsman 1995).
3. Developing a methodology to schedule highway construction projects to satisfy a specified deadline or budget, if possible.
4. Automating data acquisition for highway construction, and developing a methodology to accurately estimate cut and fill quantities.
5. Developing optimized earthmoving plans.
6. Developing a prototype software to serve as a proof of concept to the developed methodology.

1.5 Scope and Limitations

This study proposes a model to plan, schedule and control highway construction projects. Geographic information systems (GIS) is employed to automate data acquisition and analyse spatial project data. Multiple soil layers are incorporated in cut sections to account for varying swell and shrinkage factors. This enables accurate estimation of cut and fill quantities used in developing optimized earthmoving plans. Resource-driven scheduling is employed to ensure crew work continuity. The proposed model is applicable to all repetitive projects, but is tailored to linear ones, such as highways and pipelines. A two-state-variable, N-stage dynamic programming procedure, in conjunction with a set of heuristic rules, are employed to optimize either: 1) construction duration; 2) total construction cost; or 3) their combined impact for what is known as cost-plus-time, or "A+B", bidding (Herbsman 1995). Both repetitive and non-repetitive activities are incorporated in the optimization procedure. Both typical (equal quantity of work in all units), and non-typical (varying quantities along highway length) are considered.

The model is also capable of generating schedules to satisfy a specified budget or duration. If a project needs expediting, a methodology is proposed to identify critical activities and select the optimum expediting technique. The model provides a template precedence network to schedule new and rehabilitation highway projects. The most common rehabilitation techniques (NCHRP 1999(a)) are considered, namely: 1) overlaying an existing pavement; 2) stripping an existing pavement and applying a new one; and 3) increasing highway width by adding extra lanes. A relational database model is developed and employed to store available resources and their availability periods. The model supports tracking and controlling project progress utilising the earned value concept. A new methodology to forecast project time and cost at completion based on recent crew performance is proposed.

During scheduling, the model accounts for several practical factors, such as the impact of transverse obstructions on crew assignment and project duration and cost. An earlier survey (NCHRP 1995) found the impact of inclement weather to be the factor most frequently considered by state DoT's. It was thus deemed appropriate to account for the impact of inclement weather on crew productivity, as well as the beneficial effect of the learning curve. A prototype software incorporating the developed methodology is coded in Visual C++6, employing object-oriented programming. ArcView® 3.1 is employed as the GIS engine, and the three-dimensional data analysis is carried out employing ArcView® 3D Analyst. Microsoft Access® is employed as the database management system (DBMS). The model provides a friendly graphical user interface (GUI) and generates graphical and tabular reports. Schedules are generated in various formats and at various degrees of detail to suit the requirements of all members of the project team. The model attempts to provide the flexibility and graphic capabilities reported to be lacking in current scheduling tools (NCHRP 2000(a)).

Several aspects of construction scheduling are not considered in the current study. The proposed model does not schedule construction of structures such as bridges and tunnels; construction of bridges' foundation and super-structure are grouped into a single activity, the duration of which is provided by the user. It is assumed that only one crew can be working on any repetitive unit at a time. As such, consolidating two or more crews to develop a larger crew (with higher productivity) is not considered. Shortest travel distances between project segments are not estimated by the model, but are required as input. The loss in crew productivity due to: 1) crowding impact of more than one activity progressing in parallel in the same location (Thabet and Beliveau 1994); and 2) prolonged work schedules (e.g. working overtime and/or working weekends) is not considered. Other factors that can affect project duration, such as permits, are not considered in the proposed model.

1.6 Thesis Organisation

Chapter Two presents a review of the previous research regarding resource-driven scheduling and geographic information systems. The chapter also presents the findings of two surveys which review: 1) current highway construction practices; and 2) weather impact on the progress of highway construction operations. Chapter Three presents an overview of the developed model and its main components, while Chapter Four describes the planning and scheduling module. The proposed optimization procedure is presented in Chapter Five, while Chapter Six describes the computer implementation and validation stages of the proposed model. Chapter Seven presents a summary of the study, concluding remarks, and recommendations for future research.

CHAPTER TWO

INDUSTRY PRACTICES AND LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of the literature regarding the use of GIS for data acquisition and analysis, as well as methods used for scheduling repetitive projects, and related optimization techniques. The core of the literature review focuses on optimized scheduling of linear projects. However, because of the use of GIS in early planning phases and in defining the scope of earthmoving operations, it will be dealt with first. A survey of the current practices in planning and scheduling construction projects is also presented. The survey is carried out to assist in developing a practical methodology that serves users' needs.

2.2 Geographic Information Systems (GIS)

GIS has evolved from various technologies, including cartography, information management and computer science (Antenucci *et al* 1991). Recent advancements in information technology enabled the development of various GIS-based applications in the construction industry (Holdstock 1998). Over the last decade, GIS has been proven to be a versatile and effective tool in various civil engineering applications (Miles and Ho 1999). Many definitions exist that attempt to describe GIS, the most representative is: *"...an organized collection of computer hardware, software, geographic data and personnel designed to efficiently capture, store, update, manipulate, analyse, and display all forms of geographically referenced information"* (Holdstock 1998). Three main areas of computer technology enable the existence of GIS. These are: i) a relational database management system; ii) spatial analytical capabilities; and iii) cartographic capabilities to describe and analyse geographic information. GIS is designed to arrange spatial and non-spatial data such that they can be analysed to aid in the decision making process. There are three main components of a GIS: i) data and database; ii) software; and iii) hardware.

2.2.1 Database of GIS

Developing the database of a GIS is the most costly, time-consuming, and potentially problematic aspect of implementing GIS (Antenucci *et al* 1991). Most commonly, a relational model is employed, which enables efficient and expeditious queries, while adding flexibility in the range of queries that can be carried out. There are two categories of data types managed by a GIS, namely; graphic and non-graphic data. Data such as co-ordinates and symbols that determine geographic locations of various elements are processed as graphic data, while data describing specific features of an element or its attributes are processed as non-graphic data.

Six types of graphic elements are employed to represent map features. These are points, lines, areas, grid cells, pixels and symbols. Graphical data is often conceptualised as being stored as a series of layers, each layer containing functionally related data. Layers are referenced geographically, defining the geographic location of the items displayed in any layer. A control system is employed to manipulate the various layers and produce the complete map, which is achieved by identifying layers of interest and superimposing them to a common geographic reference. This concept is schematically illustrated in Figure 2.1 (Holdstock, 1998).

Figure 2.1: Storage of graphic data (Holdstock 1998)

Non-graphic data, on the other hand, can generally be divided into four main types: 1) non-graphic attributes; 2) geographically referenced data; 3) geographic indices; and 4) spatial relationships. Non-graphic attributes provide descriptive data about elements included in a map, such as the diameter of an existing pipeline, material of which it was made and installation date. Geographically referenced data describe incidents that take place at specific locations, such as permit status and accident reports at specific intersections. Geographic indices such as street and mailing addresses are employed to select and obtain data based on geographic locations. Spatial relations among entities define the proximity of entities to one another.

Identifiers are employed to link the graphic to non-graphic data. These identifiers are commonly referred to as "geocodes". Geocodes are stored with both data types, which enables accurate and efficient data manipulation, and ensures that a modification to one element is correctly reflected in all related fields.

2.2.2 Software and Hardware

Recently, there has been an increase in the number of commercially available GIS software packages. These packages vary in degree of complexity and levels of functionality. Some packages can be implemented on personal computers, while others require workstations or mainframes. Software typically includes a database management system able to query, update and manipulate elements of the database. Hardware should support data input, output and analysis. Recent advances in the field of computer engineering have resulted in more efficient computers with higher processor speed, enabling faster data processing and shorter retrieval time.

2.2.3 Applications of GIS

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

GIS has been successfully utilised in the field of construction management. Although environmental engineering has been the prime field that benefited from GIS (e.g. Gomez *et al* (1996), Gooding *et al* (1993)), GIS is increasingly being utilised in transportation engineering (e.g. NCHRP (1998)), highway management (e.g. Abkowitz *et al* 1990; Li *et al* 1996; Oloufa *et al* 1997; Chang *et al* 1997), evaluation of alternatives for highway route alignment (Sadek *et al* 1999), groundwater modelling (El-Kadi *et al* 1994), as well as the construction industry (e.g. Oloufa *et al* 1992 and 1994). GIS has also been employed to: 1) select the optimum routes for highways and location of bridges (Hammad *et al* 1993); 2) monitor pavement compaction (Li *et al* 1996); 3) select the optimum location for landfills (Kao *et al* 1996); and 4) sequence snow removal operations (Antenucci *et al* 1991).

Jeljeli *et al* (1993) explored potential construction applications that could benefit from implementing GIS, and addresses issues such as utilising GIS to select equipment based on soil type and work conditions. The possibility of employing GIS in both the bidding and design phases was also explored, as was its use in pre-qualification of contractors. The use of ArcView's 3D Analyst® was investigated by Price (1999). The study showed that 3D Analyst® can be readily utilised to determine cut and fill quantities. Providing a comprehensive list of GIS applications in the engineering field is beyond the scope of this study, but the above-cited studies provide a representative sample of research directions that relate to the scope of the proposed study.

2.3 Resource-Driven Scheduling

The awareness that traditional network scheduling techniques are not well suited for planning and scheduling repetitive projects resulted in the emergence of resource-driven scheduling, commonly referred to as linear scheduling (Handa and Barcia 1986). The origins of resource-driven scheduling are not clear, and there might have been multiple origins (Rahbar and Rowings 1992). The need to develop scheduling tools tailored to repetitive projects was realised decades ago (Lumsden 1968), and several models have since been proposed (Carr and Meyer 1974; Ashley 1978; Birrell 1980; Stradal and Cacha 1982; O'Brien et al 1985; Rahbar and Rowings 1992; Handa *et al* 1992; Lutz and Halpin 1992; Yamamoto and Wada 1993) to schedule this class of projects. Vorster (1992) suggested that resource driven scheduling models be categorised based on their ability to accommodate activities with non-constant quantities of work. The term "linear scheduling method" (LSM) was suggested to refer to methods that could accommodate activities with varying quantities of work, while the term "line of balance" (LOB) was suggested to refer to methods that could only model activities with constant quantities of work.

The line of balance (LOB) technique was developed by the U.S. Navy in the early fifties (Harmelink 1995), and has been successfully employed to plan, schedule and control repetitive projects (Carr and Meyer 1974; Arditi and Albulak 1986). Al Sarraj (1990) proposed a mathematical formulation, enabling the development of computer-based applications of LOB. Other models to advance the capabilities of LOB have been developed (Suh 1993; Suhail and Neale 1994; Harris 1996). However, the inability of LOB to accommodate activities with non-uniform quantities of work in its units has limited its application in the construction industry, where activities frequently have non-uniform work quantities. Applications of LSM to the construction industry have been proposed by Johnston (1981), Chrzanowski and Johnston (1986) and Rowings and Rahbar

(1992). The need to develop models integrating both repetitive and non-repetitive activities in the scheduling procedure was identified by O'Brien (1975) and Laramee (1983). On the other hand, adding flexibility by enabling multiple predecessors and successors for each activity was addressed by Birrell (1980) and Cole (1991). Several models integrating linear and network scheduling techniques have been proposed to address these issues (Birrell 1980; Russell and McGowan 1993; Russell and Wong 1993; Suhail and Neale 1994).

On the other hand, several attempts have been made to define critical activities for repetitive projects, analogous to critical activities in network scheduling methods. Suh (1993) proposed a recursive approach, whereby the duration of each activity is extended by one day. If project duration is increased, that activity is declared critical. Handa *et al* (1992) applied the positional weights technique (Helgeson and Bernie 1961) to determine critical repetitive activities. Another approach was adopted by Harmelink and Rowings (1998), where critical portions of repetitive activities were identified. The critical activity path (CAP) was determined following forward and backward passes through the schedule. Proximity between successive activities in the time-location space defined potential points on the CAP. However, multiple predecessors and/or successors were not considered. Based on their model, the concept of rate float, an analogy to float in network scheduling, was later introduced (Harmelink 2001). Another approach to determine the critical path through repetitive projects was presented by Harris (1996), who proposed identifying critical activities based on the job logic representing all activities in a repetitive unit and production rates of activities. Unlike earlier models (Harmelink 1995), multiple predecessors and/or successors can be defined. Control points between successive activities are identified in a manner similar to that proposed by Harmelink (1995).

An essentially graphical method, termed "Repetitive scheduling method" (RSM) was later developed by Harris and Ioannou (1998) to integrate earlier linear scheduling models (Johnston 1981; Chrzanowski and Johnston 1986; Russell and Caselton 1988). Two new concepts were introduced, namely; control points and controlling sequence. A conceptual model was later proposed by Kang *et al* (2001) to minimise crew idle time between assignments. Their model employs network scheduling techniques, and can determine the optimum number of crews assigned to each activity in order to minimise crew idle time. However, the model assumes that: 1) any activity has identical quantities of work in all units; and 2) all crews working on any activity are assumed to have equal productivity. However, none of the above models (Harmelink 1995, Harris 1996, Harmelink and Rowings 1998 and Harmelink 2001) allow for multiple crews working simultaneously on the same activity, and crew unavailability periods are not considered.

While resource levelling has been thoroughly addressed for network scheduling methods (e.g. Easa 1989; Harris 1990; Shah *et al* 1993; Hiyassat 2001), it was rather limited for resource-driven scheduling (Mattila and Abraham 1998). One of the earlier models addressing resource utilisation in repetitive projects was presented by Perera (1982), where a linear programming formulation was developed to optimize resource sharing among activities. Resource sharing was later considered in a resource-constrained scheduling model utilising genetic algorithms (Leu and Hwang 2001). Bafna (1991) presented the first study addressing resource levelling for this class of projects, where heuristic rules were employed to minimise daily variations in resource demands. Suhail and Neale (1994) developed a model that applies resource levelling and float times, as calculated in CPM-type analysis, to repetitive scheduling. The model determines the optimum number of crews required to satisfy a given deadline. Later, Russell and Dubey (1995) employed the minimum moment algorithm to level resources for this class of projects. Both models were integrated with network analysis (CPM). A resource levelling formulation independent of CPM and developed for repetitive projects was proposed by Mattila and Abraham (1998). Based on the model developed by Harmelink (1995), Mattila and Abraham (1998) employed integer linear programming to level resources employed on linear projects. Adopting an approach similar to one that had been earlier applied for network scheduling (Easa 1989), a model was proposed to minimise the sum of the absolute value of the daily variations in resource demand from an average value. Another model developed to optimize resource utilisation through minimising project duration was proposed by El-Rayes and Moselhi (2001(a)). The model accounts for unavailability periods for crews, the impact of weather on crew productivity and the learning curve effect.

Other aspects of repetitive scheduling were also investigated over the last few years. Thomas *et al* (1986) reviewed the learning curve models, and by investigating the correlation between predicted and actual productivity rates, concluded that the cubic model (Carlson 1973) is the one that most closely predicts crew productivity. The straight-line learning curve model was reported to be the most commonly used model for construction activities (Gates and Scarpa 1978). Another aspect of repetitive scheduling was investigated by Dressler (1974), who presented the only stochastic, non-simulation-based scheduling method for linear projects found in the literature.

2.4 Optimized Resource-Driven Scheduling

The need to develop schedules satisfying a specified objective is pressing, particularly for highway construction projects. This class of projects is typically large in terms of capital requirements (Adeli and Karim 1997), and thus the need to minimise construction cost is evident. On the other hand, one of the main objectives is minimising public inconvenience during construction through minimising project duration. Thus, minimising total construction costs and/or duration is of paramount importance when scheduling highway projects. As discussed in Chapter One, highway projects are categorised as linear projects; a subdivision of repetitive projects. Consequently, a review of models developed to optimize scheduling of repetitive projects in general, and linear projects in particular was necessary to determine the current state of research in the field. As will be discussed below, several models have been developed to optimize scheduling of repetitive projects, but only a handful have been tailored for linear projects. Optimizing construction duration was found to have been addressed more frequently in the literature than optimizing total construction cost. Until recently, linear scheduling was mainly regarded as a graphical scheduling method (Gorman 1972; Stradal and Cacha 1982; Chrzanowski and Johnston 1986; Vorster *et al* 1992). Over the last two decades, several mathematically based models have been proposed to optimize the scheduling of repetitive projects. These models are reviewed in the following sections.

2.4.1 Operations Research Models

Operations research techniques have been the tool of choice of most previous researchers working on optimizing repetitive construction. Linear programming models to optimize scheduling of repetitive projects were proposed by Reda (1990) and Perera (1983). The former computes the lowest possible cost corresponding to a given project duration, while the latter identifies the maximum rate of completion and its associated resource requirements. A model with graphical interface, but essentially similar to that proposed by Perera (1983), was later presented by Huang and Halpin (1994). These models, however, require that duration of works in all units of any activity be constant (typical activity), limiting their applicability. A model that accounts for variable production rates was presented by Handa and Barcia (1986). A discrete formulation employing optimal control theory was developed to minimise project duration. Work continuity is maintained but not enforced, but only single crews can be assigned to any activity.

The first dynamic programming formulation minimising overall duration of repetitive projects was presented by Selinger (1980). Work continuity is maintained for all crews, but cost is not considered in the formulation. Russell and Caselton (1988) extended Selinger's (1980) work by introducing a two-state variable N-stage dynamic programming formulation to minimise project duration. Pre-defined interruption vectors are defined for each activity, and a sensitivity analysis is enabled to investigate near-optimal solutions. However, similar to the model proposed by Selinger (1980), cost is not considered. Another limitation shared by both models is that neither can account for multiple predecessors and/or successors; an issue addressed by the model proposed by El-Rayes and Moselhi (2001). Other advantages this model has compared to that developed by Russell and Caselton (1988) are: 1) it can generate interruption vectors that would result in minimum project duration; and 2) equipment availability periods are considered.

Other models have employed dynamic programming to minimise total project cost. Moselhi and El-Rayes (1993 (a) & (b)) developed a formulation to minimise total construction cost, while enforcing work continuity. Another model was later proposed by Eldin and Senouci (1996), where a two-state variable, N-stage dynamic programming formulation was employed to minimise total project cost.

The model accounts for non-serial activities, and considers pre-defined multiple work interruptions. Another model was later presented by El-Rayes and Moselhi (1998), where a two-state variable, N-stage dynamic programming formulation was employed to minimise either the project duration or total cost. Unlike the model developed by Eldin and Senouci (1996), this model does not require work interruption to be defined at the outset, but can generate interruption vectors that would minimise total construction cost. The model (El-Rayes and Moselhi 1998) accounts for non-serial activities, and both repetitive and non-repetitive activities are considered, but only repetitive activities are incorporated in the optimization procedure. The optimum crew formation to be employed in each activity is identified to satisfy the scheduling objective. The model was later extended (El-Rayes 2001) to account for the combined impact of time and cost in what is known in highway construction as cost-plus-time, or A+B, bidding (Herbsman 1995; NCHRP 2000(c)). However, most optimization models discussed above are not tailored to linear projects. As such, crews are assigned to non-adjacent units, resulting in additional costs and delays, as discussed earlier. The need for a model optimizing schedules tailored for linear, repetitive projects is therefore evident.

2.4.2 Artificial Intelligence Models

Artificial intelligence (AI) techniques, such as knowledge-based expert systems, neural networks and genetic algorithms, are increasingly being applied to various segments of the construction industry (e.g. Alkass and Harris 1988; Amirkhanian and Baker 1992; Shi 1999). Neural networks mimic the biological neural structures of the central nervous system (Adeli and Karim 1997). They have been successfully employed in various aspects of construction management, such as mark-up estimation (Moselhi and Hegazy 1993), scheduling (Alsugair and Cheng 1994) and highway cost estimating (Hegazy and Ayed 1998). Adeli and Karim (1997) developed a mathematical formulation to minimise direct construction cost of repetitive projects. A neural network model developed by Adeli and Park (1995) was employed to solve the nonlinear cost optimization problem. Adeli and Karim's (1997) model is one of the few models found in the literature specifically tailored to linear repetitive projects (e.g. Kang *et al* 2001), as crews are assigned to pre-defined sections of the project rather than assigned alternating units, as discussed in Chapter One (Kang *et al* 2001). The model yields the minimum direct cost corresponding to a given duration. Multiple crew strategies were accounted for, and work continuity was maintained, but not enforced. A factor was employed to account for the impact of variable conditions, such as weather and distance to mix plant for paving operations, on crew productivity. However, a limitation of neural networks is that it operates as a black box, providing no justification to rationalize the provided solution.

Another AI technique that has recently been introduced to the construction industry is genetic algorithms. Like neural networks, this technique stems from a function of the human anatomy, only this one mimics gene multiplication. A "survival of the fittest" approach is employed to determine the optimum solution among a pool of possible alternatives. Some of the applications of genetic algorithms to the construction industry include those proposed by Li and Love (1997), Hegazy (1999) and Leu and Yang (1999). Hegazy and Wassef (2001) developed a spreadsheet application employing genetic algorithms and Microsoft Project® to optimize the total cost of repetitive projects. Multiple identical crews are considered, and work interruption is considered as an expediting technique, but limited to a ceiling of five days. Activities with varying quantities of work are not considered, and a limit of three predecessors or successors can be defined for any activity. However, obtaining an optimum schedule is not ensured, as rules developed to limit the solution space could result in overlooking the optimum solution. Compared to the capabilities of operation-research-based models, the ones proposed by Adeli and Karim (1997) and Hegazy and Wassef (2001) are rather limited. However, these models verify the applicability of AI techniques to developing optimized schedules for repetitive projects.

2.4.3 Simulation Models

Several models have been developed to explore computer simulation modelling of repetitive projects. Simulation is typically employed to estimate the output of a construction process by varying some of the deterministic input elements. Ashley (1978) employed process interaction simulation techniques to model the construction planning phase of repetitive construction. A sensitivity analysis to determine resource usage was also presented. Kavanagh (1985) later presented SIREN (SImulation of REpetitive Networks), a computer model repetitive construction. SIREN simulates crews' queuing to carry out various construction operations, and employs Monte-Carlo simulation to account for the probability distributions associated with activity durations. AbouRizk and Halpin (1990) reviewed techniques applicable to simulation of repetitive construction operations and demonstrated their applicability. Procedures for selecting input models, methods for solving for the parameters of selected distributions, and goodness-of-fit testing for construction data are reviewed. However, the randomness inherent in simulation models renders them inaccurate in modelling construction operations, which are not random in nature (Barrie and Paulson 1992). The complexity of developing an accurate correlation matrix limits the use of simulation models in construction.

2.5 Industry Survey

In order to develop a practical model that would aid highway construction personnel in completing projects successfully, and in order to fill knowledge gaps in the literature, two survey studies were conducted. The first study is designed to capture the current practices in planning, scheduling and controlling highway projects, and identify the requirements of highway personnel, while the second is designed to quantify the impact of inclement weather on crew productivity. These studies are presented below. All large contractors in Ontario and Quebec working on highway construction were contacted, and three of the largest in Alberta.

2.5.1 *Planning and Scheduling Survey*

This survey is divided into three sections: 1) the company; 2) current practices; and 3) crews, labour and equipment. The first section is designed to obtain data regarding the responder's company, such as its field of specialization, size, and scheduling practices. Section two is tailored to identify key requirements in planning and scheduling tools developed for highway construction. The third and last section is designed to identify contractors' practices regarding their own resources (crews), subcontractors and equipment providers. Structured interviews were carried out to facilitate responding to all survey questions. A copy of the survey questionnaire is presented in Appendix I. A total of 29 questionnaires were mailed out to contractors, and a total of 14, 8 and 6 responses were received for Sections One, Two and Three, respectively. The main findings of the survey can be summarised in the following points:

1. Physical transverse obstructions, either natural (e.g. rivers, creeks) or man-made (e.g. highways, railroads), help define boundaries between project segments.
2. Efficient resource management is crucial to completing projects successfully. This dictates maintaining work continuity for all crews. That is to say, once a crew arrives on site, it is assumed to work without interruptions until its job is completed.
3. Multiple crews are frequently assigned to activities.
4. Inter-segment movement for crews is to be minimised. Thus, if multiple crews are assigned to work on an activity, each is assigned to a project segment.

5. The most commonly applied scheduling technique is network scheduling, critical path method (CPM) in particular. The most commonly scheduling softwares used are Primavera Project Planner® and Microsoft Project®.
6. Mass haul diagram is the tool of choice to develop earthmoving plans.
7. Resource-driven scheduling, despite being intuitively appealing, is not currently employed in scheduling highway construction.
8. Working overtime on a regular basis is not a commonly adopted approach to expedite construction work in an activity.
9. Working double shifts, on the other hand, was found to be the most commonly adopted expediting technique, along with increasing crew size.
10. Inclement weather has significant impact on crew productivity.
11. Additional equipment is typically rented to supplement scarce resources.

2.5.2 Weather Impact Survey

Highway construction operations are particularly susceptible to weather elements (NCHRP 1978; El-Rayes and Moselhi 2001 (b)). The degree to which an activity is impacted by inclement weather depends on the severity of the weather conditions and type of work performed in that activity. The most significant of the weather elements are precipitation, temperature and wind speed (NCHRP 1978). For example, in earthmoving operations, precipitation can result in muddy soil conditions, reducing soil's trafficability. When saturated, soil being handled is heavier, which can have a negative impact on productivity. For safety reasons, and to minimise possible damage to completed embankments, heavy equipment operators are more cautious in muddy conditions (NCHRP 1978). This leads to an increase in the cycle time of their operation, resulting in productivity losses. Bad weather conditions might eventually cause operations to halt altogether (El-Rayes and Moselhi 2001 (b)).

Precipitation significantly affects the moisture content of soil, which is crucial to efficient compaction. The optimum density can only be obtained if soil is compacted at a specific moisture content. Depending on the degree of precipitation, its duration and site drying conditions (soil permeability, drainage conditions and sun and wind conditions), unfavourable conditions may prevail long after precipitation has ended. Consequently, construction crews might not regain normal productivity until days after precipitation has stopped and suitable trafficability has been restored. El-Rayes and Moselhi 2001(b) developed a knowledgebase to quantify total time lost due to rainfall. Precipitation could result in operations being halted long after precipitation has stopped. The duration of work stoppage following precipitation is found to be governed by several factors including: 1) intensity and duration of precipitation; 2) soil type and permeability; 3) weather conditions following the rainfall; and 4) drainage conditions on site. Windy conditions are favourable after rainfall as they expedite drying on site.

The impact of wind and temperature on construction productivity is not as evident as those associated with precipitation. Cold and windy conditions generally result in worker discomfort, consequently resulting in a loss in productivity. Certain activities cannot be conducted if the temperature falls below a certain value. For example, asphalt paving is halted when overnight temperature falls below –5°C (NCHRP 1978). Table 2.1 (modified after NCHRP 1978) lists the surface temperature limitations for asphalt concrete paving as set in 1974 Washington Standard Specifications (5-04.3 (16)). Sub-zero temperatures over prolonged periods result in freezing of top soil, which results in: 1) greater energy expended in excavation; 2) material handling of the excavated soil is difficult; and 3) reduced volume hauled per hauling unit (NCHRP 1978). Table 2.2 (NCHRP 1978) summarises the effect of these elements on workers, equipment, quality of work performed and ease of handling material.

Table 2.1: Surface temperature limits for paving (modified after NCHRP 1978)

Compacted thickness	Surface course (°C/F)	Subsurface courses (°C/F)
Less than 0.1' (2.5 mm)	12.5/55	12.5/55
0.1' to 0.2' (2.5 to 5 mm)	7.2/45	1.7/35
0.21' to 0.35' (5.1 to 8.9 mm)	1.7/35	1.7/35
More than 0.35' (8.9 mm)	D.N.A.	(-3.9)/25*

* Only on dry subgrades, not frozen, and when air temperature is rising.

In order to quantify the impact of the above weather elements, a questionnaire was prepared and mailed to several highway construction personnel. A copy of the questionnaire is presented in Appendix II. A total of 25 questionnaires were mailed, and responses to 7 of the mailed questionnaire were received. Structured interviews, either in person or over the telephone were also conducted to augment the questionnaires and elicit the required knowledge.

Table 2.2: Effect of weather elements on workers, equipment, work and material handling (NCHRP 1978)

	Precipitation			Temperature		Wind		
	Rain	Snow	Sleet	Hot	Cold	0-10 Low	10-30 Med	30+ High
Work	S	S	S	L	M-S	L	M	M
Men	S	S	S	L-M	M-S	L	M	S
Equipment	M-S	S	S	L	M	L	L	M
Materials	M	S	S	L	M	L	M	M

S – Severe M – Moderate L – Little

In order to accurately determine the impact of the various weather elements on productivity, it was deemed necessary to ensure that no ambiguities exist regarding terminology. Regional offices of Environment Canada were contacted to establish their relative criteria for classifying the various weather elements. For example, what qualifies as “light” rain in British Columbia would be considered “moderate” in other provinces. However, what qualifies as a “rain storm” is uniform across Canada (>50 mm/day). In order to avoid such ambiguities, the classification adopted in the questionnaire is in accordance with that adopted in Québec. Precipitation rates are also provided as a range of mm/hr. Figure 2.2 (Environment Canada 2002) shows the average daily spring precipitation across Canada. The figure shows the variations in weather patterns across the country. This vast variation resulted in each province adopting its own classification of precipitation. Table 2.3 compares the classification of rainfall for Québec and British Columbia. Figures 2.3 and 2.4 (Environment Canada 2002) show daily precipitation for Montréal and Vancouver, respectively, over the last twelve months. The figures show that the average daily precipitation is higher for Vancouver, while Montréal had more days where precipitation was in excess of 25 mm. The national classification regarding wind speeds is listed in Table 2.4 (Environment Canada 2002).

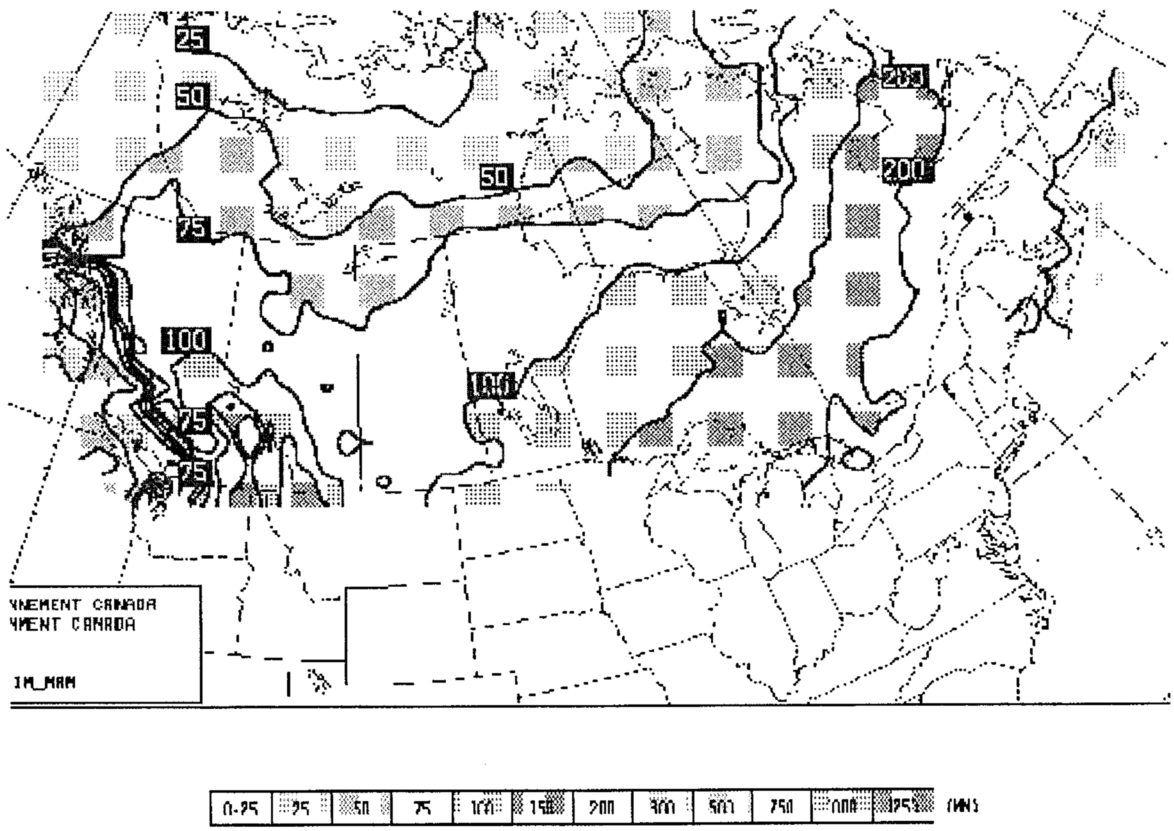


Figure 2.2: Average daily spring Precipitation (Environment Canada 2002)

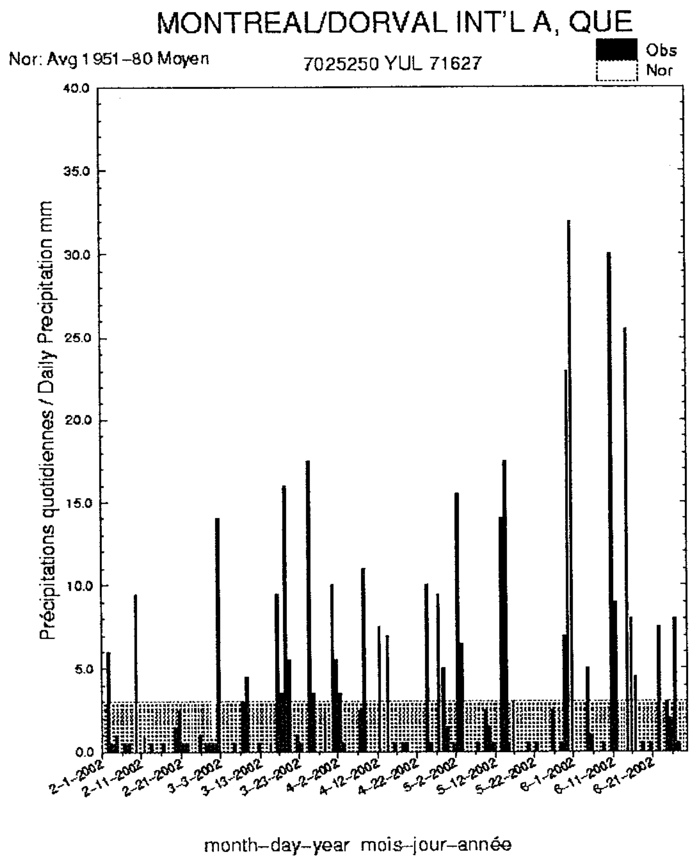


Figure 2.3: Daily precipitation in Montréal in 2001-2002

(Environment Canada 2002)

Table 2.3: Classification of rainfall for Québec and British Columbia

Province	Rainfall classification			
	Very little	Little	Moderate	Heavy
Québec	<0.2 mm/hr	0.2-4.6 mm/hr	4.6-7.6 mm/hr	>7.6 mm/hr
British Columbia	<0.35 mm/hr	0.35-5.2 mm/hr	5.2-9.2 mm/hr	>9.2 mm/hr

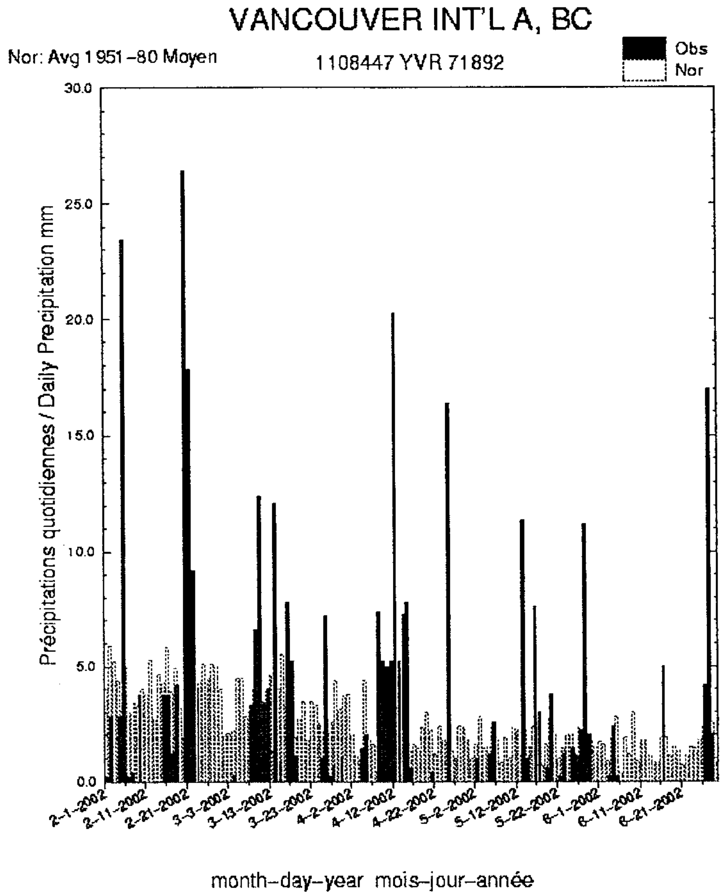


Figure 2.4: Daily precipitation in Vancouver in 2001-2002

(Environment Canada 2002)

Table 2.4: National classification of wind speed (Environment Canada 2002)

Classification	Speed (km/hr)
Light	<9
Moderate	10-40
Strong/windy	41-60
Very strong/gales	61-90
Very strong/storm force	91-115
Hurricane force	>115

The findings of the survey regarding weather impact on crew productivity are summarised in Table 2.5. The terms "severe" (S), "moderate" (M) and "little" (L) indicate losses in productivity of 50% or more, between 10% and 50% and less than 10% respectively. Severe weather conditions could also halt operations altogether. The table reveals that precipitation is the factor that most impacts crew productivity, which is in agreement with earlier studies (NCHRP 1978 & 1995) and that all activities affected by precipitation to varying degrees. Paving and earthmoving activities are identified as the ones most susceptible to weather elements in general, and precipitation in particular. Paving requires dry conditions to be performed, and any significant rainfall would thus cause crews to halt operations altogether. It is worth noting that it is possible to pave following rain if placing the first lift, but not if it has rained between lifts, as this might cause separation between the existing lift and that being applied. As mentioned earlier, precipitation greatly reduces soil's trafficability, thus affecting earthmoving operations. Scraper operation was identified by most respondents as the one most susceptible to precipitation. This can be attributed to the fact that scrapers and dozers would lose their traction in slippery, muddy conditions. Most respondents agreed that windy conditions help dry up the site faster than sunny but calm conditions.

Low temperatures lead to worker discomfort, and might cause equipment malfunctioning. Surveying was found to be particularly susceptible to cold temperatures, as workers encounter difficulties adjusting their equipment while wearing gloves. As mentioned earlier, asphalt paving operations are halted when overnight temperature falls below –5°C (NCHRP 1978). In cold conditions, curing of concrete requires a longer time, which would result in delaying subsequent activities.

Table 2.5: Impact of weather elements on productivity

Operations	Precipitation Mod.	Precipitation Heavy	Temperature <9°C	Wind speed >45 km/hr
Pioneer road const.	M	S	L	L
Clearing	M	S	L	L
Surveying	M	S	M	M
Earthmoving (dozers)	M	S	L	L
Earthmoving (loader-truck fleets)	M	S	L	L
Earthmoving (scrapers)	S	S	L	L
Compaction	M	S	M	L
Grading	M	M	L	M
Subgrade preparation	S	S	M	M
Culvert installation	M	M	M	L
Aggregate base course	M	S	L	L
Concrete paving	S	S	S	L
Asphalt paving	S	S	S	L

High wind speeds cause worker discomfort, and could reduce visibility to the extent that operations are halted. Certain activities, such as installation of overhead signs, are significantly affected by high winds, and could be halted altogether. For safety reasons, operations requiring cranes are halted when strong winds prevail. The findings of this survey are found to be in general agreement with those of earlier studies (NCHRP 1995; El-Rayes and Moselhi 2001(b)) and are incorporated in the scheduling module to assess the impact of inclement weather on crews' productivity (Section 4.5.2). For comparison, the findings of the former study are presented in Table 2.6 (NCHRP 1995).

Table 2.6: Effect of weather conditions on highway construction (NCHRP 1995)

	Severity of effect						
	Low temp.	Rain	Sleet	Snow	Ice	Frozen ground	Wind
Traffic handling	L	M	S	S	S	L	L
Layout and staking	M	S	S	S	S	M	M
Clearing and grubbing	L	M	M	M	M	L-M	L
Material delivery and storage	L-S	S	S	S	S	L-M	L
Excavation	L	S	M	M	M	M	L
Embankment construction	M-S	S	S	S	M	M-S	L
Structure site grading	M-S	S	S	S	M	M-S	L
Pile driving	L	M	M	M	M	M	L
Dredging	M-S	L	L	L	S	L	M
Erection of coffer dams	M-S	M	M	M	S	L	L-M
Form work	M	S	S	M	S	L	L-M
Steel erection	M	S	S	M-S	S	L	M-S
Placing of reinforcing steel	M	S	S	S	M-S	L	L
Mixing and placing concrete	S	S	S	M	M	L	L
Curing concrete	S	M	M	M	S	L	M
Stripping forms	L	M	M	L	M	L	L-M
Backfill	S	S	S	M	M	M-S	L
Base placement	S-M	S	M	M	M	M-S	L
Paving	S	S	S	S	S	M	L
Landscaping and seeding	S	S	S	S	S	S	L
Painting	S	S	S	S	S	-	M
Fencing	L	M	M	M	M	M-S	L
Lighting	M	M	M	M	M	L	L
Signs	L	M	M	M	M	M	M

A sample of the rules used by the latter study (El-Rayes and Moselhi 2001(b)) to estimate the days lost in earthmoving operations due to rainfall under average drainage conditions (El-Rayes and Moselhi 2001(b)) is presented in Table 2.7. The table lists eight (8) of the rules developed to quantify number of working days lost due to rainfall in earthmoving operations. Similar if/then rules were developed to estimate the number of working days lost due to rainfall for base construction, construction of drainage layers and paving under various drainage conditions (good, average and poor).

Table 2.7: Sample rules for earthmoving operations (average drying conditions)

(El-Rayes and Moselhi 2001(b))

Rule	If total rainfall			Then shutdown		Total working days lost
	Amount (mm)	Daily hours	Daily period	Current day	Following days	
1	13-25	5	Morning	Full day	1	2
2	13-25	5	Afternoon	50%	1	1.5
3	13-25	10	Morning+afternoon	Full day	1	2
4	13-25	14	Overnight	Full day	0.5	1.5
5	6-13	5	Morning	Full day	0	1
6	6-13	5	Afternoon	50%	0	0.5
7	6-13	10	Morning+afternoon	Full day	0	1
8	6-13	14	Overnight	50%	0	0.5

2.6 Summary

This chapter presented the findings of surveys of both the current state of highway industry, and the review of literature. Geographic information systems (GIS) was introduced, and its applications reviewed. The evolution of resource-driven scheduling from a graphical scheduling tool to a mathematically based one was also discussed. The literature review helped identify some common assumptions in earlier models along with their advantages and limitations. The various tools employed to optimize the scheduling of repetitive projects were reviewed. The findings of two surveys designed to identify planning and scheduling practices in the Canadian highway construction industry and to quantify weather impact on highway construction operations were also presented. These surveys helped identify the practical requirements and desirable features of planning and scheduling tools for highway construction.

CHAPTER THREE

PROPOSED METHODOLOGY

3.1 Introduction

This study presents a model to plan, schedule and control highway construction operations. The model utilises spatial technologies, such as geographic information systems (GIS), to acquire and analyse spatial data. The model builds on the scheduling algorithm and object oriented model developed earlier by El-Rayes (1997) to tailor it to highway construction. A dynamic programming formulation is developed to minimise either: 1) total construction cost; 2) duration; or 3) their combined impact for what is commonly known as cost-plus-time, or "A+B" bidding (Herbsman 1995). The model can also generate schedules to: 1) fit a certain budget; or 2) be completed within a certain duration, if possible. Relational database models are designed to store data related to: 1) available resource pool and their availability dates; 2) soil swell and shrinkage factors; and 3) average daily precipitation and its duration, temperature and wind speed during the morning, afternoon and overnight periods. The proposed model is composed of five (5) modules (see Figure 3.1): 1) data acquisition and analysis module; 2) database module; 3) planning and scheduling module; 4) tracking and control module; and 5) reporting module. These modules are discussed individually in the following sections.

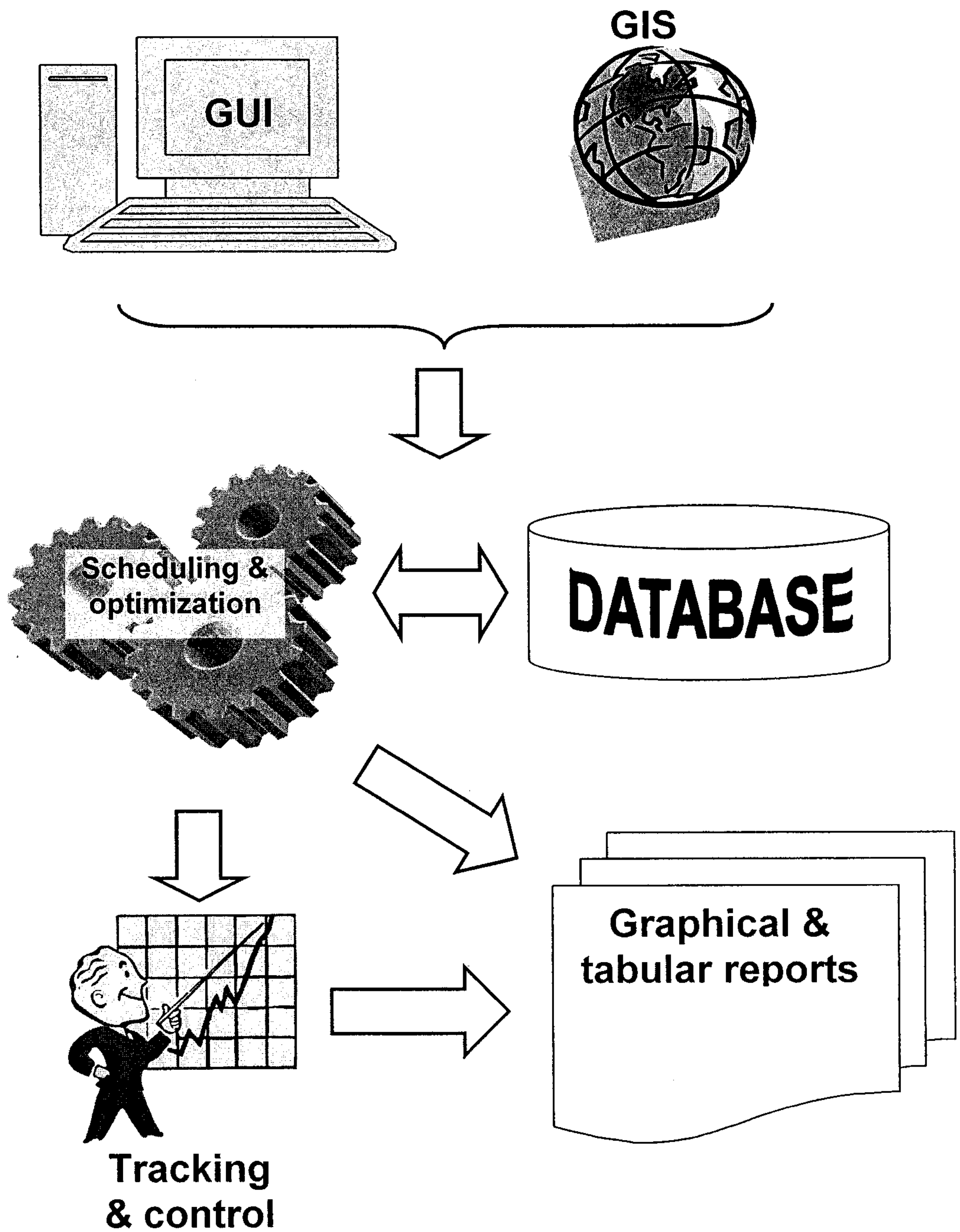


Figure 3.1: Model outline

3.2 Data Acquisition and Analysis Module

This module is designed to: 1) automate data acquisition; 2) eliminate potential inaccuracies in quantity estimates attributed to surveyors' bias (Nkado and Meyer 2001; Fan *et al* 2001); 3) analyse spatial data; and 4) propose an earthmoving plan that minimises total cost of earthmoving operations. It is composed of two sub-modules, namely: 1) graphical user interface (GUI); and 2) geographic information systems (GIS) sub-modules. The function of the GUI sub-module is to acquire non-graphic project data, such as optimization objective and activity and crew definitions. The functions of the GIS sub-module, on the other hand, extend beyond acquiring spatial data (such as highway profile and site topography) to include data analysis and developing the optimum earthmoving plan. The GUI sub-module can be employed to input all project data if no maps are available in a digital format. These two sub-modules are described in the subsequent sections.

3.2.1 Geographic Information Systems (GIS) Sub-Module

In highway construction projects, earthmoving operations generally represent a major bid item, making their optimization of paramount importance to developing successful bids (Jayawardane and Harris 1990). Traditionally, a manual approach has been adopted to correlate boring logs and their surface locations, which has been regarded as a time-consuming task, that is seldom done thoroughly (Oloufa *et al* 1994). Several methods have been proposed for accurate estimation of cut quantities (Siyam 1987; Epps and Corey 1990; Easa

1991 & 1992). It was also reported (Siyam 1987) that errors arising from the use of approximate methods for cross-sectional area calculation are insignificant in earthwork volume determination. Considerable work has been done to optimize earthmoving operations (Stark and Nicholls 1972; Stark and Mayer 1981; Nandgaonkar 1981; Easa 1987; Christian and Caldera 1988; Alkass and Harris 1988; Jayawardane and Harris 1990; Shi and AbouRizk 1997; Shi 1999). These models, however, neither account for the impact of transverse natural and man-made obstructions on the earthmoving plan, support 3-D visualisation, provide automated data entry, nor provide scheduling capabilities.

This sub-module utilises GIS and extends the capabilities of the traditional mass haul diagram (Stark and Mayer 1983). Features of the sub-module include: 1) accounting for variations in the soil strata; 2) generating the mass haul diagram automatically; 3) accounting for transverse obstructions, such as rivers and creeks, along the highway route when developing the mass haul diagram; and 4) estimating quantities of gravel and asphalt concrete required for the base and paving operations, respectively. Since most highway specifications stipulate the degree of compaction of the subgrade to be 95% of the maximum dry density, the model defaults to that value unless otherwise specified. Soils below the water table are assumed to be saturated when computing their weight for hauling calculations.

The sub-module generates digital terrain models (DTMs) to store land topography and underlying soil strata. DTMs can be stored either as a grid or as triangulated irregular networks (TINs) (Oloufa 1991). Grids have been criticized for being too rigid, resulting in either an increase in computation time or lower accuracy (Oloufa 1991). Unlike the rigid structure of grid models, TIN models are flexible, and can provide more details in areas where topography varies rapidly. Due to its superior ability to represent abrupt topography changes, TIN models are used in this study.

Generating TINs from elevation data points has been addressed in the literature (e.g. Jones and Nelson 1993; ESRI 1997). The first stage in developing a DTM from a line theme is to generate the TIN nodes, which, in this study, are taken along contour lines. Typically, contour interval varies between ten (10) cm and 150 m depending on site area and required accuracy (Oloufa 1991). In order to develop a DTM that does not place superfluous demands on the system's memory, a procedure is developed to determine the intervals between developed nodes along contour lines. The procedure is iterative, and generates nodes that are not regularly spaced. Initially, the interval is assumed to be equal to the horizontal component of the distance to the nearest contour line, and the initial mesh is developed accordingly. Having developed the nodes, the DTM is generated and the volume of earth between the generated DTM and the ground water table is computed. In the case where no water table is defined, a horizontal plane passing through the lowest point in the generated DTM is used as datum.

The interval is then reduced to one half of its previous value and another set of nodes is generated, producing a revised DTM. The volume of earth contained between the revised DTM and the water table is recalculated and compared to that calculated in the previous iteration. This process is repeated until the change in volume is less than a user-specified value, or 10%. The default value (i.e. 10%) is well below what is considered acceptable for earthwork computations (Meyer and Gibson 1980; Kavanagh 1992). This procedure generates an accurate DTM without placing unnecessary demands on the memory.

3.2.1.1 Estimating Quantities of Material

Accurate estimating of earthmoving quantities is crucial to developing realistic plans. Traditionally, cut and fill quantities between two successive sections along an embankment are calculated using the average end-area method or the prismoidal method (Meyer and Gibson, 1980; Easa 1989). For unequal end sections, the latter tends to yield more accurate estimates than the former, but requires additional field data gathering, limiting its use (Epps and Corey 1990). Easa (1991) noted that both methods yield inaccurate estimates if two successive sections are not of the same type (cut or fill), and proposed employing the pyramid frustum formula to compute quantities of cut and fill at such sections. Epps and Corey (1990) proposed a modification to the average-end-area to circumvent these drawbacks. Their procedure is reported to yield more accurate estimates than those estimated using the average-end-area method (Epps and Corey 1990), and is incorporated in the proposed model.

Estimating the volume of soil contained in a curved segment of an embankment has typically been carried out employing Pappus's theorem (Easa 1992). However, the accuracy of estimates provided by that theorem deteriorates as the difference between the two end areas increases (Easa 1992). Easa (1992) proposed a mathematical model that accounts for transition sections (sections containing areas of both cut and fill) and moderate changes in ground cross slope in curved portions of the highway. Use of that model requires simplifying the end sections, assuming a linear ground profile. Siyam (1987) had recommended employing the theory of least squares to determine the equation of the line of best fit to represent an approximation of the ground elevation. However, this can result in a simplified section with a different cross-sectional area than that of the original section (Easa 1989). An alternate method to determine the equation of the line of best fit without reducing volume accuracy was presented by Easa (1989), and is employed in the proposed model to simplify sections in curved portions of the embankment. In order to increase the estimating accuracy (Siyam 1987), the longitudinal interval "L" between end sections is made dependant on the horizontal curvature of the highway at that location, and is determined from:

$$L = X\left(1-\frac{1}{R}\right) \tag{3.1}$$

Where L is the longitudinal interval between end sections at current location (see

Figure 3.2),

X is the specified interval (or default value of one (1) m), and

R is the radius of horizontal curvature (m).

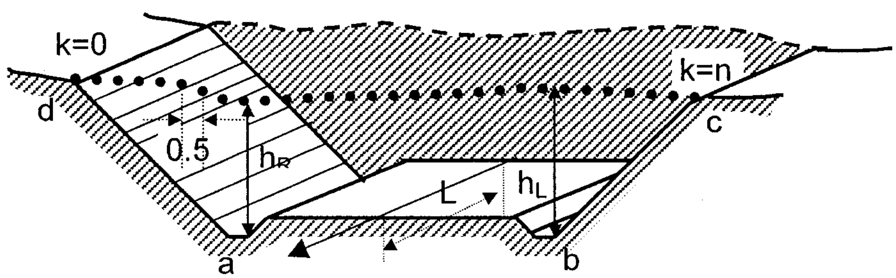


Figure 3.2: Typical cut segment

The procedure for estimating cut and fill quantities along highway route is schematically represented in Figure 3.3. Details depicting cut and fill sections are shown in Figures 3.4(a) and (b), respectively. Elevation of the finished highway grade is determined at both edges of the end section (point "A" Figure 3.4), and differences in elevation between the highway profile and the original ground topography, ("h_L" and h_R", in Figure 3.2) are computed. If cut and fill limits are not provided, they are determined through an iterative procedure, whereby the elevations of both the embankment and the original ground are determined at 0.5-meter intervals along the embankment slope, as shown in Figure 3.4. The location of the embankment endpoint (point "E" in Figure 3.4) is determined by linear interpolation. Once locations of both endpoints are determined, the cross-sectional area and hence the quantities of cut and fill are calculated, and the mass haul diagram can be generated.

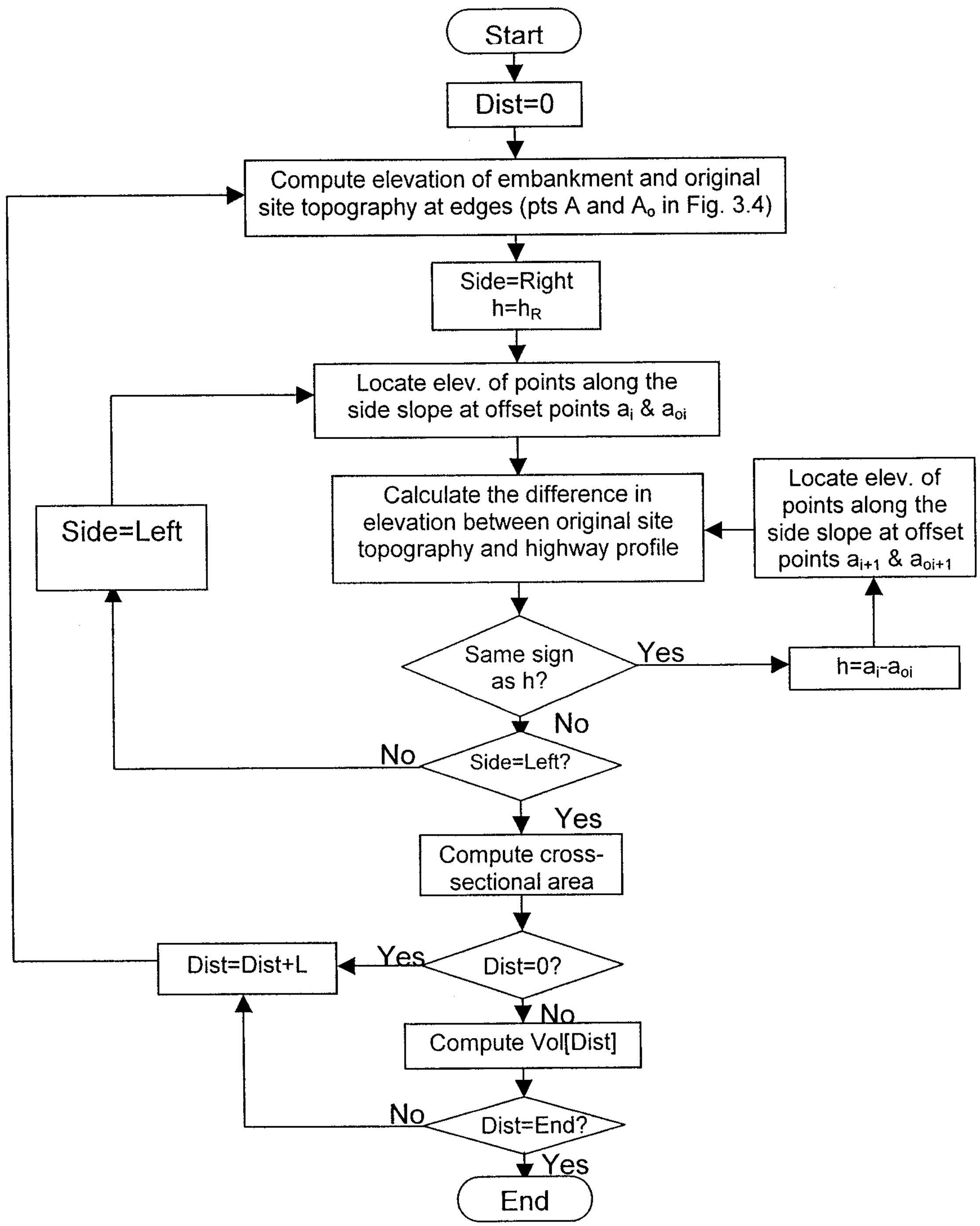


Figure 3.3: Algorithm for estimating cut and fill quantities

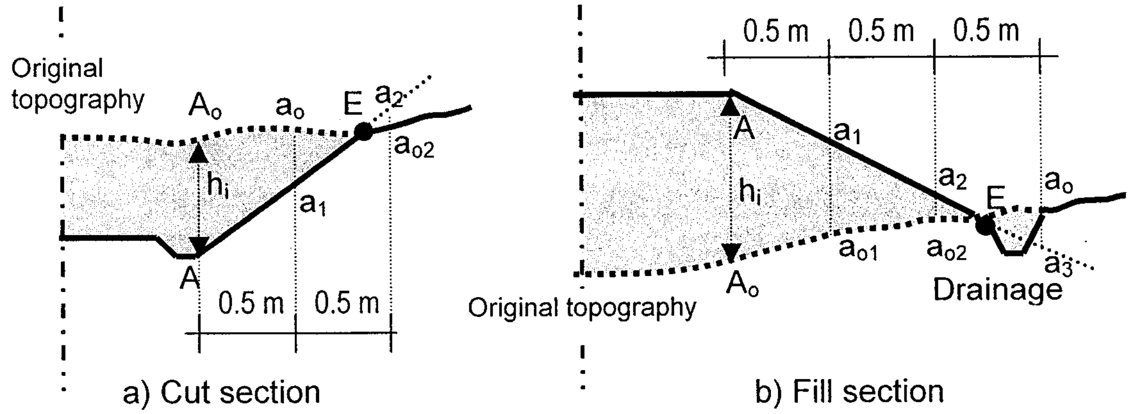


Figure 3.4: Determination of cut and fill limits

3.2.1.2 Generating Soil Strata

Frequently, cut sections of a highway contain different soil strata (see Figure 3.5). In such cases, variations in swell and shrinkage factors should be taken into account when estimating the quantities of cut and fill (Oloufa 1991). Variations in the degree of compaction, if specified, should also be considered. Specifications often identify certain types of soil, such as peat, to be unsuitable as fill material, and thus should either be removed or used for embankments of non-structural nature.

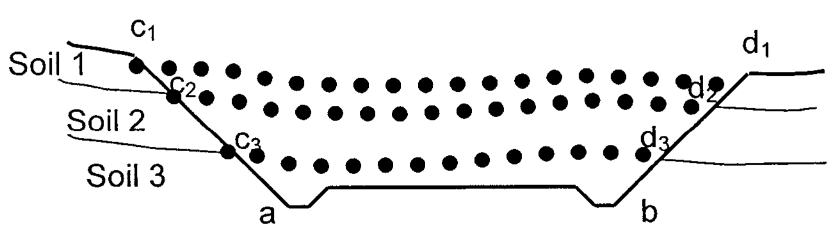


Figure 3.5: Typical cut section with varying soil strata

Accounting for varying soil strata is therefore essential to developing realistic earthmoving plans. Figure 3.6 shows a longitudinal section of a sample highway, where results of the geotechnical exploration are superimposed at borehole locations. The figure shows a typical case, where soil strata vary in thickness between boreholes along the highway route. The procedure employed to determine the cut and fill limits is employed for each stratum "i" (i=2, 3,…,n, where "n" is the total number of soil types in the borehole) to determine the locations of points "c_i" and "d_i" (see Figure 3.5).

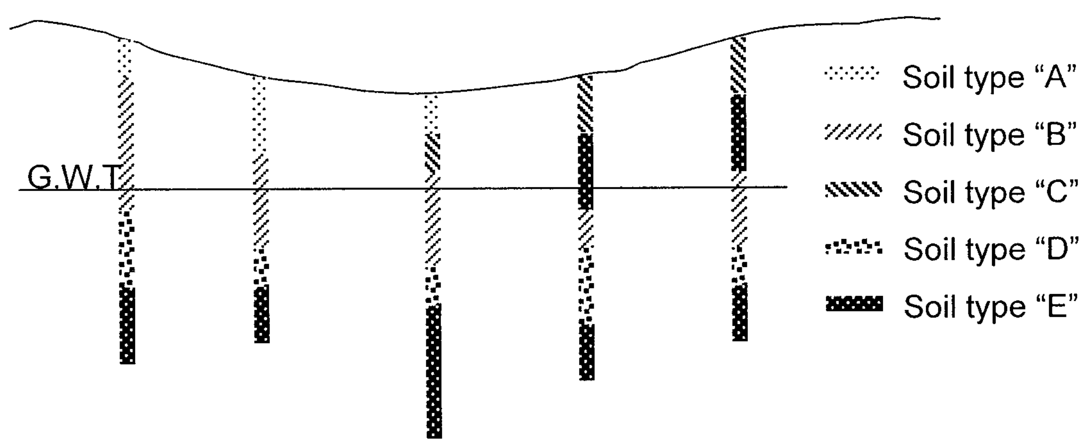


Figure 3.6: Sample borings results along route

Determining the soil profiles between boreholes is essential to accurate estimating of cut quantities. Predicting strata transition between boreholes locations is location-specific and requires knowledge of several factors, such as the region's geological history, soil's geophysical nature and the likelihood of the presence of soil pockets (Oloufa *et al* 1992). In the proposed model, the strata profiles can either be: 1) defined by the user, by specifying the strata connectivity between boreholes; or 2) automatically generated by the model, and revised as needed by the user. In the latter case, each soil layer in a borehole is assigned a number, "i", that accounts for its sequence from top to bottom, starting with i=1 at ground level. The model assumes that the assigned number for each layer can go up or down by one level between two successive boreholes. This is a reasonable assumption, particularly for closely spaced boreholes. If a stratum is not found in the next borehole test results, it is assumed that the stratum tapers linearly to reach a thickness of zero (0) at the location of that borehole. The algorithm developed for generating the strata profiles is shown in Figure 3.7.

Elevations of soil strata between borehole locations are generated using linear interpolation. Having determined the ground elevation and the thickness of the overlaying strata at section "X", the top elevation of stratum "i" is determined at all "k" points (k=1 to n) across the highway section using Equation (3.2):

$$E_{i,k} = G_k - \sum_{s=1}^{s=i-1} t_{s,k} \tag{3.2}$$

Where $E_{i,k}$ is the top elevation of stratum "i" at point "k"

G_k is the ground elevation at point "k"

$t_{s,k}$ is the thickness of stratum "S" at point "k"

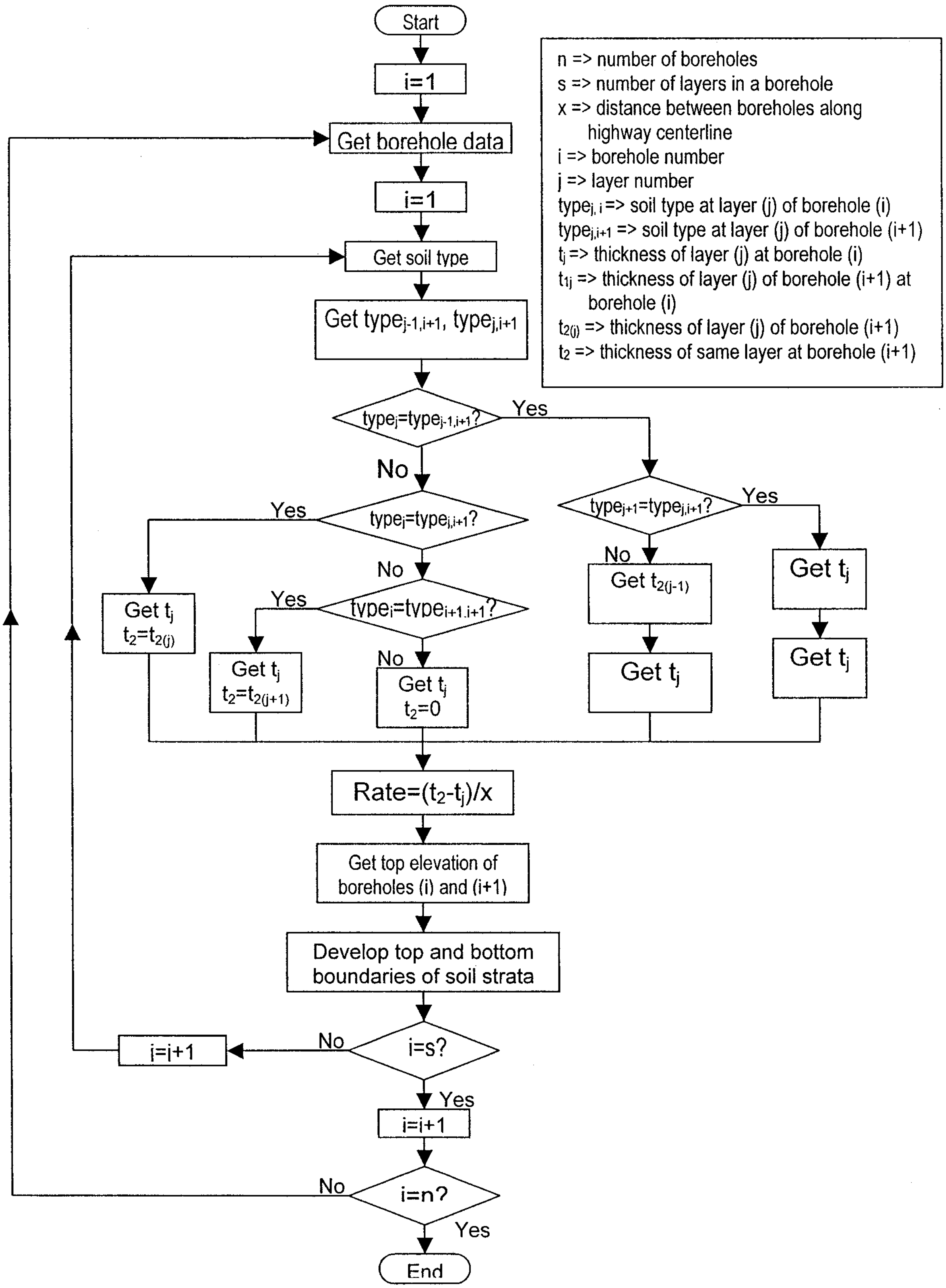


Figure 3.7: Algorithm for generating strata profiles

The model is employed to analyse the borehole data shown in Figure 3.6, and the generated soil strata are shown in Figure 3.8. It should be noted that the model operates in a three-dimensional environment, and that the two-dimensional image of Figure 3.8 is used here for simple illustration.

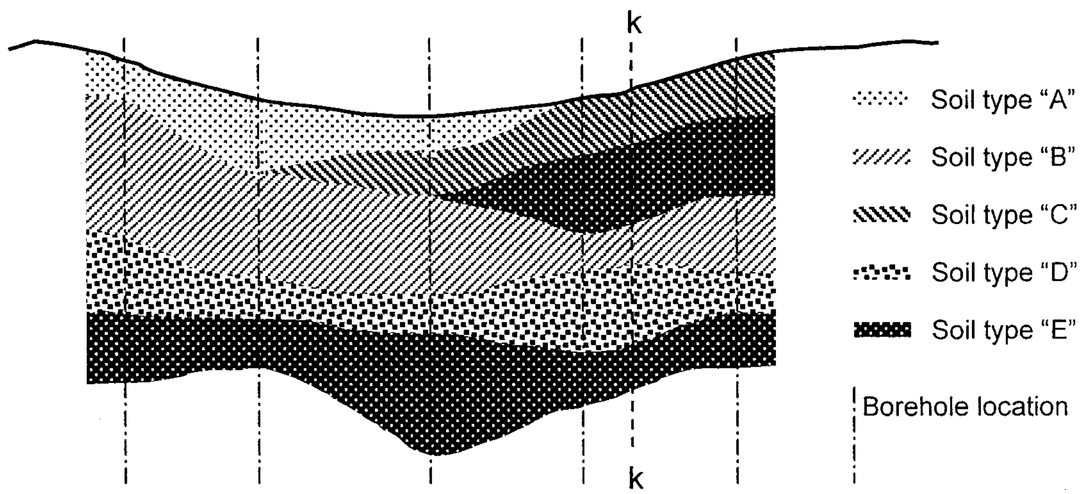
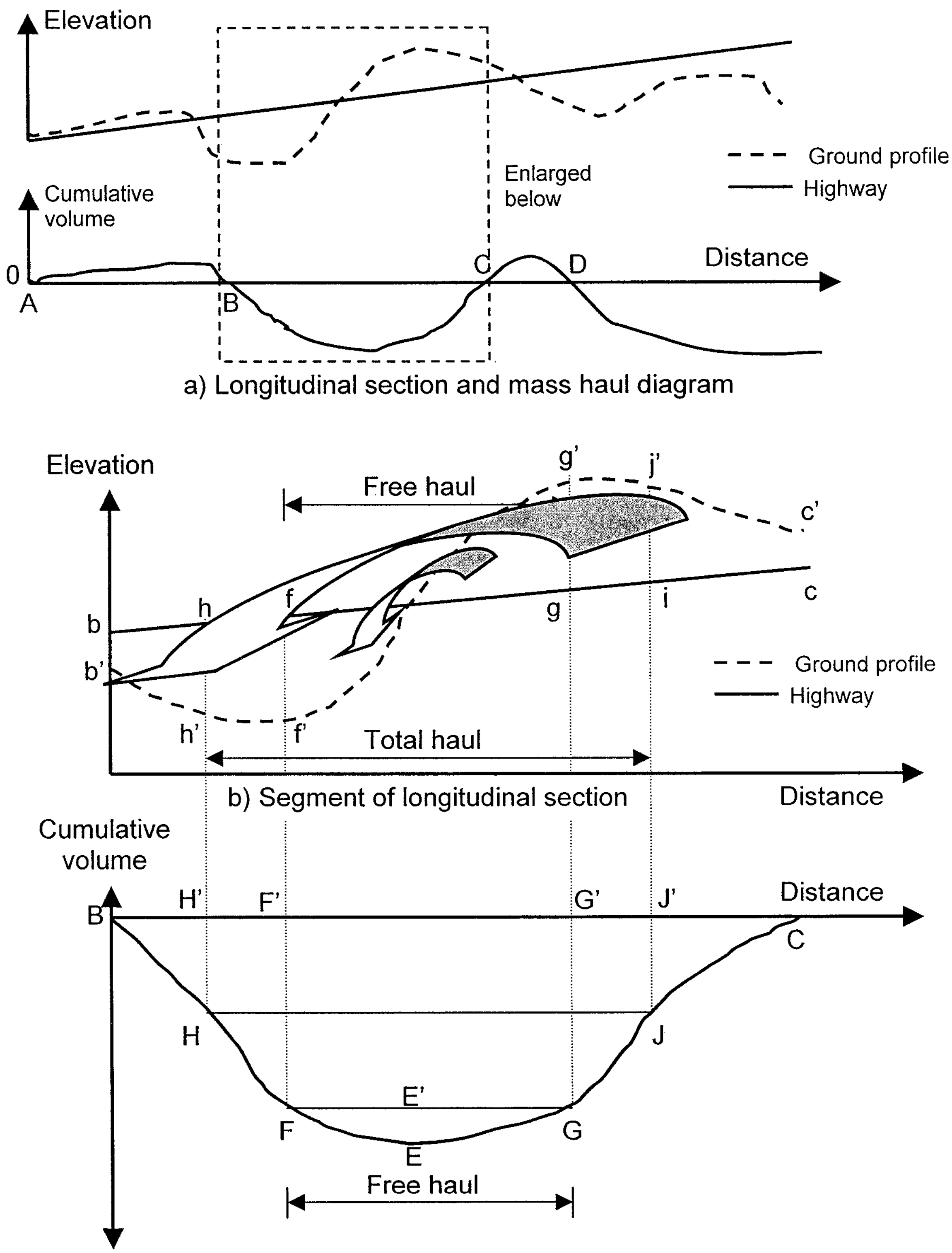


Figure 3.8: Generated strata for boreholes in Figure (3.6)

3.2.1.3 Estimating Earthmoving Costs

The cost of an earthmoving operation is readily computed using the mass haul diagram. Figure 3.9(a) shows a sample highway profile and its corresponding mass haul diagram. Part (b) of the figure shows the portion of the highway and ground profiles between two balance points, while part (c) shows the corresponding segment of the mass haul diagram. The free haul distance can be superimposed on the mass haul diagram (points "F" and "G" in Figure 3.9(c)), and the quantity of free haul volume is given by the ordinate "E". Earth movement within the free haul distance is as shown in part (a) of the figure, and its cost, "C_{free}", is expressed as:



a) Longitudinal section and mass haul diagram

b) Segment of longitudinal section

c) Segment of mass haul diagram

Figure 3.9: Sample longitudinal section and mass haul diagram

$$C_{free}=c_f \times E \tag{3.3}$$

where c_f is the unit cost of free haul (\$/loose cubic metre) and

E is the ordinate of the mass haul diagram.

In order to determine overhaul cost, the average overhaul distance needs to be determined. This distance is computed as the distance between the centroids of the cut and fill sections (centroids of areas "bff'b'" and "g'c'cg" in Figure 3.9(c)). The locations of these centroids are identified by plotting a horizontal line, bisecting the ordinate "F" (points "H" and "J" in the figure). The cost of overhaul (C_{over}) is expressed as:

$$C_{over}=H \times (HJ-FG) \times c_o \tag{3.4}$$

where HJ and FG are the lengths of HJ and FG, respectively, as measured on the mass haul diagram,

H is the ordinate of the mass haul diagram (see Figure 3.9(c)) and

c_o is the unit cost of overhaul (\$/m^3/station).

Polus (1987) suggested not to subtract the free haul from the total haul when calculating overhaul distance. This recommendation is based on the fact that there exists a distinct difference in the nature of operations between haulage performed over distances less than, and greater than, the free haul limit. A study to locate the centroids of earthwork when using the mass haul diagram was presented by Easa (1988). A mathematical formulation was developed assuming a second degree polynomial to model section height. The study concluded that a maximum deviation of –16% in the overhaul distance from the correct value occurs when locating the centroid using traditional methods. However, the validity of the assumption that a second-degree polynomial accurately models soil profiles was not verified.

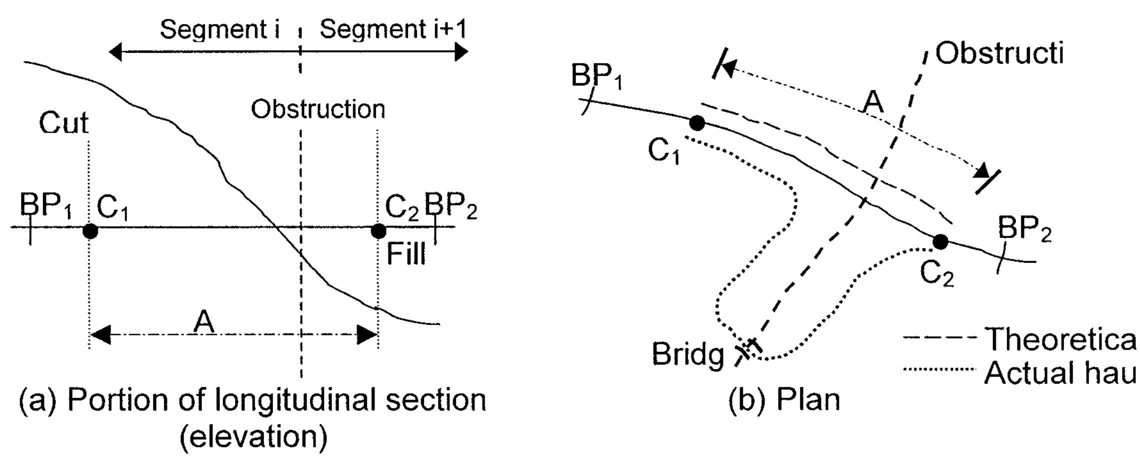


Figure 3.10: Impact of obstruction on haul distance

The presence of transverse obstructions, such as rivers and creeks, can affect earthmoving plans, and crews carrying out the operations (for example, it isn't practical for a dozer to take an alternate and longer route while pushing earth). Additionally, haul distance will not be readily obtainable from mass haul diagrams. This is due to the increase in haul distance necessary to overcome any obstacles, which leads to an increase in the cycle time of earthmoving operations, resulting in a drop in productivity. This scenario is schematically represented in Figure 3.10. Using the traditional mass haul diagram, the average haul distance would have erroneously been "A" as shown in Figure 3.10(b). The actual haul distance would account for the additional travel distance to cross the bridge, as shown by the dotted line in part (b) of the figure.

Earthmoving costs are significantly impacted by transverse obstructions, as the free haul and overhaul distances would not be readily obtainable from the mass haul diagram. For continuity, the equations defining freehaul and overhaul distances in the presence of transverse obstructions are described in Appendix III.

Transverse obstructions might eventually render the traditional mass haul diagram calculations inadequate. Figure 3.11 illustrates the potential impact of an obstruction on an earthmoving plan. If the increase in haul distance warrants altering the earthmoving plan, then the model considers the obstruction to be a balance point. Excess soil in segment "i" is disposed of, and needed soil for backfill in segment "ii" is imported from a borrow pit. The original mass haul diagram in this case (Figure 3.11(b)) would have to be revised as shown in Figure 3.11(d), and the modified earthmoving plan would be as shown in part (e) of the Figure. Based on a cost or schedule criterion (minimising time or cost), the possible scenarios highlighted above for earthmoving operations are compared, and the one that satisfies user's objectives is selected.

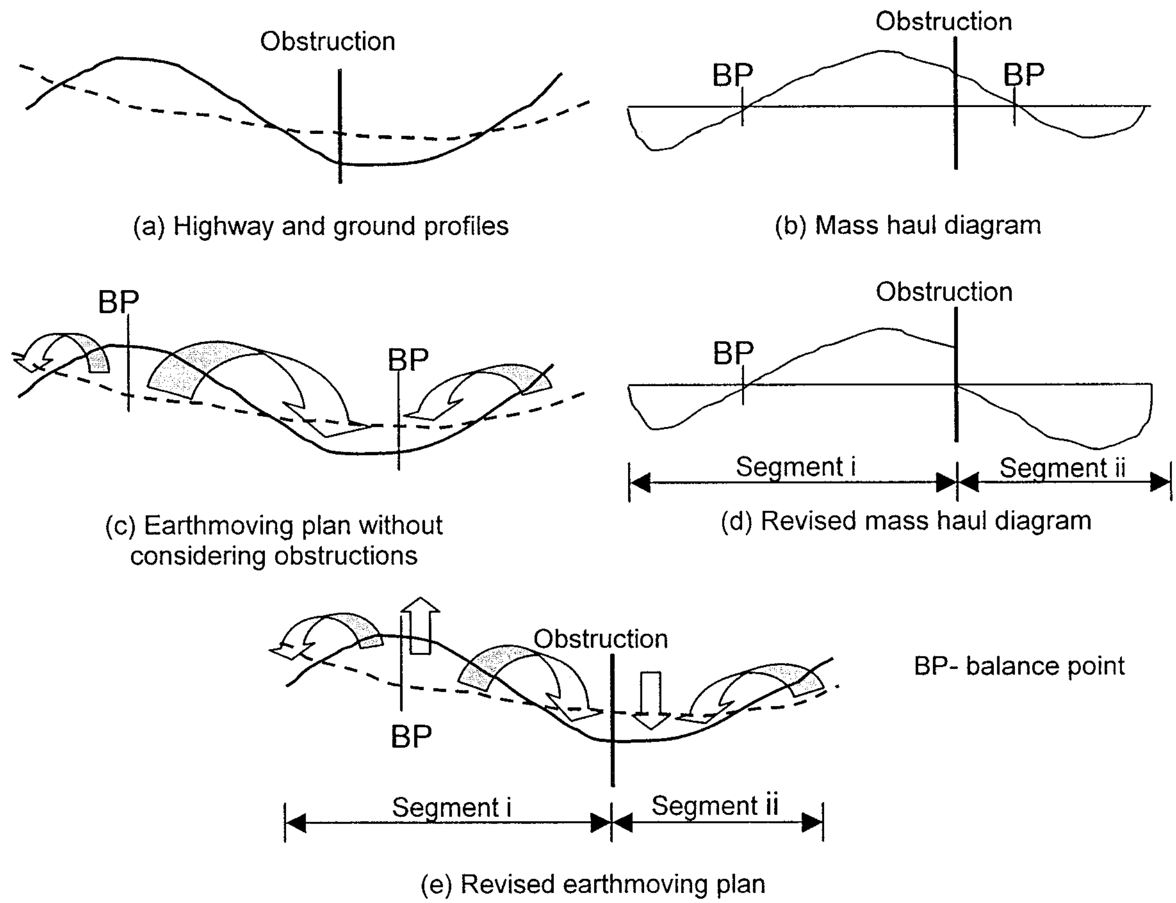


Figure 3.11: Potential effect of obstruction on earthmoving plan

3.2.2 Graphical User Interface (GUI) Sub-Module

The GUI sub-module is mainly employed as a supplement to the GIS sub-module, acquiring project non-graphical data, such as:

1. General data, such as project name, owner, contract type and start date.
2. Activity data, such as activity description, precedence relations, quantities of work involved and potential assignments of crew formations.

3. Scheduling options, such as: 1) considering weather impact and learning curve on productivity; and 2) policy regarding equipment rental (if no owned equipment is available).
4. Scheduling objective, which could be one of the following:
   a. Minimising construction duration, total construction cost or their combined impact for cost-plus-time bidding.
   b. Scheduling project to meet specific deadline or budget.
5. Preferred expediting technique, if any (overtime/extra shifts/weekends).

3.3 Database Module

As with most heavy engineering construction projects, the construction phase of highway projects is equipment-intensive, characterized by large fleets (Barrie and Paulson 1992). As such, the need for an efficient management strategy of owned equipment is crucial to complete projects successfully, specially given the competitive nature of today's construction industry. For this reason, at the core of the model is a database module designed primarily to serve this function. The module is composed of three separate relational databases; 1) resources; 2) soil; and 3) weather databases. The resources database stores: 1) own equipment; 2) own labour force; 3) known subcontractors; and 4) equipment providers. This database also stores pre-defined crew templates (Section 4.4.1), and keeps a record of all assignment dates of each equipment and labour. The resource database stores the data listed in Table 3.1. These data items are necessary to support the computations of the proposed model, and were mostly obtained from equipment manufacturers (e.g. Caterpillar 1997). In addition to the data items obtained from equipment manufacturers, others were introduced to add flexibility to the developed model. For example, equipment purchase date was introduced to accommodate the case when not all equipment are available at project start (see numerical example III in Chapter Six). A more detailed listing of data stored for equipment is dependent on its type, and is discussed below.

The developed entity relation diagram for the resource database is shown in Figure 3.12. Based on the literature review and the survey of industry, the following eleven equipment types were identified as mostly employed in this class of projects: 1) asphalt mix plants; 2) backhoes; 3) loaders; 4) dozers; 5) trucks; 6) cranes; 7) compactors; 8) scrapers; 9) pavers; 10) motor graders; and 11) crushers. Dozers can be fitted with several blade types, hence an entity entitled "dozer blades" was developed to capture the attributes of blades, such as type, width and height. Dozers can have one of several blade attachments, and therefore a one-to-many relation exists between "dozer" and "dozer blades" entities. Similarly, backhoes and pavers have one-to-many relations with buckets and screeds, respectively.

This design enables the assessment of the availability of any piece of equipment along with all its required peripherals within any specified period. In order to enhance the model's flexibility, and enable employing additional equipment types, an entity "other equipment" is introduced.

Table 3.1: Data stored by resource database

Resource	Data stored
Equipment	• Manufacturer and model • Unique identifier (chassis number, license plate) • Purchase date • Travel speed (on and off-highway) • Equipment particulars (see Appendix IV) • Daily cost • Total hours worked
Labour	• Trade • Unique identifier (employee number) • Name • Address, phone number • Date of birth • Hourly wages • Hiring date
Subcontractors	• Name, address, phone and fax numbers, and internet data • a list of all the trades to which the subcontractor could be assigned • production rates at which the contractor can operate and the corresponding unit cost (for each trade)
Rental equipment	• supplier name • supplier address, phone and fax numbers • available equipment and rental rates

Entity "Equipment" shown in Figure 3.12 stores attributes common to all equipment types, such as manufacturer, model, mobility (on and off-highway travel speeds, whether a float is required for transport, and whether any assembly is required on site), equipment ID and daily cost. Since a contractor can own more than one pieces of equipment of the same model, "equipment" is connected by one-to-many relations to entities representing each of the above-mentioned equipment types. Particulars defining each of the equipment types are developed in accordance with "Caterpillar Performance Handbook" (Caterpillar 1997), and are listed in Appendix IV. These particulars are employed to aid in selecting suitable equipment for each crew.

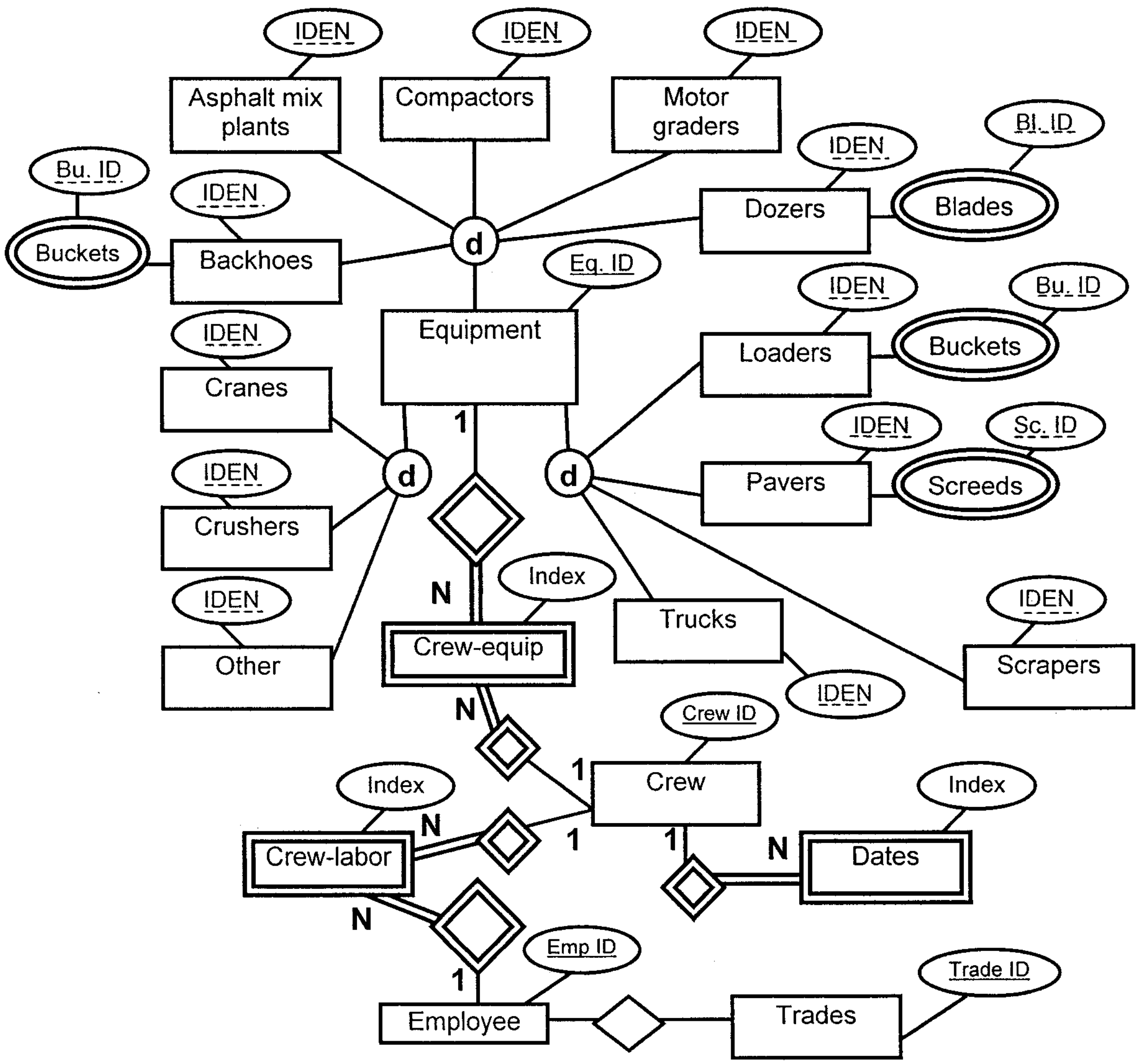


Figure 3.12: Developed entity-relation diagram

The database module also stores crew templates (Section 4.4.1), which enables storing typical crews for future use. Crew templates are represented by three entities: “crew ID”, “crew-equip” and “crew-labour”. The first stores crew particulars such as crew name, daily cost, daily productivity and units of measurement in which the productivity is reported (e.g. m^3, m, ton). The other entities define crew composition in terms of equipment and labour. Entity “crew-equip” shares a one-to-many relation with “equipment” to enable defining multiple pieces of equipment for any crew. Similarly, entity “crew-labour” shares a one-to-many relation with “trade wages”. This design enables defining crews in terms of their general requirements, while actual crew composition is determined during scheduling (Section 4.4.2). Multiple assignment periods are defined employing entities “equip-ass” and “lab-ass”, which store assignment dates for all pieces of equipment and all labourers, respectively. A separate table is developed for each resource type (equipment and labour) to avoid conflicts that can arise from a labourer and a piece of equipment sharing the same identifier. Each time the database is queried for the availability status of a resource within a certain time period, it compares that time period with all periods that the resource is already committed. If no overlap exists between the required time period and any of the prior assignments, the resource is declared available. If, on the other hand, a resource is found unavailable, and renting additional equipment is considered as an option, the database is employed to replace the scarce resource with one from the defined rental pool. The role of the database in the scheduling phase will be discussed in more detail in Section 4.4.2.

The soil database stores the swell and shrinkage factors for various types of soil. This data is required when estimating cut and fill quantities. The weather database stores daily records of precipitation, temperature and wind speed for the locations where operations are in progress, enabling the consideration of weather impact on crew productivity (Section 4.5.2). For each day, records are kept for morning, afternoon and overnight periods (6:00 AM to noon, noon to 6:00 PM and 6:00 PM to 6:00 AM, respectively), storing total precipitation expected for each period, along with the average wind speed and temperature. The role played by the databases is expressed in more detail in Chapter Four.

3.4 Planning and Scheduling Module

This module is responsible for developing the precedence network respecting job logic, and generating the schedule utilising the defined resources. The schedule can be optimized to minimise either: 1) total construction time; 2) total construction cost; and 3) their combined impact for what is commonly known as cost-plus-time (A+B) bidding (Herbsman 1995). This module is described in detail in Chapter Four, while the developed optimization procedure is discussed in Chapter Five.

3.5 Tracking and Control Module

Considerable work has been done over the last 30 years focussing on tracking and controlling highway construction operations (NCRHP 1970; Tavakoli 1988 and 1991; Rowings and Rahbar 1992). Project tracking and control encompasses monitoring project progress, comparing actual progress to that planned and determining if any variances exist (Moselhi 1993). Analysing actual crew performance and forecasting project time and cost at completion are also basic functions of project tracking and control. Tracking construction projects enables timely detection of cost overruns and schedule delays, if any. A detailed comparison between planned and incurred costs enables the identification of cause(es) behind unacceptable performance. This Section presents the tracking and control module responsible for performing these functions. The module proposes an alternate methodology to forecast project time and cost at completion for linear projects.

The proposed work breakdown structure described in Chapter Four provides the foundation for the tracking and control module by defining the scope of work in each work package. Based on the schedule sequencing these work packages, along with its allocated resources, the project baseline can be established (Moselhi 1993). It should be noted that the vertical axis (Figure 3.13) could represent any one of an array of criteria (e.g. cost, work complete, man-hours) to be monitored. Integrated cost/time/work graphs, such as the one shown in Figure 3.13, define project status in terms of both cost and schedule. A brief description of project baseline and earned value in reporting project progress is summarised in Appendix V. The methodology developed to estimate daily planned costs for each activity in a linear project is presented in Appendix VI.

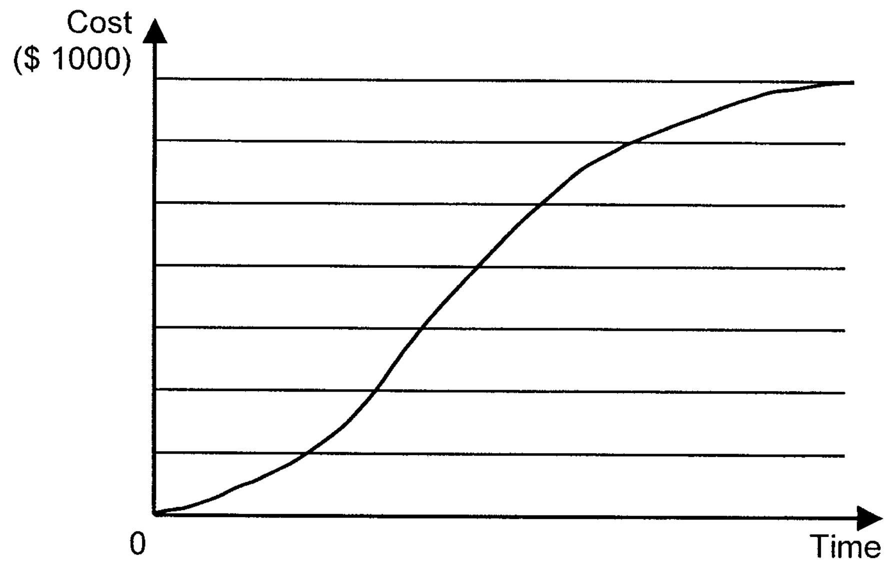
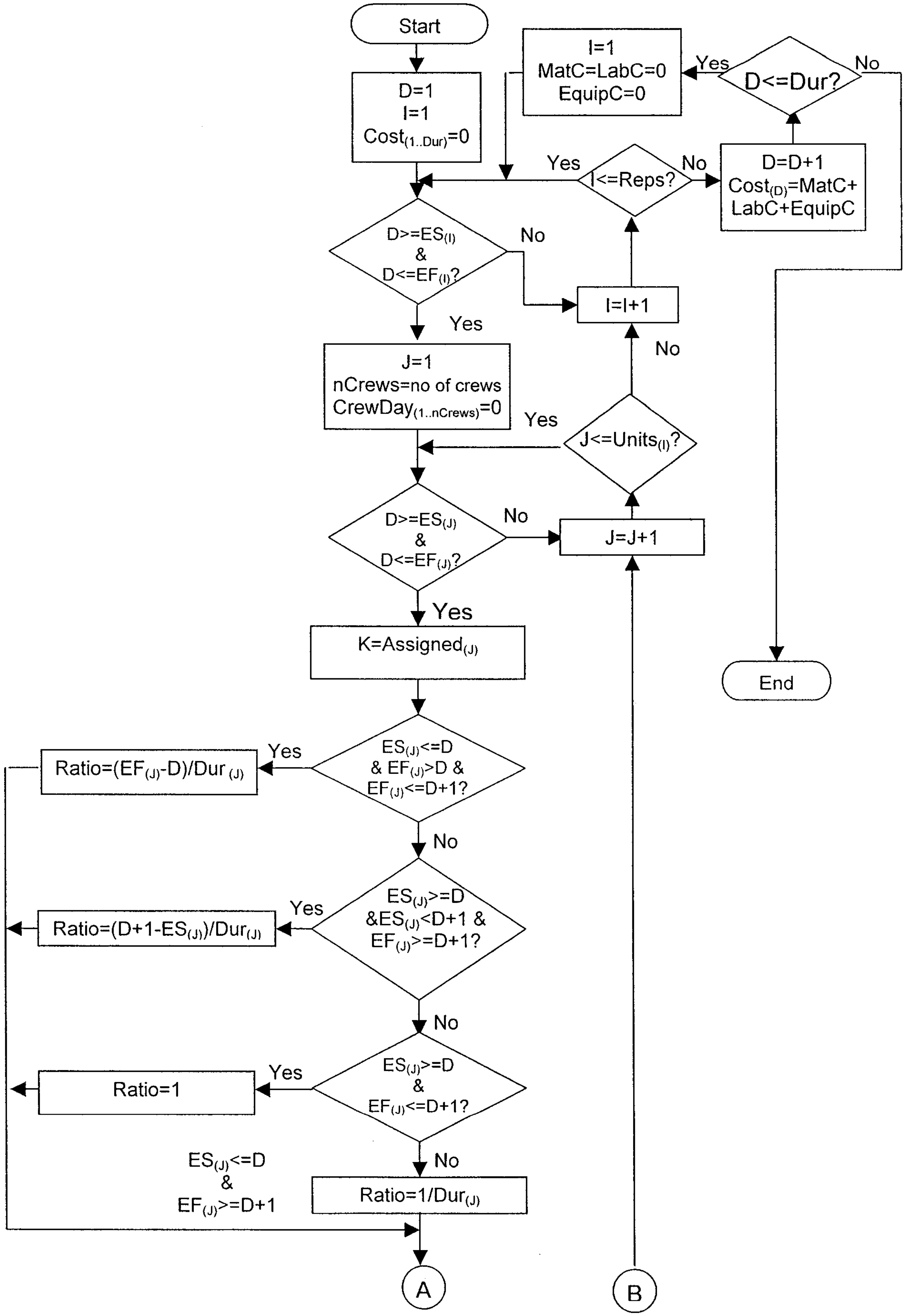


Figure 3.13: Sample progress curve

3.5.1 Monitoring Cost

Generally, highway construction projects are large projects in terms of capital expenditure (Adeli and Karim 1997), necessitating the development of an efficient methodology to monitor these expenses on monthly, bi-weekly, weekly or even daily basis. As mentioned earlier, equipment typically employed in this class of projects are large (Barrie and Paulson 1992), and their mobilization and demobilization costs could constitute a significant portion of total cost. These costs, as well as equipment set-up and assembly/disassembly times and costs, are accounted for in the proposed model.


Start
D=1
I=1
Cost(1..Dur)=0
I=1
MatC=LabC=0
EquipC=0
Yes
D<=Dur?
No
Yes
I<=Reps?
No
D=D+1
Cost(D)=MatC+
LabC+EquipC
D>=ES(I)
&
D<=EF(I)?
No
I=I+1
Yes
No
J=1
nCrews=no of crews
CrewDay(1..nCrews)=0
Yes
J<=Units(I)?
D>=ES(J)
&
D<=EF(J)?
No
J=J+1
Yes
K=Assigned(J)
End
Yes
Ratio=(EF(J)-D)/Dur (J)
ES(J)<=D
& EF(J)>D &
EF(J)<=D+1?
No
Yes
Ratio=(D+1-ES(J))/Dur(J)
ES(J)>=D
&ES(J)<D+1 &
EF(J)>=D+1?
No
Yes
Ratio=1
ES(J)>=D
&
EF(J)<=D+1?
No
ES(J)<=D
&
EF(J)>=D+1
Ratio=1/Dur(J)
A
B

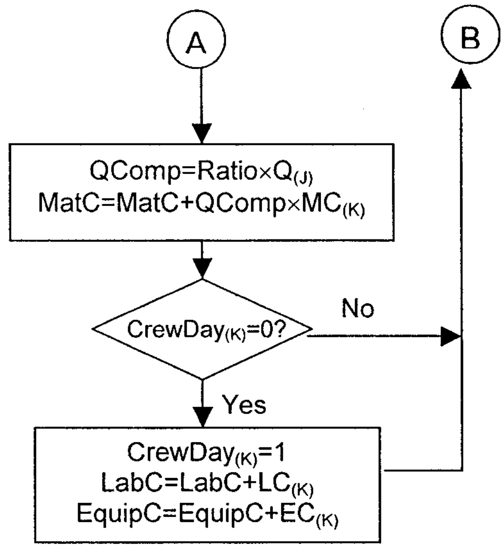


Figure 3.14: Algorithm developed to estimate daily costs

An algorithm is developed to estimate daily costs incurred on a project, and is shown in Figure 3.14. Initially, a vector storing daily costs, **Cost**, is generated, and all its elements are initialised ($Cost_{(1\times DUR)}=\{0\}$). The day at which cost is computed, "D", is also initialised to unity. Start and finish dates of each activity are then queried to determine whether that activity is scheduled to be in progress on day "D". If $D \leq ES_{(i)}$ or $D \geq EF_{(i)}$, (where $ES_{(i)}$ and $EF_{(i)}$ are the start and finish times of activity "i", respectively) then no work is in progress on day "D" for that activity, and "i" is incremented. Otherwise, work is scheduled to be in progress in activity "i" on day "D", and the quantity completed on that day remains to be estimated. The size of a crew formation (noCrews) and total number of units ($Units_i$) of that activity are then queried. It is worth noting that, for non-repetitive activities, only one crew can be assigned, and there only exists one location at which that activity is performed ($noCrews=Units_i=1$). A counter "J" is set equal to unity, and is employed to iterate through all units of activity "i" to determine whether any work is scheduled to be in progress on day "D". If any work is scheduled, the crew assigned to unit "J" is identified ($c=assigned_{(J)i}$, where **$assigned_i$** is a vector storing crew assignments for all units of activity "i"). Upon identifying the crew assigned to unit "J", its previous assignments are reviewed to determine whether any mobilization/demobilization is required. Two possible scenarios exist:

1. Crew "c" was previously assigned to an adjacent unit, and thus no mobilization/demobilization costs are incurred or
2. Crew "c" was either previously assigned to a non-adjacent unit, or unit "J" is the first assignment for that crew. In either case, travel to unit "J", as well as any set-up costs (if any) need to be computed. Crew mobilization cost, including any set-up cost (if any), from the contractor's workshop to unit "J" is computed as discussed in Section 4.5.1.

Depending on "$ES_{(J)}$", "$EF_{(J)}$" and "D", one of four scenarios exists, as discussed earlier. The quantity of work completed on day "D", along with the required time, is computed using the applicable set of equations (see Appendix VI). Material cost is expressed as:

$$MatCost_{(D,J)}=MCU \times Quan_J \qquad (3.8)$$

where $MatCost_{(D,J)}$ is the material cost incurred on day D for unit J, MCU is the unit material cost and

$Quan_{D/J}$ is the quantity of work in unit J completed on day D.

While equipment and labour cost are expressed as:

$$EquipCost_{(c,D,J)}=T_{D/J}\times DCEC_{(c)} \quad (3.9)$$

and

$$LabCost_{(c,D,J)}= T_{D/J}\times DCLC_{(c)} \quad (3.10)$$

where

$$DCEC_{(c)} = \sum_{i=1}^{i=n} Cost_i \quad (3.11)$$

and

$$DCLC_{(c)} = \sum_{i=1}^{i=n_L} Cost_{Lab_i} \quad (3.12)$$

where $T_{D,J}$ is the duration the crew is working on unit J on dayD,

$EquipCost_{(c,D,J)}$ is the equipment cost incurred by crew c working on unit J on day D,

$LabCost_{(c,D,J)}$ is the labour cost incurred by crew c working on unit J on day D,

$DCEC_{(c)}$ and $DCLC_{(c)}$ are daily equipment and labour costs of crew c, respectively,

$Cost_i$ is the daily cost of equipment i,

$Cost_{Labi}$ is the daily cost of labour i, n is the total number of pieces of equipment comprising crew c and

n_L is the size of the labour crew (number of labourers).

Direct planned cost for activity "i" on any day "D" is computed by summing the material, equipment and labour costs as follows:

$$Direct_{i/D} = \sum_{J=1}^{J=m}(MatCost_{(D,J)} + EquipCost_{(c,D,J)} + LabCost_{(c,D,J)}) \qquad (3.13)$$

where $Direct_{i/D}$ is the planned direct cost of executing activity "i" on day "D",

m is the number of units in activity "i" (m=1 for non-repetitive activities) and

$MatCost_{(D,J)}$, $EquipCost_{(c,D,J)}$ and $LabCost_{(c,D,J)}$ are as defined in Equations (3.8), (3.9) and (3.10), respectively.

Depending upon the assignments of crew "c" after completion of work in unit "J", one of the following cases prevails:

1. There are no assignments to crew "c". The crew should return to the contractor's staging and maintenance shop. Incurred disassembly costs (if any), as well as demobilization costs are computed.
2. Next assignment of crew "c" is to work on unit "L", which is non-adjacent to unit "J". Disassembly costs (if any) and demobilization costs are to be incurred and computed. The travel distance between segments containing

units "J" and "L" is determined from the mobilization matrix, $M_{L,J}$, and costs are computed as described in Section 4.5.1.

3. Next assignment of crew "c" is to work on unit "J+1". No mobilization costs are incurred.

The above procedure is repeated for all units of all activities until the total cost planned for day "D" is computed. Total daily cost is determined by adding the daily indirect cost, an attribute of the project, to the computed direct cost. Day "D" is then incremented, and the above procedure repeated, until "D=DUR" (where "DUR" is the project duration), and the project baseline is generated.

3.5.2 Monitoring Physical Progress

Several methods have been proposed to measure actual progress in terms of work completion. Such methods include the "units completed", "incremental milestones", "start-finish basis", "supervisor's opinion", "cost ratio" and "weighted units" methods. Of these, the "weighted units" method was reported as the most capable of quantifying construction progress (Barrie and Paulson 1992), and is thus employed in the proposed module. The activities' relative weights are computed based on the man-hours expended on each activity. The relative weight (%) of activity "A" is expressed as:

$$WT_A = \frac{\text{man-hours}_A}{\sum_{i=1}^{i=n} \text{man-hours}_i} \times 100 \qquad (3.14)$$

where WT_A is the relative weight (%) of activity A in relation to project,

n is the total number of project activities and

man-hours_A and man-hours_i are the man-hours required to complete activities "A" and "i", respectively.

The daily work completed on any day "D" (where $0<D\leq$project duration) is determined by summing the daily work completed on all activities, and is expressed as:

$$WP_D = \sum_{A=1}^{A=n} \sum_{J=1}^{J=m_A} WT_A \times Quan_{D/J} \tag{3.15}$$

where WP_D is the total work completed on day D,

n is the total number of activities,

m is the total number of units in activity A,

$Quan_{D/J}$ is as defined in Equation (3.8) and

WT_A is as defined in Equation (3.14).

Progress curves representing work complete are then plotted by computing the cumulative work completed throughout the project duration. It is worth noting that, unlike when costs are being estimated, mobilization and demobilization are not accounted for when plotting the progress curve for work. This is because these operations do not represent part of the delivered product.

3.5.3 Cost Breakdown Structure

Breaking down costs incurred, and determining the variance between planned and actual costs enables the identification of sources of cost overrun, if any. The module enables breaking down the project costs based on: 1) activity; 2) activity category (e.g. paving, general, services, earthmoving); or 3) cost item (material / labour / equipment / indirect). This enables detailed views of the project from different perspectives, providing an overview of project status, and identifying areas where expenditure has deviated from that planned. Planned costs are determined as discussed in Section 4.6, while the user supplies incurred costs. If incurred costs are supplied in enough detail, comparison between incurred and actual costs for each cost item can help trace the source behind unacceptable performance.

Breaking down project costs by activity is one of the more common methods adopted to monitor project progress. It is specially adopted in projects where many of the activities are subcontracted. The procedure discussed in Section 4.6 is employed to estimate the planned costs for all project activities. Costs incurred in the execution of each activity are then compared to those planned, and activities with cost overrun are determined. On the reporting day "RD", the planned costs for activity "i" are expressed as:

$$PCD=0 \qquad \text{if } RD<Start_i \qquad (3.16a)$$

$$PCD=\sum_{D=Start_A}^{D=RD} Direct_{A/D} \qquad \text{if } Start_A \le RD < Finish_A \qquad (3.16b)$$

$$PCD = \sum_{D=Start_A}^{D=Finish_A} Direct_{A/D} \quad \text{if } RD \geq Finish_A \tag{3.16c}$$

where PCD is the planned cost to be incurred on day D and

$Start_A$ and $Finish_A$ are the start and finish dates, respectively, of activity A.

If cost breakdown is to be done according to activity category, planned costs of all activities falling under the same category are grouped, and the total determined by direct addition. If cost breakdown is to be done according to cost items, Equations (3.9) through (3.12) are employed to determine the planned material, equipment and labour costs. Total cost for each cost item is then computed considering indirect cost. The model generates integrated cost-work graphs and employs the earned value concept (Moselhi 1993) to track project progress.

3.5.4 Trend Analysis and Forecasting

Evaluating actual performance throughout project progress is crucial to forecast project time and cost at completion. Several forecast models have been developed for this purpose, each with its own assumptions. The two main forecasting techniques are based on assuming that either: 1) overall project progress will continue according to the schedule; or 2) progress rates encountered thus far will prevail until project completion. This module proposes an alternate methodology, enabling the assignment of higher weight to recent performance of crews. The module also enables blacking out certain time periods during which exceptional conditions are known to have prevailed. Future crew productivity is expressed as:

$$Prod_f = A \times Prod_p + (1-A) \times \sum_{i=1}^{i=n} w_i \times Prod_{a_i} \tag{3.17}$$

where $Prod_f$ is the forecast crew productivity,

A is the weight given to planned productivity (default=0.5),

$Prod_p$ is the planned productivity,

w_i is the weight given to productivity during period i ($\Sigma w_i=1.0$),

$Prod_{a_i}$ is the actual productivity during period i and

n is the total number of periods being considered.

By default, the model divides past performance into two (2) periods: 1) from the day work commences until the start of the reporting period; and 2) during the reporting period. The default weight assignments for these periods are such that the performance during the reporting period is 10% higher than the earlier period (w_1=0.45 and w_2=0.55). The relative weights can be modified to reflect the unique characteristics of each project. The user can also elect to define multiple periods, providing the actual productivity and relative weight during each of the defined periods.

In order to suit the nature of highway projects evaluation of actual performance is carried out at the crew level. This enables realistic evaluation of actual performance, as the performance of under-achieving crews would not be masked by that of more efficient crews working on the same activity. The detailed cost breakdown carried out by the module determines if any cost or schedule variances are due to variances in material, labour or equipment.

3.6 Reporting Module

The module generates tabular and graphical reports, to enable project monitoring, tracking and forecasting time and cost at completion. While higher levels of management require an overview of project progress and milestones, personnel working on site require more detail at the activity level. An earlier study (NCHRP 1970) criticized the pyramiding information flow system, and recommended narrowing the scope of information provided and increasing its level of detail as one progresses down the management hierarchy. The reporting module generates reports at varying degrees of detail, to suit the needs of all project participants in three formats; tabular, graphical, and exception reporting.

3.6.1 Tabular Reports

Crew assignments (which crews are working on which repetitive units) are presented in tabular format, as listed in Table 3.2, which shows portions of a table reporting the schedule of an activity composed of 30 units, each 500 m long. The table indicates that crew "C_1" is assigned units 1 through 18, while crew "C_2" is assigned to remaining units. Crew "C_1" is scheduled to work from May 6 to July 25, while Crew "C_2" is scheduled to work from May 20 to August 8. The table reports crews' progress through the project, aiding the determination of crews' locations on any given day.

Table 3.2: Sample tabular activity schedule

Unit number	Chainage		Assigned crew	Schedule (d/m/y)	
	Start	Finish		Start	Finish
1	0+000	0+500	Crew C_1	6/5/02	9/5/02
2	0+500	1+000	Crew C_1	9/5/02	14/5/02
⋮	⋮	⋮	⋮	⋮	⋮
18	8+500	9+000	Crew C_1	22/7/02	25/7/02
19	9+000	9+500	Crew C_2	20/5/02	24/5/02
⋮	⋮	⋮	⋮	⋮	⋮
30	14+500	15+000	Crew C_2	5/8/02	8/8/02

Planned daily costs, along with cumulative costs to date, are broken down and reported, as shown in Table 3.3. The table shows portions of the report generated to provide the cost breakdown for a project composed of seven activities, throughout project duration (35 working days). Planned costs for materials, labour, and equipment, along with their totals, for each activity is reported. Activity "A_1" is the only activity in progress on the first day, and daily project cost is equal to the activity's cost. Equipment cost on the first and last days of a crew's assignment are higher than remaining days to account for mobilization/demobilization costs, as can be seen by comparing equipment costs for days one and two, and 34 and 35, for activities "A_1" and "A_7", respectively. Day 19 is the first day Activity "A_7" is in progress, and therefore equipment cost is equal to those planned for the last day (day 35).

Table 3.3: Sample tabular cumulative costs

Working Day	Activity 1					Activity 7				Daily cost	Cum Cost
	Mat	Lab	Eq	Total	...	Mat	Lab	Eq	Total		
1	300	1,320	7,865	11,485	...	0	0	0	0	11,485	11,485
2	300	1,320	7,865	9485	...	0	0	0	0	9,485	20,970
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
19	0	0	0	0	...	1,218	3,450	12,210	16,878	27,330	378,280
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
34	0	0	0	0	...	1,218	3,450	9,210	14,878	13,878	702,990
35	0	0	0	0	...	715	3,450	12,210	16,878	16,375	719,365

3.6.2 Graphical Reports

The module generates several charts, tailored to display information at varying degrees of detail. The basic bar chart (Gantt chart) of the project is generated, depicting start and completion date of each activity. A more detailed view of the progress of work is provided in the form of a linear chart. The chart displays the progress of the various crews for all activities along the project length. In accordance with common highway practice (Harmelink 1995), and in order to enhance visualisation of the generated linear schedule (Vorster *et al* 1992), the horizontal axis represents distance, while the vertical axis represents time. The module also generates bar charts depicting dates on which each crew is required on site. Progress curves depicting percent complete and showing the cumulative planned cost to date (S-curve) are also generated. The reporting module also presents integrated time/cost/work graphs, to enable determine project status. Pie charts depicting the project cost breakdown, either by activity or cost category (material – equipment – labour – indirect) are also generated. Samples of these charts are presented in Chapter Six.

3.6.3. Exception Reporting

Generating reports that draw attention to activities that are experiencing delays and/or cost overruns is also enabled. A threshold is set for the acceptable variance of each activity (default =15%) beyond which the activity is automatically flagged. The threshold value can be modified to accommodate the unique requirements of each activity and project. A detailed report listing actual costs incurred vs. those planned for each cost item (i.e. equipment, labour and material) of that activity is also generated.

3.7 System Configuration and Data Flow

The operation of the model is schematically illustrated in Figure 3.15. The model commences by accepting the project's data, both graphic and non-graphic. Based on the borehole test results and ground topography, the GIS module generates DTMs representing ground topography and underlying soil strata. Cut and fill quantities are then computed with the aid of the soil database, to determine the swell and shrinkage factors of encountered soil types. The mass haul diagram is then generated as discussed above. Having estimated the quantity of work involved in all activities, crews that can be assigned to each activity are selected from the available resource pool. Upon defining potential crews for all activities, and having defined the precedence network for the project (either through user-input or system-generated), and weather at the project location from the database (if impact of weather on productivity is to be considered) scheduling can commence.

During scheduling, equipment and labour availability are revised to account for the latest crew assignments. The reporting module is notified of schedule changes, and generates requested reports as discussed above. If updating a project, the tracking and control module accepts input quantities complete and incurred costs as defined by the user. Knowing the data and planned quantity complete and cost, progress curves are developed, and earned value analysis can be carried out. The tracking and control module analyses activity progress, and notifies the reporting module if any exception reports need to be generated.

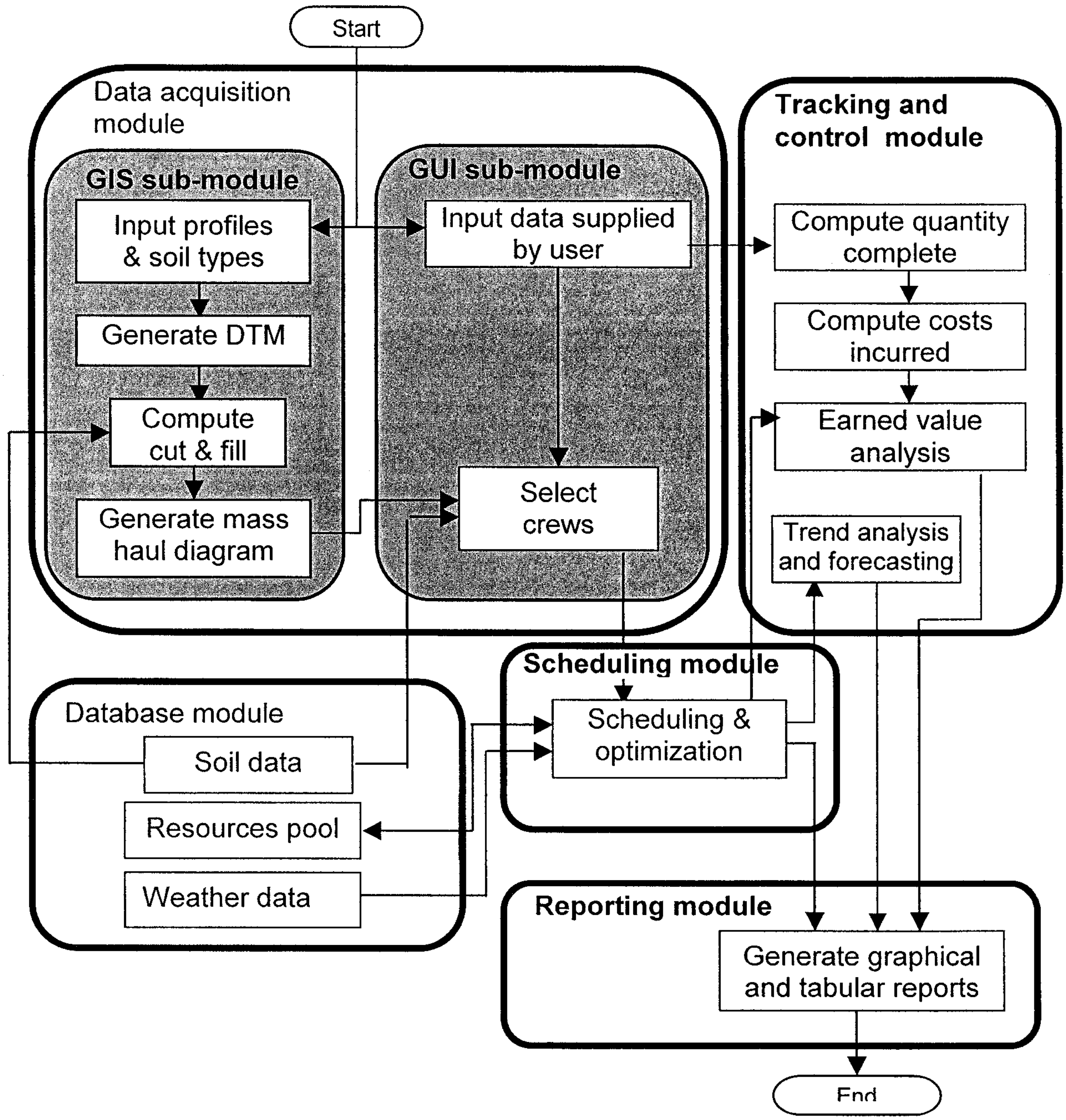


Figure 3.15: Data flow

3.8 Summary

The modules comprising the developed model were presented. The main features of the proposed model were reviewed, and each module was described.

The GIS module was discussed, and the procedure employed to estimate cut and fill quantities and generated the mass haul diagram were presented. The main elements of the database and tracking and control modules were also presented. The methodology adopted to determine crew performance and forecast project time and cost at completion also was described. The various reporting formats generated by the reporting module were also discussed. The data flow within the proposed model was described.

CHAPTER FOUR

PLANNING AND SCHEDULING MODULE

4.1 Introduction

This chapter presents the planning and scheduling module. A detailed description of the proposed work-breakdown structure (WBS) is presented, along with the activity types and precedence networks. The object-oriented model developed to plan and schedule highway projects is presented. The main attributes of each object are introduced, as well as the main functions performed by each object during scheduling. The procedure developed to determine the availability status of required resources is also discussed. Crew templates are introduced, and their role in selecting crew components is discussed. The scheduling algorithm is then presented, and the scheduling process is detailed. The procedure to estimate cost is presented, and the various expediting techniques employed to complete a project on schedule are described.

4.2 Project Planning

Planning can be defined as *"... the process of representing the project scope by its identifiable components. It involves the break-down of the project into definable measurable and identifiable work tasks/activities, and then establishes the logical inter-dependence among them"* (Moselhi 1993), and has been identified as *"... the most crucial, knowledge intensive, ill-structured and challenging phase in the project development cycle"* (Moselhi 1993). The effort required to develop a competent plan is perceived as a major obstacle to developing high quality schedules (Chevallier and Russell 2001). An earlier study (Herbsman 1987) revealed the dissatisfaction of parties involved in planning and scheduling highway operations with available scheduling tools. This sentiment was recently echoed by Anderson *et al* (1999), whose survey revealed that highway construction firms consider poor scheduling and phasing of construction to jointly represent the second most factor impeding competent construction. A later survey (NCHRP 2000) reported that 74% of the DoT's surveyed expected to change their project management systems before 2005. While several models were proposed to automate the planning process and generate precedence networks for high-rise construction (e.g. Shaked and Warszawski 1995; Moselhi and Nicholas 1990), little attention was given to planning highway construction. Planning highway projects entails:

1. developing the work breakdown structure (WBS), identifying the various tasks in all project segments, and
2. generating the precedence network respecting job logic among the identified tasks.

The planning and scheduling module is designed to automate the above functions, while enabling users to modify any default settings. This expedites data entry, while providing the required flexibility to define project-specific attributes. This Chapter presents the planning and scheduling module how each of the above functions is addressed in the proposed model. It is worth noting that this study focuses solely on the construction of flexible pavements.

4.2.1 Work Breakdown Structure

During the planning and scope definition stage, large projects are progressively divided into smaller, definable and trackable units commonly known as work packages. In the proposed model, a project is divided generically into work zones, segments, sections and units (see Figures 4.1 and 4.2). Transverse obstructions, such as rivers and creeks, play a major role in performing the WBS (Alkass and Harris 1991). There are two types of obstructions: 1) surmountable, where access is granted across the obstruction at an overhead (time and cost); and 2) insurmountable, where no access is granted. Work zones are normally defined based on the locations of insurmountable obstructions, while segments are defined based on the locations of surmountable ones. As for sections, they are mainly defined by the size of the crew formation (number of crews that can work simultaneously on any task), size of each crew, its availability and work continuity constraints, as will be discussed in Chapter Five.

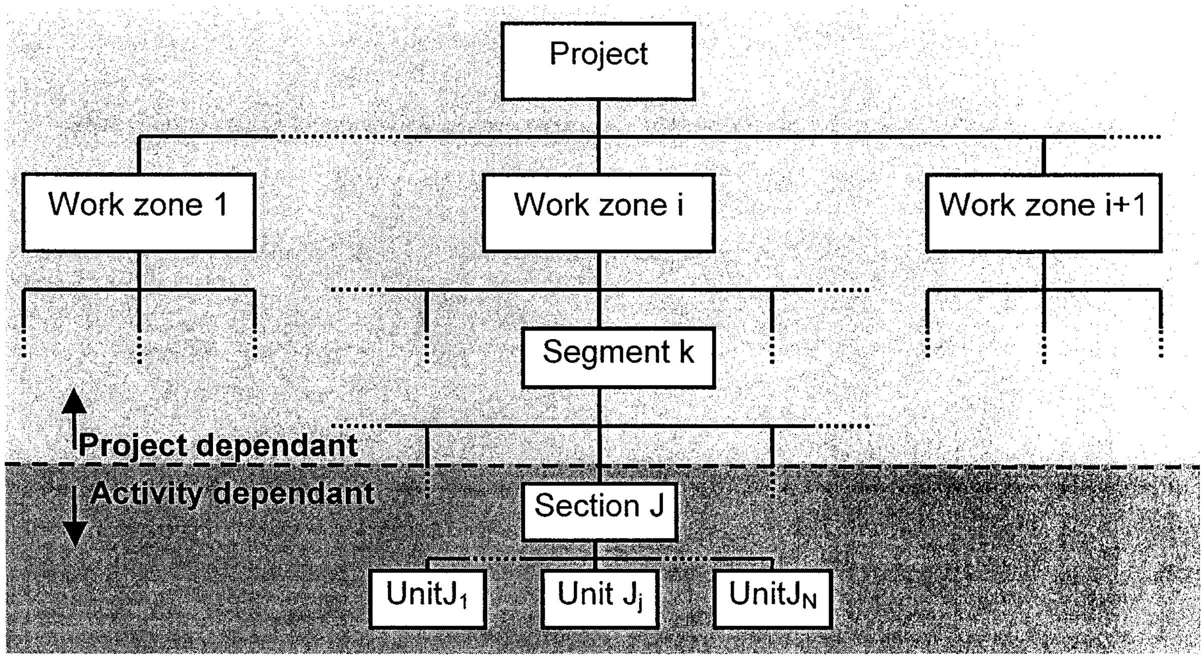


Figure 4.1: Work breakdown structure

Project division is illustrated in Figure 4.2, where two repetitive tasks, “A” and “B”, are scheduled. Four crews can work simultaneously on the former, while only two crews can work simultaneously on the latter. Figure 4.2(b) shows the linear schedule for the two tasks. As mentioned in Chapter Three, the proposed model plots linear schedules in accordance with highway practices, with chainage as the horizontal axis and time as the vertical axis (Vorster *et al* 1992; Harmelink 1995). The schedule shows that while task “A” is divided into four sections, task “B” is divided into three sections. The time required by crew “B_2“ to overcome the surmountable obstruction, “T_{travel}”, is indicated by the loss of time at the obstruction location (see Figure 4.2(b)), and depends mainly on the additional travel distance, road conditions and crew size and mobility.

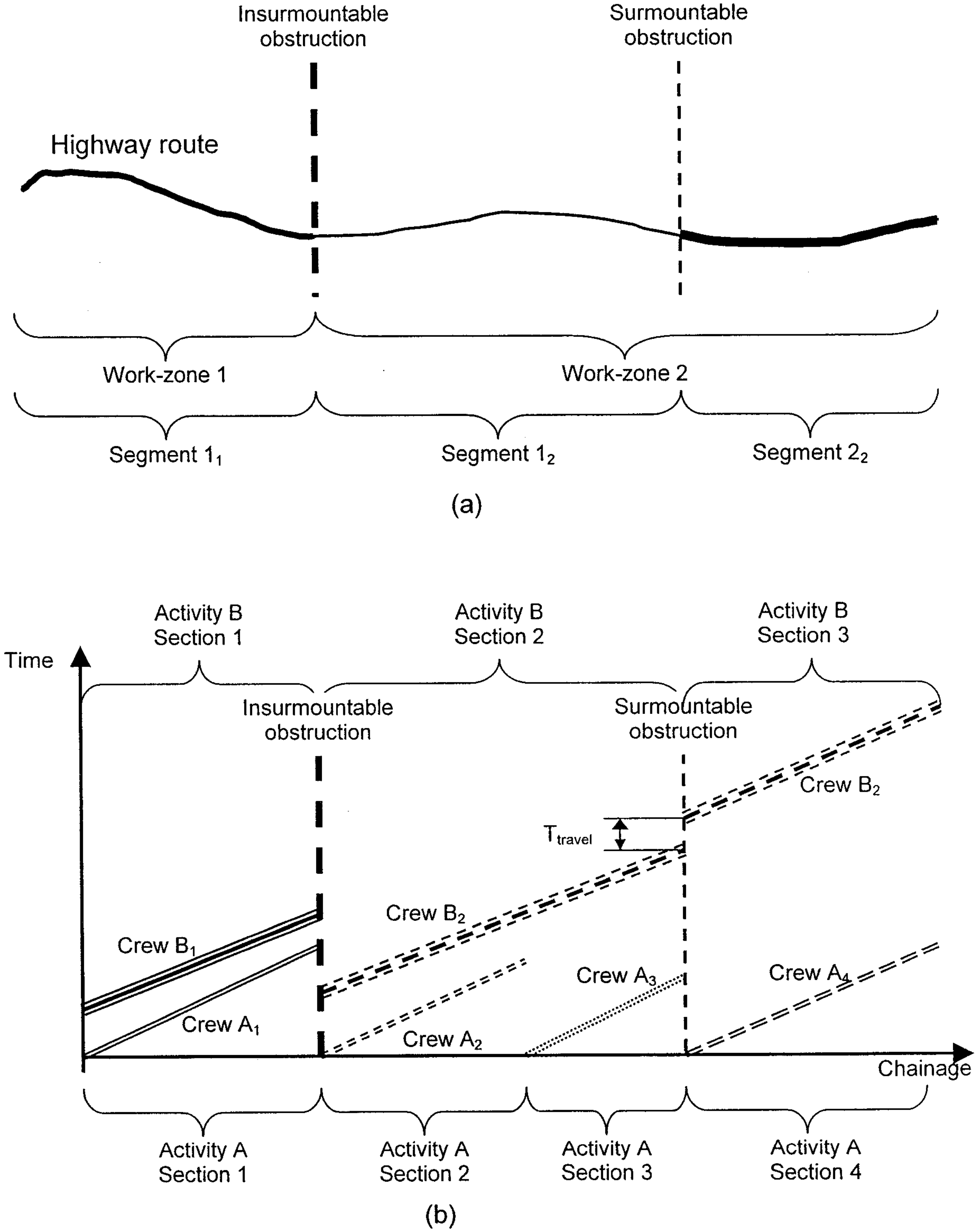


Figure 4.2: Project and activity division

It should be noted that while no resources are shared between work-zones, resources could travel between segments within a work zone. Consequently the size of a crew formation assigned to any repetitive activity must allow for at least one crew to work at each work-zone. For example, the minimum size of a crew formation that can be assigned to any repetitive activity in the project shown in Figure 4.2 is two (two crews).

The length of a repetitive unit may vary from one project to another as it mainly depends on the nature of work performed. Typically, a unit is considered to be of a certain length (e.g. 500 m in highway construction) along the highway length (Johnston 1981). Interference between different crews has been shown to negatively impact crew productivity (Thabet and Beliveau 1994). Consequently, previous studies (Harris and Evans 1977) proposed defining the unit length of a repetitive activity based on the minimum buffer required by crews to work without interference from other crews working on preceding or succeeding activities. The length of this buffer is dependent on the type of activity being performed. For example, earthmoving operations require a buffer that can stretch for kilometres over relatively long durations, depending on the locations of balance points and scope of work. Such activities are commonly referred to as "time space activities" (Stradal and Cacha 1982). Usually, an effort is made to divide a project into smaller units to accelerate the work performed. This implicitly assumes concurrent assignment of these crews to units while satisfying the minimum buffer requirements.

In the proposed model, project activities are defined utilising the WBS defined above, and are either repetitive (performed throughout the project) or non-repetitive (performed once at a specified location). Both typical (constant quantity of work in all units) and non-typical (varying quantities of work among units) repetitive activities are incorporated in the scheduling procedure. A repetitive activity might be repeated in a number of units within a section, segment and/or work-zone, possibly with units of varying scope of work. A project also could consist of multiple work-zones, segments and sections, as shown in Figure 4.2.

4.2.2 Activity Relationships

The proposed model automatically generates generic precedence networks for both construction of new highways and rehabilitation of existing ones. Lists of activities typically involved in both types of projects, and their precedence relations, are defined in the proposed model. Selection of any, or all, activities in the list is enabled, and the precedence network is generated accordingly. Additional activities, along with their precedence relations, can subsequently be added to the network. Detailed construction of foundation and superstructure of overpasses are simplified and represented by a single activity: "overpass construction". The user is required to provide the cost and duration of this activity. In order to determine the activities involved in highway construction projects, and consequently generate the precedence network, pertinent literature was thoroughly reviewed (e.g. NCHRP 1970; Oglesby 1982; Watson 1989, NCHRP 1995) and a precedence network was developed. It was then presented to seven knowledgeable highway construction personnel (see Appendix VII) to obtain their comments and feedback. The literature review and interviews were augmented with periodic visits to two (2) highway construction projects: 1) final extension to highway 407-ETR (Express Toll Route), in Toronto, Ontario; and 2) construction of a concrete overpass and its approaches to Highway 364 across the Riviére Rouge at Huberdeau, near Arundel, Québec. The former is the first toll highway in Canada, and is considered a large project according to the classification proposed by Herbsman (1987). The latter represents a medium size project according to the same classification (Herbsman 1987).

4.2.2.1 New Highway Construction

The proposed model embraces industry practices, and generates precedence networks to schedule both: 1) mainline operations; and 2) location specific operations. Mainline operations are those concerned with the main highway route, such as paving the highway, while location-specific operations are those carried out at a certain location only, such as culvert installation. In addition to mainline operations, the proposed model stores precedence networks for the construction of: 1) overpasses; 2) transverse overpasses; and 3) interchanges. The proposed precedence networks for construction of a new highway are presented in Figures 4.3 through 4.6. Unless otherwise specified, all precedence relations shown in the figure are finish-to-start, with no lag time. The main difference in sequence of operations for overpasses and transverse ones is that earthmoving for the mainline at the vicinity of the transverse overpass is done after having completed the construction of the overpass, as shown in Figures 4.5 and 4.6. It should be noted that the precedence network shown in Figure 4.3 represents the sequence of operations at a specific location along the highway. This sequence is repeated at all locations along the highway length.

The developed logic diagram was then reviewed by the experts from whom the knowledge was elicited, and was found to be accurate. The developed network was compared to the job logic for the construction of zone "W1" of the West Extension of the 407 ETR project in Toronto, Ontario. As discussed earlier, the project was divided into three work zones (see Fig. 1.2), and is discussed in Appendix VIII. Although the chart provides a higher level of detail compared with that provided by the proposed precedence network, it can be seen that they match reasonably well. However, it should be noted that there exists a great deal of flexibility in developing a project's precedence network; multiple networks could be developed to detail the construction of a highway. The proposed network captures the essence of the job logic, and can be modified to suit the unique requirements of each project.

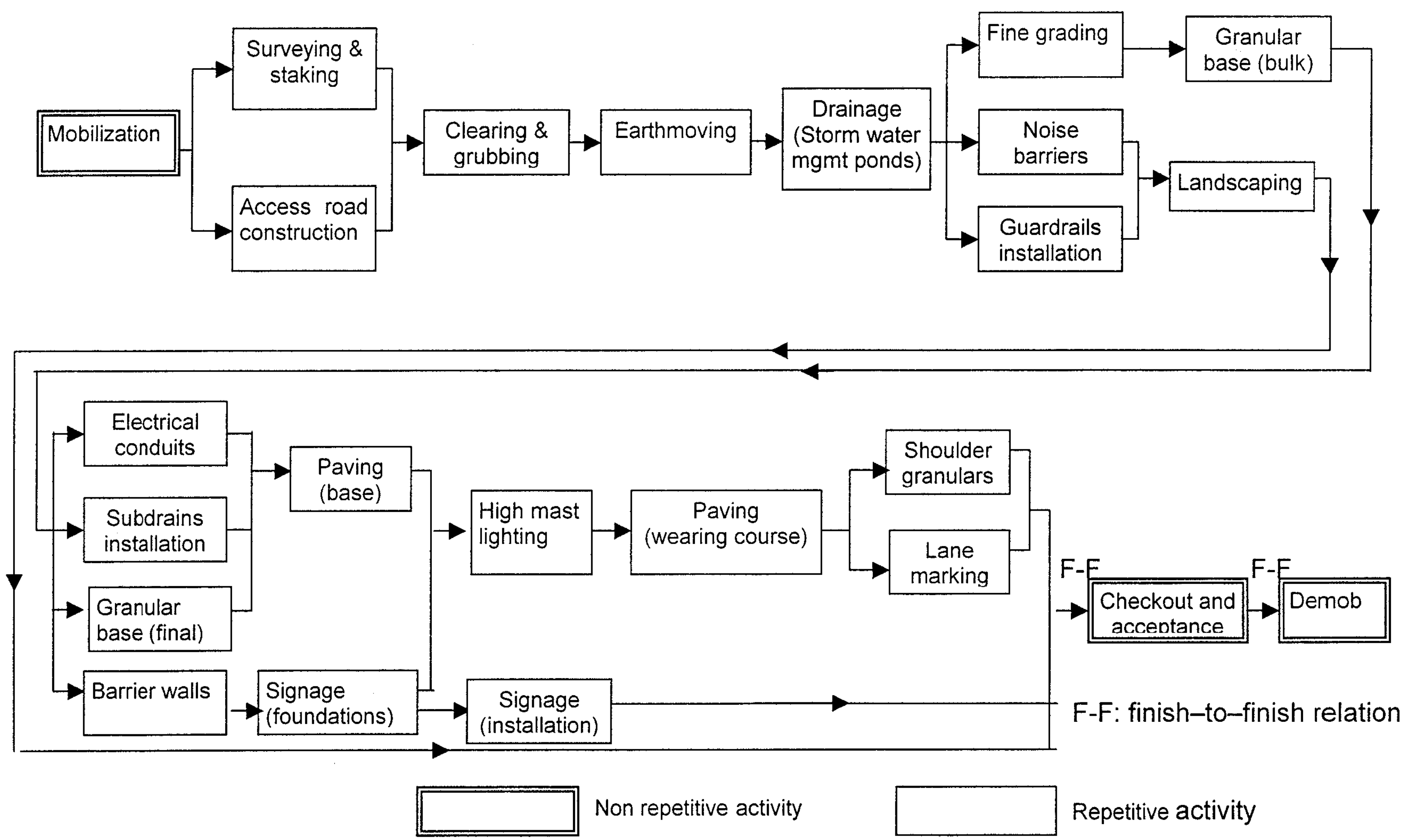


Figure 4.3: Precedence diagram for activities on mainline

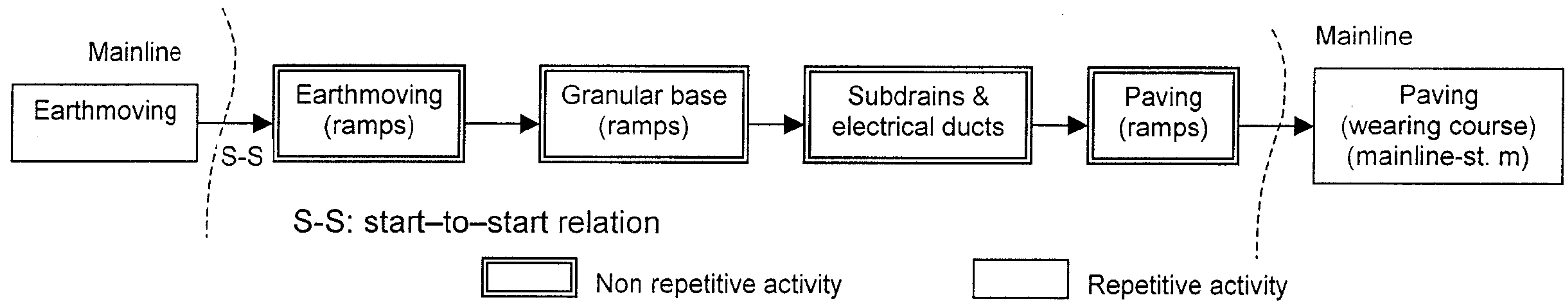


Figure 4.4: Precedence diagram for construction of interchange at station "m"

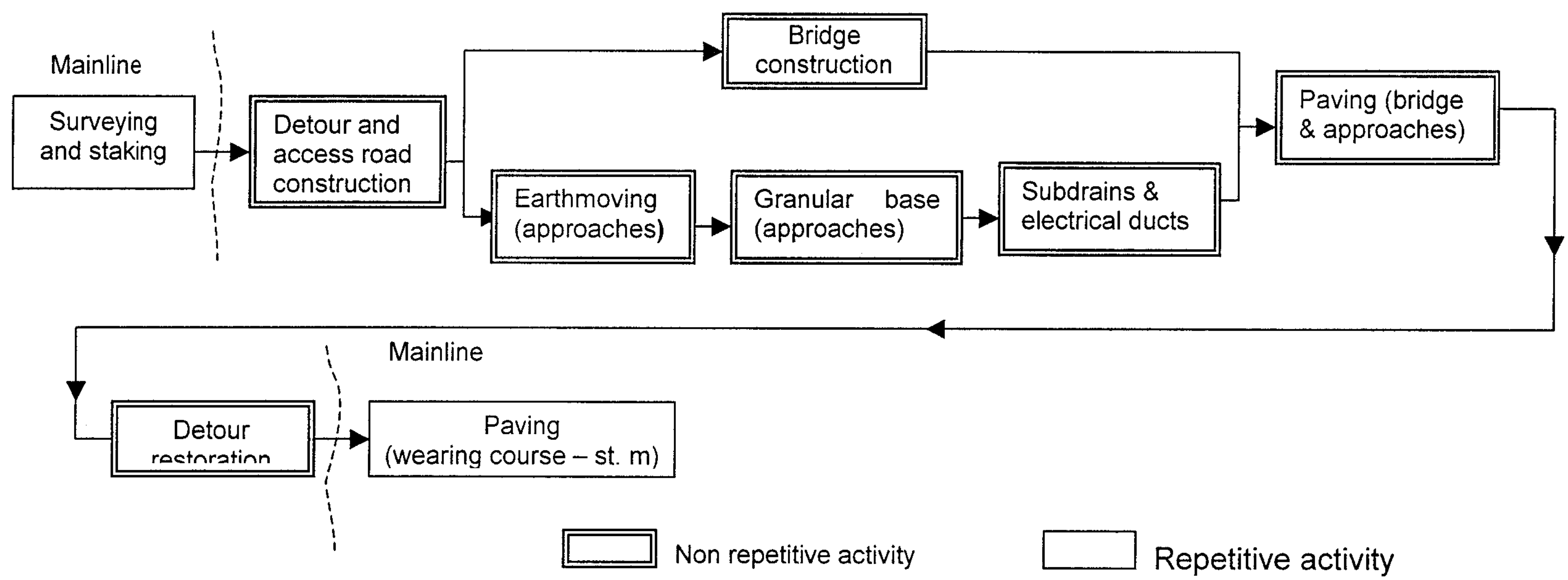


Figure 4.5: Precedence diagram for overpass construction at station "m"

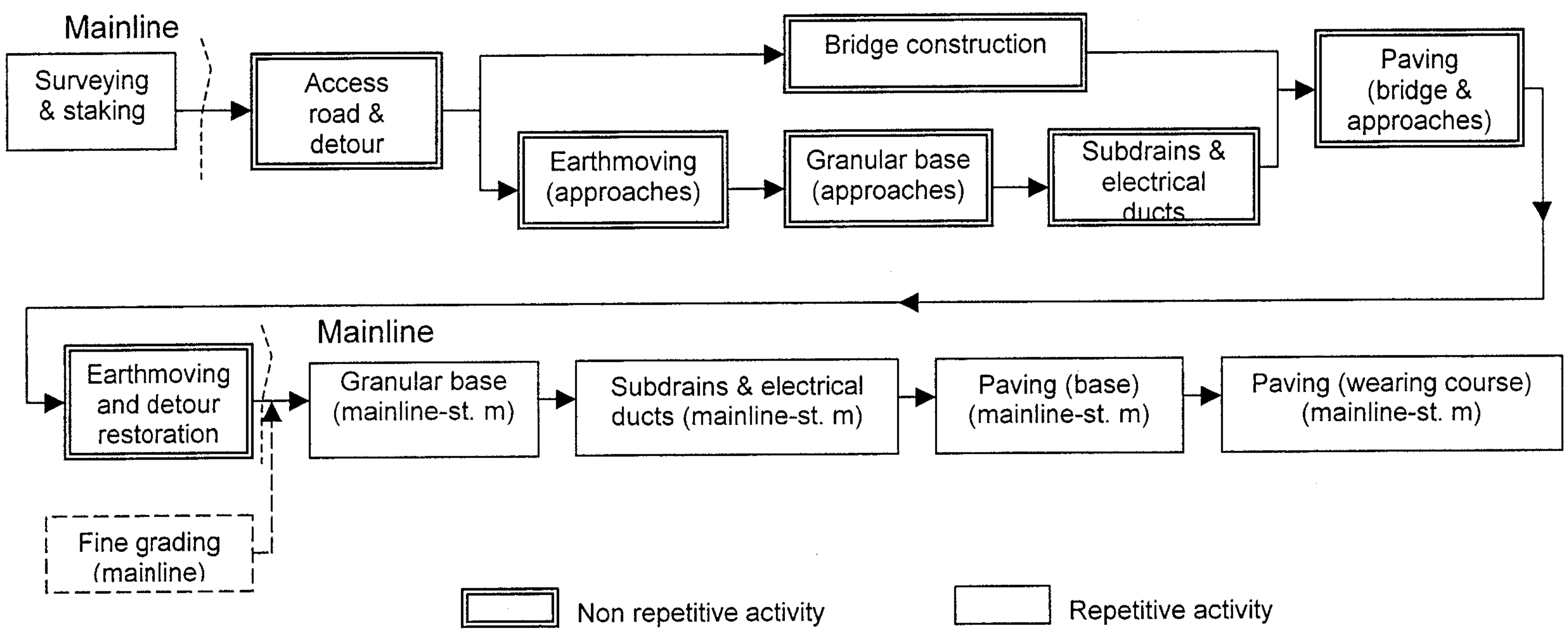


Figure 4.6: Precedence diagram for construction of transverse overpass at station "m"

4.2.2.2 Rehabilitation of Existing Highway

Over the last decade, the focus of many transportation agencies has shifted from constructing new highways to restoring existing ones (NCHRP 1995; Herbsman and Glagola 1998). In order to accommodate this industry shift, the proposed model has pre-defined lists of activities involved in the three most common types of highway rehabilitation techniques (NCHRP 1997), which are: 1) pavement overlay projects; 2) pavement replacement; and 3) adding new lanes to highways. Activities considered for overlay projects are (in their precedence order): 1) applying overlay; and 2) lane marking. For replacement projects, the following activities are defined in the model (in precedence order): 1) stripping existing pavement; 2) subgrade stabilization; 3) applying seal coat; 4) paving; and 5) lane marking. The activities involved in widening an existing highway, in precedence order, are: 1) widening and compacting embankment; 2) constructing drainage layers; 3) base construction; 4) paving; and 5) lane marking. Widening and compacting embankment is essentially an earthmoving operation, although typically on a smaller scale than for new highway construction. All activities have finish-to-start relations with predecessors and/or successors, with no lag time.

4.3 Object-Oriented Model

Object oriented modelling (Rumbaugh *et al* 1991) is utilised to represent project entities. Objects with common attributes and behaviour are grouped into a class, resulting in a concise and efficient representation of the project entities. The proposed object model makes use of abstraction, data encapsulation and inheritance concepts to develop an efficient and organized hierarchy of classes. The proposed object model builds upon that developed by El-Rayes and Moselhi (1998) to tailor it to highway construction, and is shown in Figure 4.7. Although unified modelling language (UML) is currently used for object-oriented modelling, it was not employed in the current study to build on the available model (El-Rayes and Moselhi 1998). All objects from the earlier study were modified to take full advantage of encapsulation and polymorphism. Objects shown with double lines were introduced to represent objects related to highway construction. This design imposes no restrictions on: 1) the number of preceding or succeeding activities; 2) the number of crews that can be assigned to an activity; or 3) the number of availability periods for each crew.

A project is viewed as an object composed of a group of activity objects, inter-connected to satisfy the job logic. A project object stores data such as project title, start date, working calendar and activities involved. Activity objects, on the other hand, store data such as activity name, category, predecessor(s) and successor(s), and number of potential crew formations objects. In turn, an activity is viewed as an object to which a group of one or more crew formation objects could be assigned. A crew formation object stores data such as number of crews that can work concurrently, and is a combination of one or more crews that can be assigned simultaneously to an activity. A crew object stores data such as crew daily productivity, cost and mobility data, and is represented by a series of objects, each representing an individual resource (i.e. equipment or labour).

"Obstruction" objects can be defined for a project to model transverse obstructions, while "Subcontractor" objects replace "Crew formation" objects for activities not executed by own force. Subcontractor objects store data related to expected productivity rates and associated unit cost, which can be determined through: 1) consultation with known subcontractors; 2) historical records; or 3) industry averages (e.g. R.S. Means 1993).

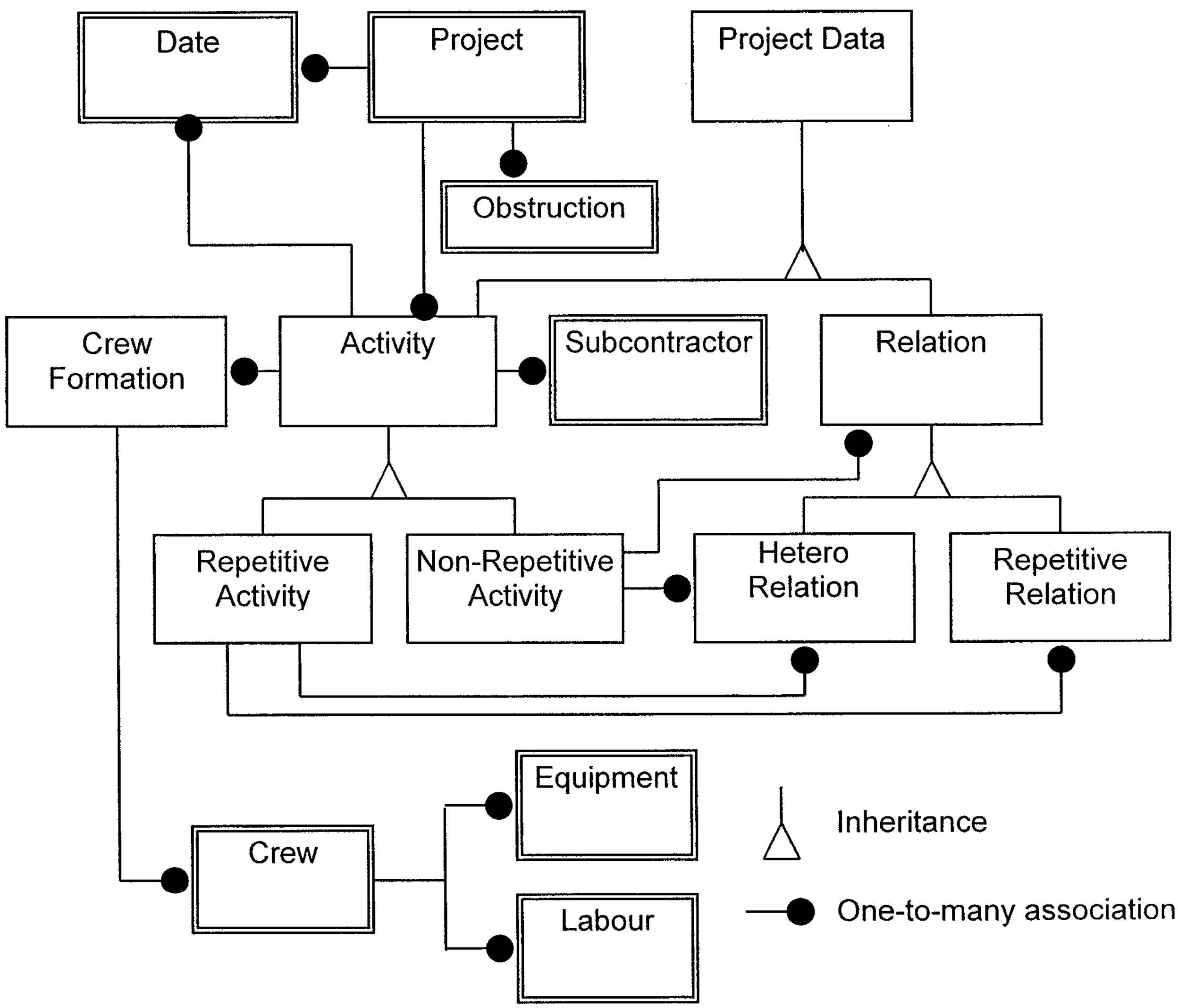


Figure 4.7: Developed object-oriented model

Modifications in inter-object relations were deemed necessary to represent highway construction operations, where "Crew formation" objects were only defined for repetitive activities. In the proposed model, crew formations are defined for "Activity" object, enabling its inheritance by both sub-classes (i.e. repetitive and non-repetitive activity objects). This enables full integration of non-repetitive activities into the scheduling process by enabling the definition of own crews for their execution. It should be noted that for non-repetitive activities, a crew formation could only be composed of a single crew. The details of the objects developed in this study, along with those developed by El-Rayes (1997), are presented below. In addition to the functions listed in the following sections, each object has functions that are responsible for interface with other objects, but are not mentioned here due to space limitations.

4.3.1 Project Representation

A project object is developed to represent any project under consideration by capturing its main features. As shown in Figure 4.7, a project object has one-to-many relations with activity, date and obstruction objects. That is to say, multiple activities, dates and obstructions can be associated with a single project. This design imposes no restrictions on the number of activities or obstructions that can be associated with a project. This design also enables adding, editing and removing activities and obstructions, increasing the flexibility of the proposed model. The functional attributes of the project object are listed in Table 4.1.

Table 4.1: Main attributes of "Project" object

Attribute	Data type	Description
BriList, culList, IntList and traList	List	Lists of names of bridges, culverts, interchanges and transverse bridges, respectively, defined in the project
BLocList, CLocList, ILocList and TlocList	List	Lists of locations of bridges, culverts, interchanges and transverse bridges, respectively, defined in the project
TheSegments	List	List of the boundaries between project segments
ProjectActivities	List	A list of activities defined in the project
ProjectRelations	List	A list of precedence relations defined in the project
ProjectObstructions	List	A list of the obstructions defined in the project
NumInsurmountable	Integer	Number of insurmountable obstructions
Optimization	Integer	Variable indicating selected optimization objective
HighwayLength	Double	Total length of project (km)
Owner	String	Project owner
ProjectDuration	Double	Total project duration
CostDay	Double	Indirect daily cost ($/day)
Weekends	List	A list of weekend days
Holidays	List	A list of annual holidays
RUC	Double	Road user cost ($/day), for cost-plus-time bidding
ProjectStartDate	Date	Possible start date for project

When constructing new projects, bridge locations are automatically treated as locations of transverse obstructions. The locations of sub-projects, such as bridges, transverse bridges and interchanges, are also stored in the project object. These locations define the boundaries between project segments, and are stored in a list entitled “theSegments”. The proposed model enables defining different working calendars and annual holidays for each project, enhancing the versatility of the model. A project object is designed to carry out the following functions:

1. Adding and removing entities (e.g. activities, relations, obstructions) to and from a project.
2. Finding, retrieving and managing entities (e.g. determining the presence of an activity in the project, ensuring that the locations of obstructions are within the project bounds, and that no two obstructions are in the same location).
3. Creating and updating the mobilization matrix.
4. Initiating schedule calculations.
5. Ensuring that the number of crews defined in each crew formation of all repetitive activities is sufficient to execute the activity.
6. Ensuring that the precedence network is free of logical errors, and that there exists only one activity with no predecessors (“start”), as well as only one activity with no successors (“Finish”).
7. Identifying the optimum activity(ies) to expedite construction (Chapter Five).

4.3.2 Activity Representation

The module accounts for all activity types shown in Figure 4.8. As the figure shows, activities can be classified into two main categories; repetitive, and non-repetitive. Inheritance (Rumbaugh *et al* 1991) is employed; object "Activity" was designed as a super-class for repetitive and non-repetitive activity objects, enabling the utilisation of polymorphism. "Activity" is an abstract class, thus no instances of it can be instantiated. Rather, it serves as a base class for repetitive and non-repetitive activity objects, defining their common attributes and behaviour. The main attributes of an activity object are listed in Table 4.2.

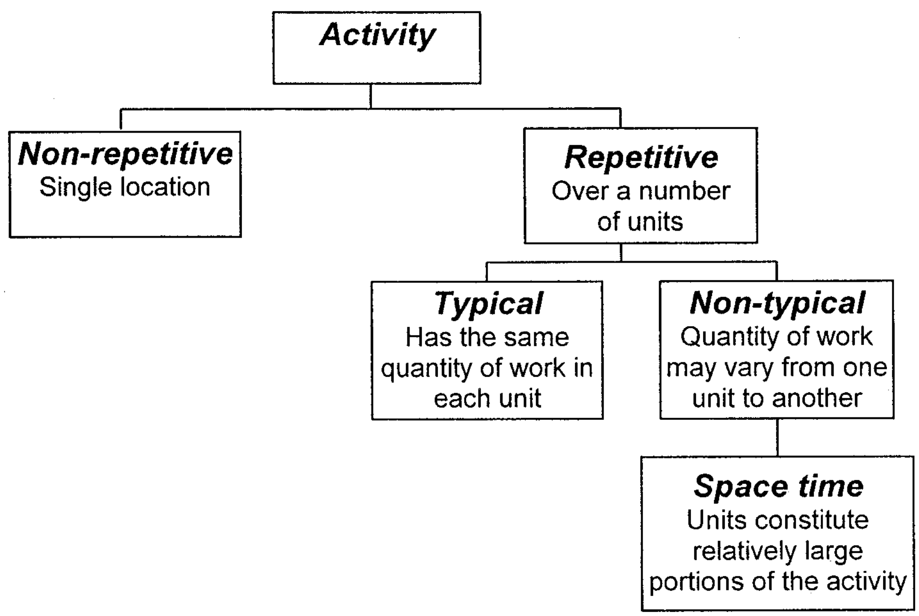


Figure 4.8: Activity types accounted for by the model

As discussed above, work on an activity is performed by crew formations, which can be composed of one or more crews. Multiple crew formation objects (see Section 4.3.4.3) can be defined for each activity. The model proposed by El-Rayes (1997) does not define a crew formation object for non-repetitive activities. As will be described in Section 4.3.4.3, the optimization procedure is mainly carried out in the crew formation object. Non-repetitive activities were thus excluded from the optimization procedure in the earlier study (El-Rayes 1997). In the proposed model, as Table 4.2 shows, a crew formation object is defined for the super-class, "Activity", and is thus inherited by both repetitive and non-repetitive activity objects. This enables the incorporation of non-repetitive activities in the optimization procedure. The proposed model assumes that only one crew can be assigned to work on any unit of a repetitive activity. Similarly, only one crew can be assigned to work on any non-repetitive activity. Thus, for non-repetitive activities, each crew formation can only be composed of a single crew.

Tasks commonly encountered in highway construction are reviewed and divided into the following categories: 1) clearing; 2) earthmoving; 3) base construction; 4) paving; 5) installations (e.g. utilities); 6) drainage; 7) services (e.g. surveying); and 8) finishing (e.g. landscaping, lane marking). In order to increase the model's flexibility, an additional category, "Other", is added to allow for activities that do not fall within any of the above categories, such as foundations and superstructure work on overpasses and culvert installation. These categories aid in defining the susceptibility of each activity to weather as well as setting unit length (minimum buffer) for repetitive activities. As discussed earlier, these two factors (weather impact and unit length) depend on the nature of the activity being performed, and should thus be evaluated at the activity level.

Table 4.2: Main attributes of "Activity" object

Attribute	Data type	Description
Category	String	Category of activity (defines category of crews – and subcontractors – that can be assigned to work on the activity)
OwnCrews	Boolean	"True"= own crews, "False"=subcontracted
RPred, rSucc	List	List of preceding and succeeding relation objects, respectively
CrewFormations	List	List of crew formations defined for the activity (if ownCrews=true)
NoPred, noSucc	Integer	The number of preceding and succeeding activities, respectively
UnitsUsed	String	Measurement units used in the activity (e.g. m^2, ton)
ChosenFormation	Integer	The number of the chosen crew formation
WeatherType	Vector [3]	Sensitivity of crew productivity to temperature, precipitation and wind speed
MaxWind	Double	Max wind speed at which the activity can progress (km/hr)
MinTemp	Double	Min temperature at which the activity can progress (°C)
MaxTemp	Double	Max temperature at which the activity can progress (°C)
MaxPrec	Double	Max precipitation (mm) at which the activity can progress
Subcontractors	List	List of subcontractor objects defined for the activity (if ownCrews=false)

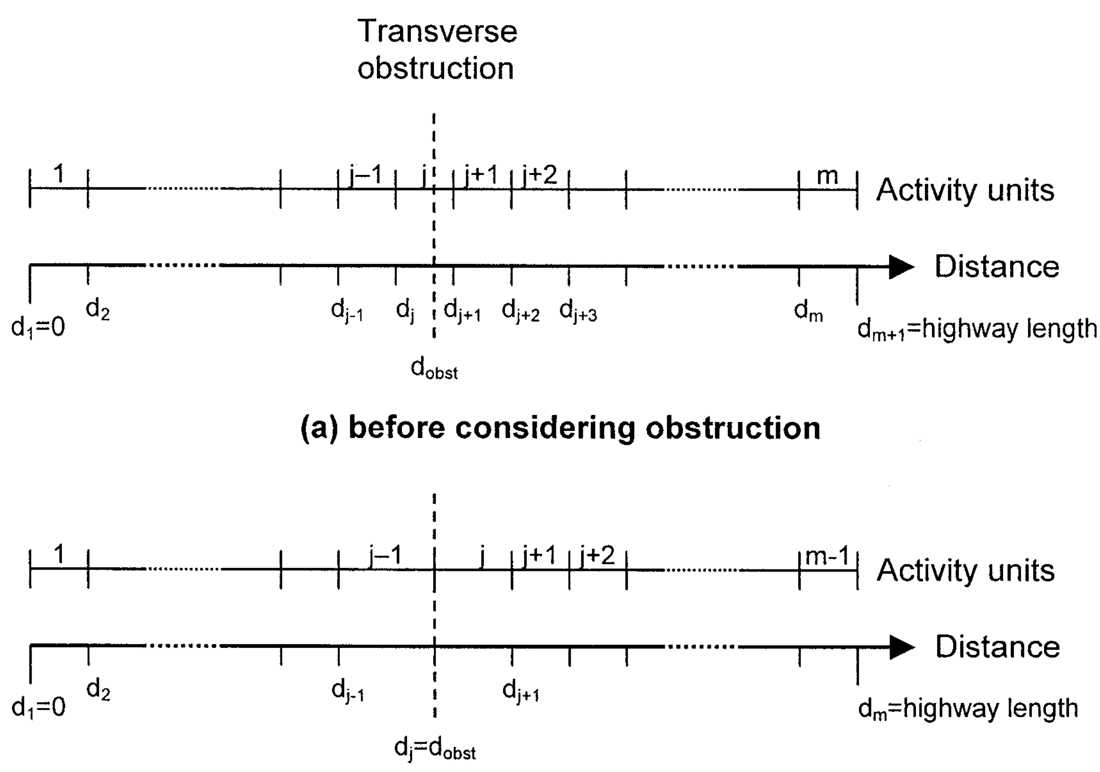
Each activity object stores a list of precedence relation objects that define the activity's relations with preceding and succeeding activities. Precedence relations objects (Section 4.3.3) enable communication amongst succeeding activities during the scheduling process. An activity can be accomplished using own work force, or can be sub-contracted to a specialized contractor. If an activity is subcontracted, one or more subcontractor objects (Section 4.3.4.4) could be defined for it. Unlike the earlier model (El-Rayes 1997) where crew formations were stored as arrays, the proposed model stores a dynamic list of crew formation objects, which enables later addition/removal of crew formation objects. The rigid structure of an array limits the number of crew formations that can be defined for an activity, and thus no crew formations could be added after activity definition. In addition, superfluous demands can be placed on the memory if not all array elements are utilised. Similarly, preceding and succeeding relation objects, stored in array structures in the earlier model (El-Rayes 1997), are stored as dynamic lists. This relieves the previous limitation of five successors and predecessors.

Table 4.3: Main attributes of "Repetitive Activity" object

Attribute	Data type	Description
DistFromStart	List	Listing of distances from start to each unit (double)
NoUnits	Integer	Total number of units comprising the activity
Quantity	List	Listing of quantity of work per unit (double)
ExecutionOrder	List	Order in which activity units are executed (integer)
PES	List	Listing of the possible start dates in all units based on precedence relations (double)

The main attributes of repetitive activity objects are listed in Table 4.3. Each repetitive activity is divided into units. Upon the creation of a repetitive activity object, stations of all units are determined. If a transverse obstruction is located within a unit, as shown in Figure 4.9(a), that unit is divided into two parts at the location of the obstruction, and each portion is blended with its adjacent unit, as shown in Figure 4.9(b). The quantity of work in a border unit is divided proportionately, assuming work is distributed evenly throughout the unit, resulting in the number of units in that activity be decreased by unity, as Figure 4.9 shows.

Table 4.4 lists the main attributes of a non-repetitive activity object. A non-repetitive activity can be viewed as a single unit of a repetitive activity. An attribute, “Location”, defines the location at which the activity is performed. The quantity of work involved in a activity is defined by the variable “Quantity”, while “startDate” and “FinishDate” are date objects that store the start and completion dates of the activity, respectively.



(b) after considering obstruction

Figure 4.9: Unit redefinition to account for transverse obstructions

Table 4.4: Main attributes of "Non-repetitive Activity" object

Attribute	Data type	Description
Location	Double	Location at which the activity is to be executed
Quantity	Double	The quantity of work involved in the activity
StartDate, FinishDate	Date	Start and finish dates, respectively, of works on the activity

4.3.3 Representation of Precedence Relations

Three types of relation objects are adopted from the model developed by El-Rayes (1997) to model precedence relations (Figure 4.7). The first relation object, "Regular Relation", represents the relation between two non-repetitive activities, and is a super-class to other two relation objects; repetitive and hetero relation. "Repetitive Relation" models the precedence relation between two repetitive activities, while "Hetero Relation", models the relation between: 1) a non-repetitive activity and a particular unit in a repetitive activity; or 2) two units at different locations in repetitive activities. Apart from enhancing encapsulation and polymorphism, these objects were not altered in this study. For a detailed review of the attributes and member functions of relation objects, the reader is referred to El-Rayes (1997).

4.3.4 Resource Modelling

A robust and efficient model was developed to represent resources. Since resource-driven scheduling is employed, the optimization process mainly takes place at the resource level. Details of objects developed to model available resources are presented below. First "Equipment" and "Labour" objects are introduced, followed by "Crew", "Crew formation", "Subcontractor" and "Rented Equipment" objects.

4.3.4.1 Equipment and Labour

Equipment and labour are the basic resources that are combined to form a crew. Objects modelling their behaviour are designed to capture their relevant data for scheduling purposes. Tables 4.5 and 4.6 list the main attributes of equipment and labour objects, respectively.

Table 4.5: Main attributes of "Equipment" object

Attribute	Data type	Description
EquipmentID	Integer	Unique identifier for equipment (e.g. chassis number)
SPEC	Integer	Identifier relating to equipment type (identical for similar models)
Model	SQL string	Equipment model
DailyCost	Double	Direct operating cost (including operator)
Assembly	Boolean	"True"=requires assembly on site, "False"=does not require assembly
Mobility	Boolean	"True"=can travel on its own, "False"=requires float
SelCrit	SQL string	Basis of selection of equipment for crew

Each piece of equipment is uniquely identified by the variable "EquipmentID". This identifier could be the chassis number, or licence plate of that piece of equipment. Two more variables are employed to identify an equipment, which are "SPEC" and "Model". "SPEC" is an identifier which is identical for similar models, and plays a major role in allocating equipment to crews, as will be discussed in Section 4.4.2. The other variable, "Model", stores the model type of the equipment. "DailyCost" is the direct daily cost of using the equipment, and does not include operator cost. Two Boolean variables, "Assembly" and "Mobility" are employed to define an equipment's requirements for mobilization/demobilization. The former defines whether on-site assembly is required once that equipment is mobilized (Assembly=TRUE). In that case, disassembly would also be required on demobilization. The latter, "Mobility", defines whether an equipment can travel on its own (Mobility=TRUE). If equipment cannot travel on its own (e.g. rollers), then a float would be required for its transportation, resulting in additional mobilization/demobilization costs.

Table 4.6: Main attributes of "Labour" object

Attribute	Data type	Description
EmployeeID	Integer	Unique identifier for labour
SPEC	Integer	Identifier relating to trade
HourlyWages	Double	Hourly wages
SelCrit	SQL string	Basis of selection of labour for crew

The attributes of “Labour” object are similar in concept to those of “Equipment” object. A unique identifier, “EmployeeID” helps identify a particular labourer. “SPEC” stores the trade of the labourer (e.g. equipment operator, common labourer, electrical), while “SelCrit” stores the SQL string employed to identify the selection criterion of the labourer to a crew, as discussed below.

4.3.4.2 Crew

When resources (equipment and labour) are grouped together to execute a certain task, they are referred to as a crew, or gang. In the proposed model, a crew is modelled as an object, to which resource objects (equipment and labour objects) are assigned. It is worth noting here that estimating crew productivity based on productivity of its basic components is beyond the scope of the proposed study. This is because several qualitative factors can influence the overall productivity of a group of resources given the productivity of its constituents. It is up to the user to estimate the overall crew productivity based on project conditions and to provide it as input.

Table 4.7 lists the main attributes of a crew object. While the model proposed by El-Rayes (1997) only enabled the definition of a single availability period for each crew, multiple availability periods can be defined for a crew in the proposed model. The availability status of any crew is determined at run-time, by inspecting the availability of its components (Section 4.4.2). “$minAss_c$” and “$maxAss_c$” are the min and max quantities that can be assigned to crew “c". This increases the practicality of the model, enabling the definition of a range of work which a crew can complete.

Table 4.7: Main attributes of "Crew" object

Attribute	Data type	Description
CrewID	Integer	Unique identifier for the crew
Discipline	String	The category of activities the crew can execute
EquipList	List	List of equipment employed in the crew
LabourList	List	List of labour employed in the crew
DailyProd	Double	Daily productivity (prod.units/day)
minAss, maxAss	Double	Min and max quantities, respectively, that can be assigned to the crew
ProdUnits	String	Units in which daily productivity, minAss and maxAss are defined (e.g. m^2, m^3, ton)
SetupTime, setupCost	Double	Setup time and cost, respectively, for the crew
MoveoutTime, moveoutCost	Double	Moveout time and cost, respectively, for the crew
HwySpeed, offHwySpeed	Double	Crew travel speed on and off paved roads, respectively

4.3.4.3 Crew Formation

If an activity is to be executed by own crews, then at least one crew formation needs to be defined for it. A crew formation defines crews that can work simultaneously on any repetitive activity. For example, assume crew formations CF_1, CF_2 and CF_3 are defined for any repetitive activity "A", as listed in Table 4.8. The performance (incurred costs, required duration or a combination of both, depending on optimization objective) of all crew formations when assigned the work comprising activity "A" are compared, and one crew formation (CF_1, CF_2 or CF_3) is eventually assigned to the activity. Selecting the optimum crew formation

Table 4.8: Crew formations defined for activity "A"

Crew Formation	Composition
CF_1	C_1, C_2 and C_3 working simultaneously
CF_2	C_4 working alone
CF_3	C_3 and C_5 working simultaneously

for an activity depends on the scheduling objectives, as will be discussed in Chapter Five. The model assumes that all crews defined in a crew formation are employed. For example, if "CF_1" is found to be the optimum crew formation for activity "A", then crews "C_1", "C_2" and "C_3" are assigned quantities of work greater than zero. If the possibility that, for example, crews "C_2" and "C_3" working alone is to be considered, then another crew formation, "CF_4", composed of those crews should be defined as a potential crew formation. The main attributes of the "Crew Formation" object are listed in Table 4.9.

Table 4.9: Main attributes of "Crew Formation" object

Attribute	Data type	Description
TheCrews	List	List of crew objects that comprise the crew formation
Name	String	Crew formation name
NoCrews	Integer	Number of crews comprising the crew formation
ProdFactor	Double	Factor to account for variation in productivity due to learning curve effect and/or weather impact

The main part of the optimization process, namely; optimizing crew assignments in a manner satisfying the scheduling objectives is carried out by the crew formation object. The term "crew assignments" refers to the assignment scheme in terms of which crew executes which units within an activity. While earlier models were not particularly tailored to linear projects, the proposed model divides each activity into a number of sections, assigning each crew to a section (or more). Earlier models (e.g. El-Rayes and Moselhi 1998) assigned crews to units based solely on crew availability, resulting in faster construction. As such, crew cost was not considered as a decision variable when assigning crews to units.

4.3.4.4 Subcontractor

A highway project is typically broken down to several contracts, each awarded to a specialized contractor. Even in cases when a general contractor is responsible for the whole project, subcontracts are usually awarded to specialized contractors, who are supervised by the general contractor (Barrie and Paulson 1992). In order to add practicality to the module, an object was developed to model subcontractors. In essence, a subcontractor can provide crews of varying sizes and capacities, each at a rate ($/unit of measurement). A subcontractor object thus has a list of daily productivity rates, and a corresponding list of rates. Each subcontractor can have one or more trades, and for each trade, one or more potential crews. Each crew in each trade has a daily productivity, and an associated daily cost, as shown schematically in Figure 4.10. Therefore, the object that models subcontractors should have a list of daily productivity rates and costs for each of the subcontractor's trades. Selecting the optimum subcontractor crew to execute an activity depends on the scheduling objectives. Table 4.10 lists the main attributes of the object developed to model subcontractors. Unlike own crews, subcontractor crews are assumed to be available upon request.

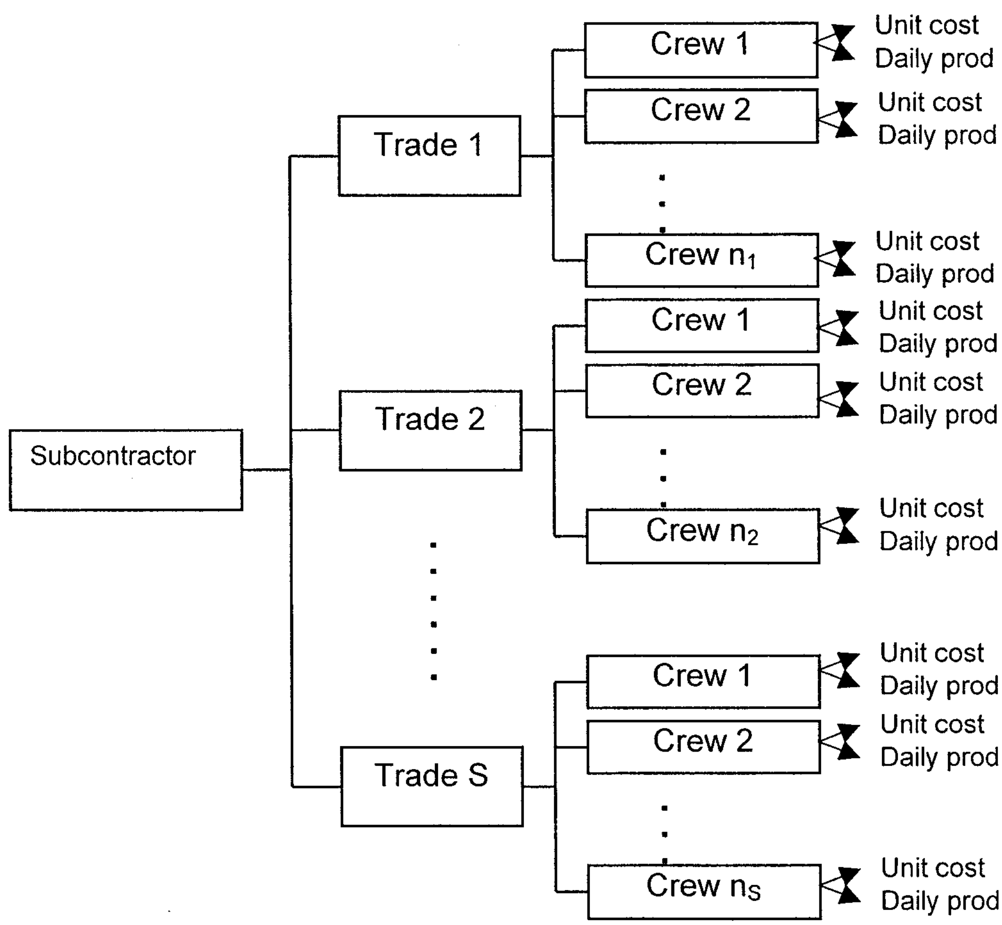


Figure 4.10: Modelling subcontractor crews

Table 4.10: Main attributes of "Subcontractor" object

Attribute	Data type	Description
Name	String	Subcontractor name
Trade	List	List of subcontractor's trades
SubCrewsProd	List	List, for each trade, of productivity of subcontractor's crews
SubCrewsCost	List	List, for each trade, corresponding to the list of productivity of crews, "subCrewsProd"

4.3.4.5 Rented Equipment

Should the resource pool be lacking a certain equipment model, the module enables the use of rented equipment to avoid resource-related delays. A recent study in the United States revealed that the frequency of renting equipment full time has tripled since 1978, and that more than one-third of state DoTs reported renting or leasing specialized equipment (NCHRP 2000(b)). In the proposed model, a threshold value is defined by the user (default=0 days), beyond which any delay incurred due to the scarcity of a resource triggers employing rented equipment. An unlimited supply of rented equipment is assumed. It is worth noting that this feature is only considered if the user wishes to employ rented equipment as an expediting technique.

4.3.5 Representation of Transverse Obstructions

As mentioned earlier, transverse obstructions can bear a significant impact on the crew assignment strategies, as well as overall project duration and cost. An obstruction object is developed to model transverse obstructions, and aid in practical and realistic modelling of site conditions. The main attributes of the developed obstruction object are listed in Table 4.11.

Table 4.11: Main attributes of "Obstruction" object

Attribute	Data type	Description
Name	String	Obstruction name
Location	Double	The location (chainage) of the obstruction
Surmountable	Boolean	"True" if obstruction is surmountable, "false" otherwise
Type	String	Type of obstruction (e.g. river, creek, existing highway)
SchedComp	Boolean	"True" if a structure is to be built to overcome the obstruction, "false" otherwise
CompDate	Date	Completion date of the construction of the structure

The completion date of the construction of a structure crossing an obstruction marks the date when direct access is granted over that obstruction. The mobilization matrix is updated to reflect recent changes. Clearly, insurmountable obstructions do not have a completion date.

4.3.6 Date Representation

The date object is developed to enable accurate date representation. Project and activity objects utilise date objects to store start and completion dates of projects and activities, respectively. Knowing the duration (in working days) and start date of any activity, the completion date is determined with the aid of the date object. Additionally, by determining the dates during which an activity is in progress, it is possible to determine the expected weather during that period, and hence quantifying the impact of weather on crew productivity. The date object is also employed to determine the calendar date corresponding to a certain date in the working calendar. This enables determining the calendar date at which an activity, or project, is completed, and thus determine availability dates of equipment and labour. The date object is also utilised to determine holidays and weekends. As mentioned earlier, the model enables using different work weeks (default is Gregorian calendar).

4.4 Resource Allocation

Accounting for resource availability is of paramount importance to develop practical schedules. As will be discussed in the following sections, the proposed model employs crew templates to allocate resources to activities. Section 4.4.1 describes these templates, while Section 4.4.2 details the proposed resource allocation procedure.

4.4.1 Crew Templates

A crew template defines the resources employed in a crew, and stores: 1) the model type (and "SPEC") of each selected equipment; 2) the trade of each selected labour; 3) daily crew productivity; 4) whether any equipment requires assembly on site; 5) whether any equipment requires one, or more, floats for transportation; 6) the SQL string (SelCrit) for each resource; and 7) minimum and maximum quantity of work that can be assigned to that crew, "MinAss" and "MaxAss", respectively. A crew template is employed to create a new instance of that crew each time it is assigned to an activity. During scheduling, the resource pool is queried to determine availability of crews for activities being scheduled. This is achieved by inspecting the availability status of each resource employed by the crew components (equipment and labour) during the period at which the activity is scheduled to be in progress, as discussed below.

4.4.2 Crew Building

An algorithm has been developed to assign resources to crews (see Figure 4.11). The algorithm essentially ensures availability of all equipment initially assigned to crews, making use of crew templates. In this process, the algorithm is repeated for each crew in each crew formation assigned to each activity in the project. Initially, the total delay incurred by a crew due to resource unavailability, "Tdelay", is set to zero. For component "i" of a crew formation composed of "n" crews, the resource pool is queried for the number of available resources (nR) that satisfy the criterion "SPEC", which is either the equipment model, or the labour trade identifier (Figure 4.11 – LOOP 1). The algorithm then iterates through all potential resources (Figure 4.11 – LOOP 2), determining the unique identifier for each resource ($Iden=Resource\_Identifier_{(k)}$), and inspecting its availability status at the required time period (from d_1 to d_2). If an item that satisfies the criterion is found available, resource "i" is declared available ($Status_{(i)}$=available), and the resource identified by "Iden" is selected ($Item_{(i)}=Iden$). Otherwise, the availability status of that resource, "$Status_{(i)}$", and that of the entire crew, "Crew_Sta", are set to "unavailable", and the earliest time at which that resource becomes available, "ES_k", is determined ($ES_k=EAD_k$, where EAD_k is the earliest available date of resource k). If the resource is found unavailable, a replacement resource that causes the minimum delay (smallest ES_k) is assigned to the crew ($ES_i=\min(k=1..nR)\{ES_k\}$).

The delay incurred due to the unavailability of crew component "i" is computed as the difference between the earliest possible date of forming the crew, "ES_i", and the scheduled start of the activity, d_1. Upon iterating through all crew components, crew availability status, "Crew_Sta", is inspected. If a crew is found available, its daily cost is computed and the procedure progresses to the succeeding activity. Otherwise, the delay incurred is computed as the largest delay incurred by any resource employed by that crew ($Delay=Max(i=1..n)\ delay_{(i)}$), and total delay is revised ($Tdelay'=Tdelay+Delay$). If renting additional equipment is considered as an option, and the total delay incurred exceeds the pre-defined threshold ($Tdelay>Threshold$), then rented equipment are assigned.

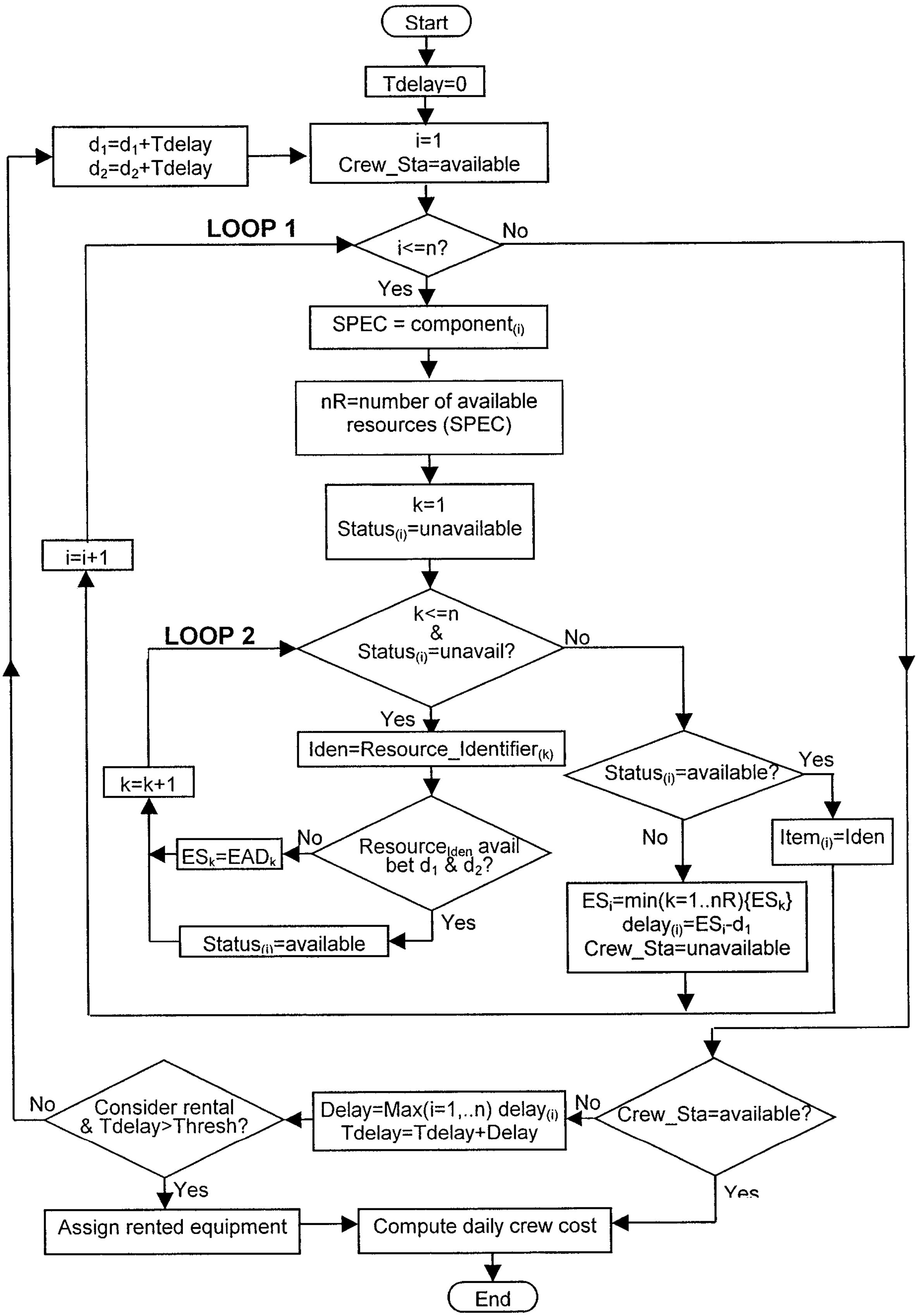


Figure 4.11: Algorithm assigning resources to crews

Otherwise, the activity is delayed by a time period equal to the total delay (Tdelay'), and the resource availability is verified at the revised time period (d_1=d_1+Tdelay', d_2=d_2+Tdelay'). The procedure described above is repeated until all resources are assigned to the crew under consideration.

4.5 Scheduling Algorithm

Maintaining work continuity for crews has been recommended to minimise disruptions and maximize the effect of the learning curve (Selinger 1980; Reda 1990). However, allowing for crew work interruptions has been proposed as a means to reduce project duration (Russell and Caselton 1988; Russell and Wong 1993; El-Rayes and Moselhi 2001). While this might be a valid option for high-rise building projects, the same argument does not stand in the case of linear projects in view of the associated mobilization/demobilization costs. Equipment used in this class of projects are heavy, expensive, and their idle time is costly (Barrie and Paulson 1992). Accordingly, work interruptions are not permitted in the proposed model. Since scheduling is tied to estimating, budgeting and claims, an improved schedule would have a positive impact on the construction process (Herbsman 1987).

Accounting for resource availability while optimizing cost and/or duration of repetitive construction projects has been addressed (Moselhi and El-Rayes 1993; El-Rayes and Moselhi 2001). These models treat a crew as an entity that has a single availability period. In order to account for multiple availability periods for each crew, alias crews are created, each with its own availability period. The proposed model overcomes this limitation through a flexible object-oriented model, interacting with a specially designed set of crew templates (Section 4.3.4.3). The algorithm developed by El-Rayes (1997) is extended to enable the determination of possible start dates of all units of all activities. These are possible start dates respecting job logic, while ensuring work continuity for all crews. The crew assignment strategy (which crew is assigned to which units), however, is carried out in a different manner, and depends upon the scheduling objectives, as will be discussed in Chapter Five.

The scheduling algorithm is included in the “Crew formation” object. When an activity receives messages from all its predecessors, the crew formation object is notified that the activity is ready to commence according to precedence relations. If the activity is repetitive, the crew formation object is notified of: 1) the possible start times of all units respecting job logic; 2) the quantity of work in each unit; and 3) the total number of units. If, on the other hand, the activity is non-repetitive, the crew formation object is notified of the activity's possible start date and quantity of work involved. The crew formation object then determines actual start and finish times for all units (of repetitive activities) such that work continuity is maintained. The proposed model employs the scheduling algorithm developed by El-Rayes (1997) to determine the possible start times for works in all repetitive activity units. The algorithm is performed in two stages; the first ensures compliance with job logic and crew availability, while the second ensures work continuity for all crews. For a detailed discussion of the algorithm, the reader is referred to El-Rayes (1997). The algorithm accounts for variations in crew productivity due to the learning curve effect and inclement weather. The impact of inclement weather on crew productivity and activity durations, however, is addressed differently, as discussed in the following sections.

4.5.1 Accounting for Transverse Obstructions

A square matrix of the order (n+1) (where "n" is total number of transverse obstructions), hereinafter referred to as the mobilization matrix, is designed to determine crew travel time and cost to, from and between segments. In this matrix, travel distance between segments (i) and (j) is represented by $M_{i,j}$ (i>j), and travel conditions are represented by $M_{i,j}$ (i<j) ($M_{i,j}$=unity and zero for paved and off-highway conditions, respectively). Diagonal elements $M_{i,j}$, where i=j, store data related to travel distances from the contractor's staging and maintenance shop to each of the project segments.

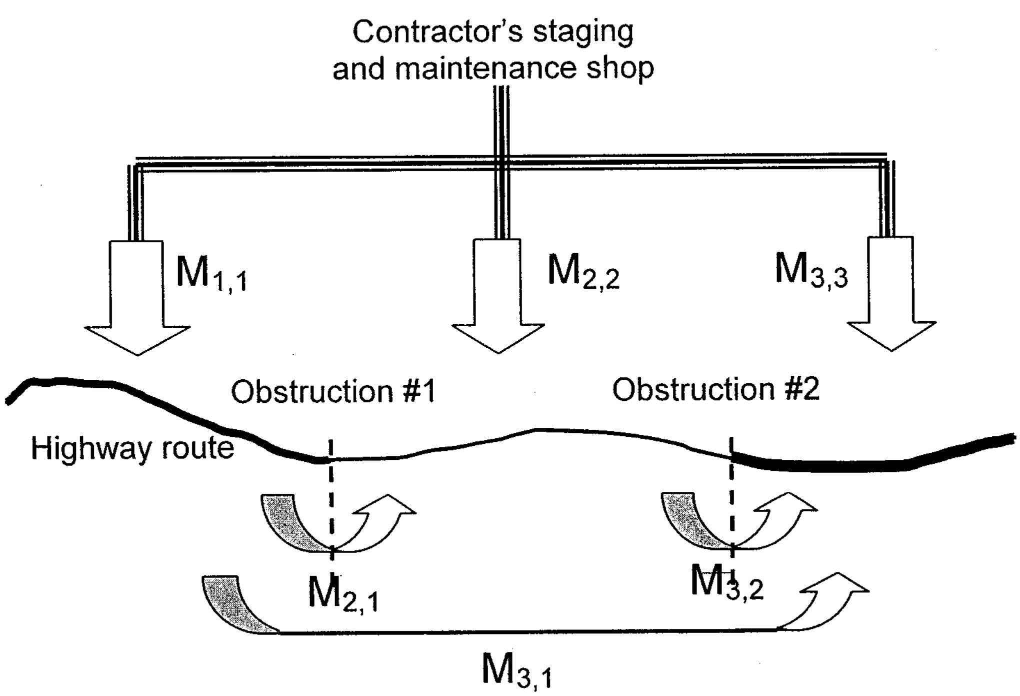


Figure 4.12: Elements of the mobilization matrix

As shown in the figure, travel distance to overcome any obstacle "i" (separating segments "i" and "i+1") is given by $M_{i+1,i}$. For insurmountable obstructions, $M_{i+1,i}$ and $M_{i,i+1}$ are set to a negative value (-1), indicating that no access is granted across the obstruction. Unless otherwise specified, all elements $M_{i,j}$, where "i>j+1" default to the total distance travelled along the highway route, and can be expressed as:

$$M_{i,j} = \sum_{k=i}^{k=j-1} M_{k+1,k} + \sum_{k=i+1}^{k=j-1} L_k \qquad (4.1)$$

where L_k is the length of segment (k), and $M_{k+1,k}$, (for k=i, i+1,.., j-1) is greater than zero. Otherwise

$M_{i,j}$= -1

The first term of the right-hand-side of Equation (4.1) is the total distance travelled to overcome all obstructions between segments (i) and (j), while the second part is the total travel distance between the same segments, measured along project route. If any element $M_{k+1,k}$ (for k=i, i+1,.., j-1) is negative, this indicates the presence of an insurmountable obstruction between segments "k" and "k+1", and access between sections (i) and (j) is denied (M_{ji}=−1).

To demonstrate the use of Equation (4.1) above, consider the highway projects shown in Figures 4.13(a) and (b). The details of the transverse obstructions for parts (a) and (b) of the figure are listed in Tables 4.12(a) and (b), respectively.

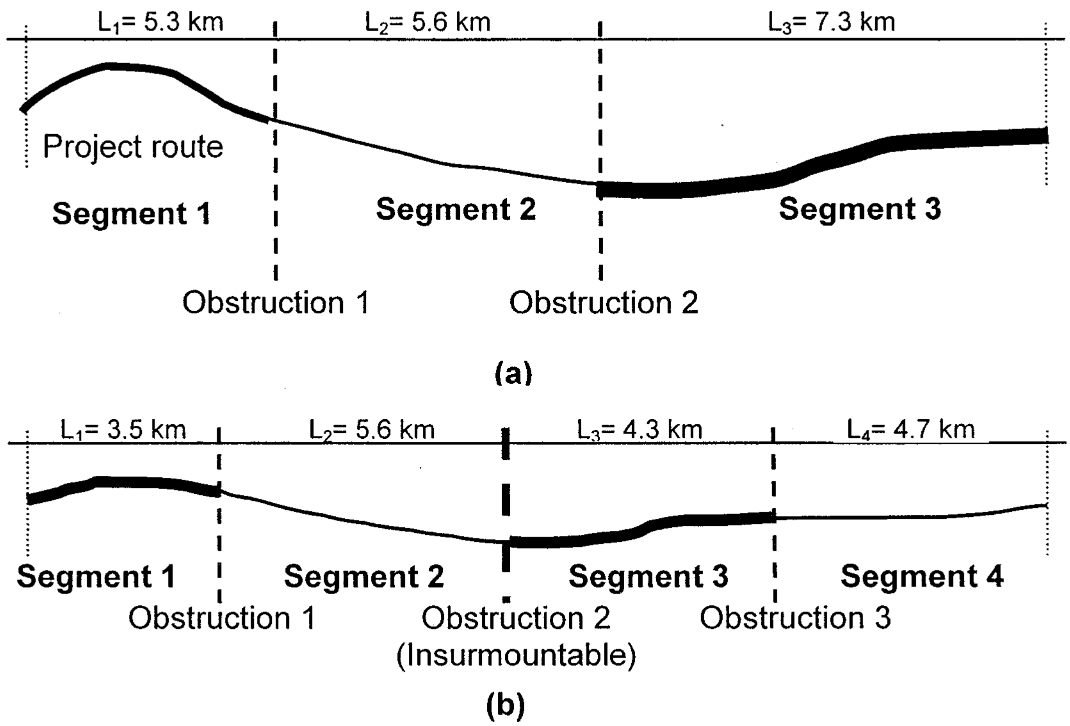


Figure 4.13: Sample highway projects with transverse obstructions

For the highway shown in part (a) of the figure, the travel distance from segment 1 to segment 3, $M_{3,1}$ defaults to:

$$M_{3,1} = (3.6+4.2) + 5.6 = 13.4 \text{ km}$$

and

$$M_{1,3}=0$$

Table 4.12: Obstruction details for projects shown in Figure 4.13

a) For project in Figure 4.13(a)

Obstruction number	Location (station)	Distance to overcome (km)
1	5.3	3.6
2	10.9	4.2

b) For project in Figure 4.13(b)

Obstruction number	Location (station)	Distance to overcome (km)
1	3.5	3.4
2	9.1	*
3	13.4	5.7

* obstruction is insurmountable

Assuming the contractor's staging and maintenance shop is 100 km from all project segments (travel routes to all project segments are assumed to be paved), the mobilization matrix is expressed as:

$$M_{(3\times3)} = \left\{ \begin{array}{ccc} 100 & 3.6 & 13.4 \\ 0 & 100 & 4.2 \\ 0 & 0 & 100 \end{array} \right\}$$

For the highway shown in part (b) of the figure, the mobilization matrix is expressed as:

$$M_{(4\times4)} = \left\{ \begin{array}{cccc} 100 & 3.4 & -1 & -1 \\ 0 & 100 & -1 & -1 \\ -1 & -1 & 100 & 5.7 \\ -1 & -1 & 1 & 100 \end{array} \right\}$$

Should a bypass for a transverse obstruction be planned, its completion date marks the elimination of the impact of that obstruction on crew movement between project segments. The completion date of a bypass is represented by the finish date of its surface preparation, and the mobilization matrix, in this case, is updated accordingly.

The scheduling algorithm accounts for the presence of transverse obstructions by computing the time required to mobilize all crews from a project segment to another. If crew is assigned to multiple project segments, the time required for that crew to relocate from one segment to another is governed by that piece of equipment that requires the most time, and can be expressed as:

$$t_{c/j-k} = \frac{1}{wh} \times (MAX_{i=1..n_{eq}}\{Tdemob_i + \frac{M_{i/j-k}}{v_{i,j-k}} + Tmob_i\}) \tag{4.3}$$

where $t_{c/j-k}$ is the time (working days) required to relocate crew c from segment j to segment k,

$Tmob_i$ and $Tdemob_i$ are assembly and disassembly times (hrs) required by equipment i, if any, respectively,

wh is the number of working hours per day (default=10),

$M_{j,k}$ (j>k) is the travel distance (km) between segments j and k,

$v_{i,j-k}$ is the travel speed (km/hr) of equipment i corresponding to the road conditions as given by $M_{k,j}$ (k<j), and

n_{eq} is the number of pieces of equipment comprising the crew.

The possible start time of work on the new segment is then computed from:

$$PST_k=EFT_j+t_{c/j-k} \tag{4.4}$$

where PST_k is the possible start time in first unit of segment k,

EFT_j is the early finish time in last unit of segment j and

$t_{c/j-k}$ is as defined in Equation (4.1).

In order to add practicality to the developed schedule, the possible start time, "PST_k", of the first unit in any section is approximated to the following work shift. For example, if it is found to be in the afternoon, then crew "c" is assumed to commence work on the new segment on the next working day. If, on the other hand, crew "c" arrives before noon, it can only commence work at noon.

4.5.2 Accounting for Weather Impact on Productivity

In highway construction, virtually all operations are exposed to weather, and are thus susceptible to the weather elements. Several highway activities, such as earthmoving, base construction and paving, are particularly susceptible to precipitation, which causes significant losses in productivity, and can halt operations altogether (El-Rayes and Moselhi 2001(b)). In addition, contract specifications prohibit certain operations when unfavourable weather conditions prevail (NCHRP 1978). Accounting for the impact of weather on productivity is thus of paramount importance to developing realistic schedules. An earlier study (Russell and Wong 1993) recommended not accounting for the learning curve or impact of weather on crew productivity. This recommendation was because their study (Russell and Wong 1993) found that users did not like to delegate such judgements to a machine. However, it was deemed appropriate to account for both in the proposed study, and provide the user with the option to incorporate either, both or neither, in the scheduling procedure.

To account for weather impact on productivity, the daily productivity, "P_c", of crew "c" is revised based on the calendar day and type of operations the crew performs. The findings of the above-mentioned study (El-Rayes and Moselhi 2001(b)) are incorporated in the proposed model to account for the impact of precipitation on: 1) earthmoving; 2) base construction; 3) construction of drainage layers; and 4) paving operations. Also, findings of the weather survey (Chapter Two) are incorporated in the model to account for the impact of inclement weather on crew productivity.

Figure 4.14 shows the algorithm employed to account for the impact of weather on the duration of activity "i" in unit "j". The algorithm commences by determining the calendar date, "CD", corresponding to the actual start date of work on unit "j", "ES_j". As the work on that unit progresses, "C_Temp" updates and stores the remaining quantity of work to completion of that unit. The duration of works on unit "j", "Dur_j", is initialised to zero (0). The start date of an activity can contain a fraction, "Fday", indicating that works can only commence after a certain hour of

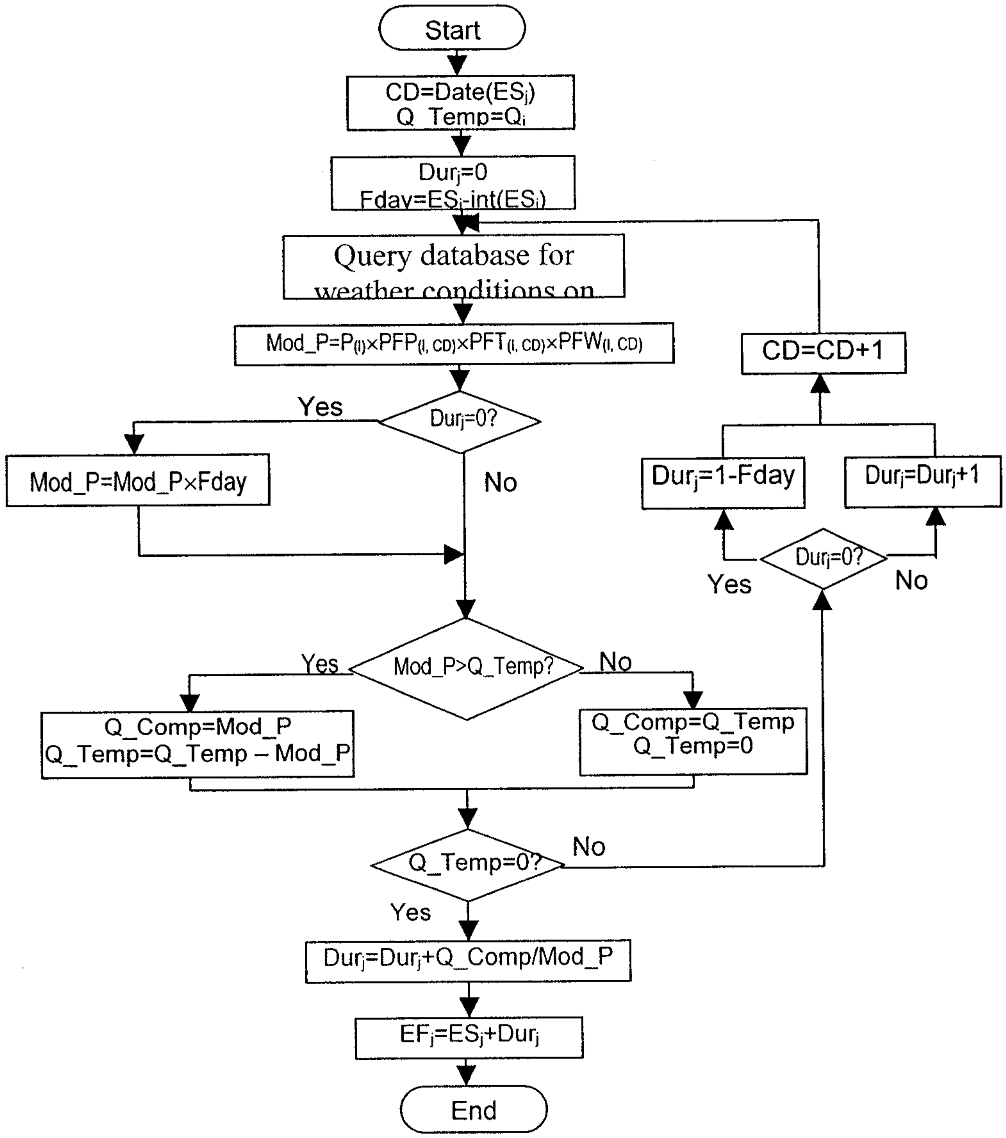


Figure 4.14: Proposed algorithm to account for weather impact

the day. The weather database is queried to determine the adjustment factors for activity "i" due to precipitation "PFP_i", temperature "PFT_i" and wind speed "PFW_i", based on the type of activity in progress. The quantity of work completed during that workday, "Q_Comp", is computed, and deducted from the remaining quantity of work (C_Temp'=C_Temp–Q_Comp). The above procedure is repeated until

"C_Temp" is less than, or equal to, "Q_Comp", signifying that work in the unit is completed on that day. The completion date of works on unit "j", "EF_j", is determined from

$$EF_j = ES_j + Dur_j \tag{4.5}$$

4.5.3 Accounting of Learning Curve Effect

The beneficial effects of the learning curve effect have been long reported (Thomas *et al* 1986). Due to its widespread acceptance in the construction industry, the straight-line learning curve model (Thomas *et al* 1986) is employed in the proposed formulation. Similar to the earlier model (El-Rayes 1997), the learning rate, "R", is set equal to 0.9. A detailed discussion of how the learning curve is incorporated in the formulation can be found in El-Rayes (1997).

4.6 Cost Estimating

Direct costs incurred by a crew assigned to an activity can be divided into: 1) mobilization/demobilization costs; and 2) costs arising from executing the work (material/labour/equipment). Unlike earlier models, the proposed methodology accounts for: 1) costs incurred in the mobilizing crews from contractor's staging and maintenance shop to the project site and back; and 2) costs incurred in relocating crews between project segments. On the other hand, indirect costs are solely dependent on the project duration. The procedure employed to compute each of the above costs is outlined below.

4.6.1 Mobilization Cost

Costs incurred when mobilizing crews can be divided into two main categories. These are: 1) direct costs incurred in mobilizing the crew, such as set-up, assembly/disassembly of equipment (if any) and rental of floats to transport equipment (if any); and 2) indirect costs incurred due to the equipment remaining idle during the mobilization process. The proposed model accounts for both cost categories mentioned above. In order to estimate the cost incurred in mobilizing a crew, data regarding the mobility of that crew is retrieved from the database. As mentioned in Section 4.4.1, crew templates store data regarding the mobility of each piece of equipment employed by a crew, such as: 1) whether a float is required for transportation; 2) whether assembly/disassembly is required on site; and 3) travel speed, on and off-highway. The procedure developed to estimate mobilization costs is discussed below.

If a float is required to transport any piece of equipment employed by a crew, the duration it would be required to transport that piece of equipment from the contractor's staging and maintenance workshop to segment "j" of a project, "T_{float}", is expressed as:

$$T_{float}=2\times M_{jj}/v_{float} \qquad (4.6)$$

where M_{jj} is element [j][j] of the mobilization matrix and

v_{float} is the float travel speed (default = 70 km/h).

The corresponding cost (C_{float}) is expressed as:

$$C_{float} = T_{float} \times RR_{float} \tag{4.7}$$

Where T_{float} is the time (hrs) the float is required, as given by Equ. (4.6) and RR_{float} is the hourly rental rate of the float.

The total float cost to transport a crew composed of "N_f" equipment requiring floats for transportation from contractor's staging and maintenance shop to site (or vice versa) is expressed as:

$$TC_f = \sum_{i=1}^{i=N_F} C_{float_i} \tag{4.8}$$

where TC_f is the total cost incurred for float,

N_f is the number of equipment in the crew requiring a float for transportation and

C_{float_i} is the float cost incurred for equipment i as given by Equ. (4.7).

If set-up and assembly of any equipment is required on site, then the cost incurred in assembly/disassembly is also retrieved from the crew template. For a crew composed of "N_a" pieces of equipment that require assembly on site, the direct cost incurred for equipment assembly and disassembly is expressed as:

$$TC_a = \sum_{i=1}^{i=N_a} (C_{assembly_i} + C_{disassembly_i}) \qquad (4.9)$$

where TC_a is the total assembly cost for a crew,

N_a is the total number of equipment requiring on-site assembly,

$C_{assembly_i}$ and $C_{disassembly_i}$ are assembly and disassembly costs for equipment i (requiring assembly) of the crew, respectively.

The above discussion has been primarily focussed on mobilization from the contractor's staging and maintenance shop to project site, and back. Frequently, the schedule requires that a crew relocates between project segments. The main difference between mobilizing (to and from a site) and relocation (between project segments) is that in the former, each piece is equipment is occupied in the mobilization process only for the duration it is being mobilized. In the latter, on the other hand, each piece of equipment is engaged in the relocation process for a duration that is dependent on the slowest equipment being mobilized.

For example, consider a crew composed of two pieces of equipment, "A" and "B", assigned to execute an activity in a highway project composed of two segments. Assume that equipment "A" requires assembly on site, while equipment "B" does not, and can travel twice as fast as equipment "A". For mobilization from the contractor's staging and maintenance shop to segment one (1) of the project, each piece of equipment would be sent to site at a different time such that the crew could start working on the scheduled start of the activity. When relocating between project segments, both pieces of equipment finish work at the same time, and commence work in the new segment at the same time as well. Hence, both pieces of equipment would be engaged for an equal period of time. During relocation, equipment "B" would arrive at the new segment before equipment "A", but would not be productive as a crew until both pieces of equipment are mobilized. The cost arising from float rental for relocation between project segments is expressed as:

$$CRel_{float} = N_f \times \sum_{i=1}^{i=NRL} \frac{M_{j,k}}{v_{float}} \tag{4.10}$$

where $CRel_{float}$ is float rental cost for relocation between project segments,

NRL is the total number a crew is relocated between segments,

$M_{j,k}$ is the element of the mobilization matrix corresponding to the travel distance between segments j and k (corresponding to the i^{th} relocation for the crew),

v_{float} and N_f are as defined in Equations (4.6) and (4.8), respectively.

Regarding assembly and disassembly, it is assumed that all equipment requiring assembly are disassembled and re-assembled each time they are relocated. The corresponding assembly/disassembly cost is expressed as

$$CRel_{ass} = \sum_{i=1}^{i=NRL} TC_a \qquad (4.11)$$

where TC_a and NRL are as defined in Equations (4.9) and (4.10), respectively.

The direct cost incurred in mobilizing a crew is given by summing float and assembly costs for mobilization to and from project site and within project segments

$$MobCost_{direct} = TC_a + TC_f + CRel_{float} + CRel_{ass} \qquad (4.12)$$

where $MobCost_{direct}$=is the total direct cost incurred for a crew,

TC_f and TC_a are as defined in Equations (4.8) and (4.9) respectively and

$CRel_{float}$ and $CRel_{ass}$ are as defined in Equ. (4.10) and (4.11), respectively.

4.5.2 Direct Activity Cost

Direct activity cost is that incurred in executing that activity. Three main cost items are defined, namely; equipment, labour and material costs. The duration any crew "c" is required on site is estimated, and corresponding labour and equipment costs are computed by direct multiplication. Material cost is computed by multiplying the total quantity of work involved in the activity by the unit cost as expressed in Equation (4.13):

$$\text{MatCost} = \text{unit cost} \times \sum_{j=0}^{j=m} Q_j \tag{4.13}$$

where MatCost is the material cost incurred in a repetitive activity,

m is the number of units comprising the activity and

Q_j is the quantity of work in unit j.

Equipment cost is computed by inspecting each piece of equipment employed by the crew, and multiplying its daily rate by the duration (in working days) that equipment is away from the contractor's staging and maintenance shop. The duration (in working days) which a piece of equipment spends on site, "DUR", is computed based on the activity duration and the number of relocations of the crew, and accounts for any overtime or double shifts. Equipment cost is expressed as:

$$\text{EquipCost} = \sum_{e=0}^{e=N_e} (DC_e \times (T_{mob} + T_{ass} + DUR + T_{dis} + T_{demob})_e) \tag{4.14}$$

where EquipCost is the total cost incurred for crew's equipment,

N_e is the number of pieces of equipment comprising the crew,

DC_e is the daily cost of equipment e,

DUR is the duration (working days) the crew is working on the activity,

T_{mob} and T_{demob} are times required to mobilize equipment e from contractor's staging and maintenance shop to project site and back, respectively, and

T_{ass} and T_{dis} are assembly and disassembly times, respectively, for equipment e.

Mobilization of labour is not considered in the proposed study, thus the duration labour is occupied in any activity is equal to the duration of work in that activity. The expediting technique adopted in the activity under consideration (if any) is inspected, and any premium for labour is computed. Labour cost is expressed as:

$$\text{LabourCost} = \text{DUR} \times \text{wh} \times \sum_{L=1}^{L=N_L} \text{hourlyWages}_L \qquad (4.15)$$

where hourlyWages_L is the hourly wages ($/hour) of labourer L,

N_L is size of the labour force and

wh and DUR are as defined in Equations (4.3) and (4.14), respectively.

Total crew cost is then computed by adding equipment and labour costs as computed in Equations (4.14) and (4.15) above. In order to determine direct activity cost, material cost, as computed in Equation (4.13), is added to crew cost.

4.5.3 Indirect Cost

Indirect cost is dependent on the project duration. The proposed model allows defining indirect cost either as a per-dayum ($/day) or as a percentage of the direct costs to date. In the former case, the specified per-dayum is added to the daily direct cost, while in the latter the direct daily cost is computed, and indirect cost is evaluated then added to the direct cost to determine total cost.

$$\text{Total cost on day (i)} = \text{direct cost on day (i)} + \text{ind} \tag{4.16a}$$

or

$$\text{Total cost on day (i)} = \left(1 + \frac{\text{ind}}{100}\right) \times \text{direct cost on day (i)} \tag{4.16b}$$

where ind is expressed as a per-dayum in Equation (4.16a) and a percentage of direct daily cost in Equation (4.16b).

4.6 Expediting Strategies

If crews working on a regular schedule cannot complete a project at a specified completion date, or a delayed activity needs to be brought back on schedule, several expediting techniques can be adopted. Three of the common expediting techniques are: 1) working overtime; 2) working weekends; and 3) working double shifts. Factors beyond the control of the project team could eliminate the possibility of adopting one or more of the above techniques. For example, contractors constructing a bridge and its approaches on Highway 364 across the Riviére Rouge at Huberdeau, near Arundel, Québec, were not allowed to work on weekends so as not to impact the region's tourism industry. Selecting an expediting technique to apply is discussed in Chapter Five. Expediting certain segments of a repetitive activity is enabled. An expediting technique that is commonly applied to bring an activity back on schedule is to employ larger, more productive, crew. This scenario can be addressed in the proposed study by defining a new crew formation representing the revised resources and crew productivity, and defining it as a potential crew formation for the activity under consideration. The model, however, does not directly enable enlarging a crew to expedite construction. The expediting techniques considered in the proposed model are discussed below.

4.6.1 Working Overtime

The survey of industry discussed in Chapter Two indicated that working overtime on a regular basis is not a widely used expediting technique. However, working overtime to expedite an activity for a short duration is frequently adopted. The productivity of crews working overtime has been the subject of several studies (e.g. Barrie and Paulson 1992). Accounting for the impact of prolonged working hours on crew productivity (Paulson 1975) is beyond the scope of this study. A premium of 50% is assumed for overtime hours worked. This premium is considered for labour only, and the daily cost of equipment employed by the crew is revised to account for the extra hours worked.

4.6.2 Working Double Shifts

In the survey of the Canadian highway construction industry, working double shifts was found to be the most commonly used expediting technique. Night-time construction is typically utilised in rehabilitation projects to minimise motorists' discomfort, and its employment is expected to increase in the future (NCHRP 1999(a)). Night-time construction cost can be considerably higher than daytime construction because: 1) crews working the nightshift are typically paid at a premium rate; 2) crew productivity could be lower due to lower visibility conditions; 3) additional lighting costs required to illuminate the site; and 4) increased safety measures to ensure motorists' safety. The above list is not comprehensive, but serves to highlight differences between daytime and night-time construction. The module accounts for: 1) nightshift premium (default=10%); 2) reduced productivity during night-time construction (default=zero); and 3) daily charge to cover additional illumination and safety costs (default=zero). If working double shifts is adopted, the rate of progress (along the project) of crews performing the activity under consideration could be doubled (if productivity losses are neglected). Working double shifts is thus the most effective expediting technique and, therefore, is considered in the proposed study.

4.6.3 Working Weekends

Another alternative to expediting an activity could be to work weekends. In this case, crew productivity is affected in a manner similar to that discussed for crews working overtime and double shifts. Crews assigned to the activity being expedited are scheduled to work a seven-day workweek. While the daily progress rate remains unaffected, the weekly production rate is increased. Similar to working overtime, a premium of 50% is assumed for working on weekends. The model enables employing this option for any or all project activities.

4.7 Summary

This chapter describes the planning and scheduling module. The automatic generation of precedence networks was discussed for both new highway construction and rehabilitation projects. The developed object-oriented model was presented, and its main components outlined. The procedure adopted to allocate resources to activities was presented, along with the employed scheduling algorithm. The procedure developed to compute direct and indirect costs was presented, and the methodology developed to account for mobilization cost was discussed. The expediting techniques used in the proposed model were reviewed, and their impacts were briefly discussed.

CHAPTER FIVE

SCHEDULE OPTIMIZATION

5.1 Introduction

This Chapter describes the proposed dynamic programming formulation. The methodology adopted to divide the work comprising any repetitive activity is first presented. This is a process that depends on the stated optimization objective. The dynamic programming formulation developed to identify optimum crew formations for all activities, and assign the crews to their respective work areas is then presented. The methodology adopted to develop schedules that satisfy specified deadlines or budgetary limits is also presented. A procedure is proposed to identify the activity(ies) that, when expedited, reduce the overall project duration the most.

5.2 Dividing Activity Work Among Crews

The quantity of work assigned to each crew bears a crucial impact on the developed schedule. As such, division of activity work among crews comprising the crew formation at hand depends on the stated optimization objective. The three objectives considered in the proposed model are minimising either: 1) total project cost; 2) construction duration; or 3) their combined impact for cost-plus-time bidding, also known as "A+B" bidding (Herbsman 1995). These three cases are discussed below. It is worth noting that the quantities of work assigned to crews as described in the following sub-sections are used as guidelines only, and are revised based on other conditions, as will be described later (Section 5.3).

5.2.1 Minimising Duration

When minimising project duration, the quantity of work assigned to crew "c" (c=1..n, where "n" is the total number of crews in the formation), "IAQ_c", is based on the productivity of that crew. The scope of work assigned to any crew "c" is expressed as:

$$IAQ_c = P_c \times \frac{\sum_{j=1}^{m} Q_j}{\sum_{i=1}^{n} P_i} \qquad (5.1)$$

where m is the total number of activity units,

n is the total number of crews in the crew formation,

Q_j is the quantity of work in unit j and

P_c is the daily productivity of crew c.

Equation (5.1) divides the scope of work of any repetitive activity among crews in a manner such that all crews would spend equal man-hours on the job.

5.2.2 *Minimising Total Cost*

In this case, the quantity of work assigned to crew "c", "IAQ_c", is based on the cost per unit of that crew. The quantity of work assigned to crew "c" is expressed as:

$$IAQ_c = \frac{C_c}{P_c} \times \frac{\sum_{j=1}^{m} Q_j}{\sum_{i=1}^{n} P_i / C_i} \qquad (5.2)$$

where C_c is the daily cost of crew c and

m, n, Q_j and P_c are as defined in Equation (5.1).

Equation (5.2) divides the work such that crews with lower cost per unit are assigned a larger portion that more expensive ones.

5.2.3 *Minimising Combined Impact for Cost-Plus-Time Bidding*

As discussed in Chapter Two, cost-plus-time bidding, also known as "A+B" bidding (Herbsman 1995), was recently introduced to minimise public inconvenience. This is achieved by encouraging contractors to develop schedules with shorter durations. As such, the objective is actually minimising duration. Consequently, the work comprising the activity at hand is divided among the crews using Equation (5.1) above. The main difference between minimising project duration and accounting for the combined impact of cost and time for cost-plus-time bidding becomes apparent when identifying the local optimum conditions, as will be described in the following Section.

5.3 Dynamic Programming Formulation

The objectives of the developed optimization procedure are to: 1) identify the optimum crew formation for each activity; and 2) assign each crew of that formation to its work area(s) (i.e. activity units) in a practical manner that achieves the optimization objective. As the number of activities and potential crew formations increases, this problem becomes computationally infeasible if all combinations of crew formations and crew assignments are to be considered. A set of heuristic rules has been developed in conjunction with a two-state variable, N-stage, dynamic programming formulation, to provide an efficient solution for the optimization problem. The heuristic rules are designed to reduce the solution space, while ensuring an optimum (or near-optimum) solution is obtained. The first and second state variables are: 1) the chosen crew formation; and 2) crew assignments. Each activity represents one of the "N" stages in the formulation, where "N" is the total number of activities in the project under consideration. For each activity, the model identifies the optimum crew formation from a given pool, and assigns each crew within that formation to a set of units in order to minimise either: 1) project duration; 2) project total cost; or 3) their combined impact in cost-plus-time bidding (Herbsman 1995). The optimization process takes place at the activity and project levels.

5.3.1 Activity Level

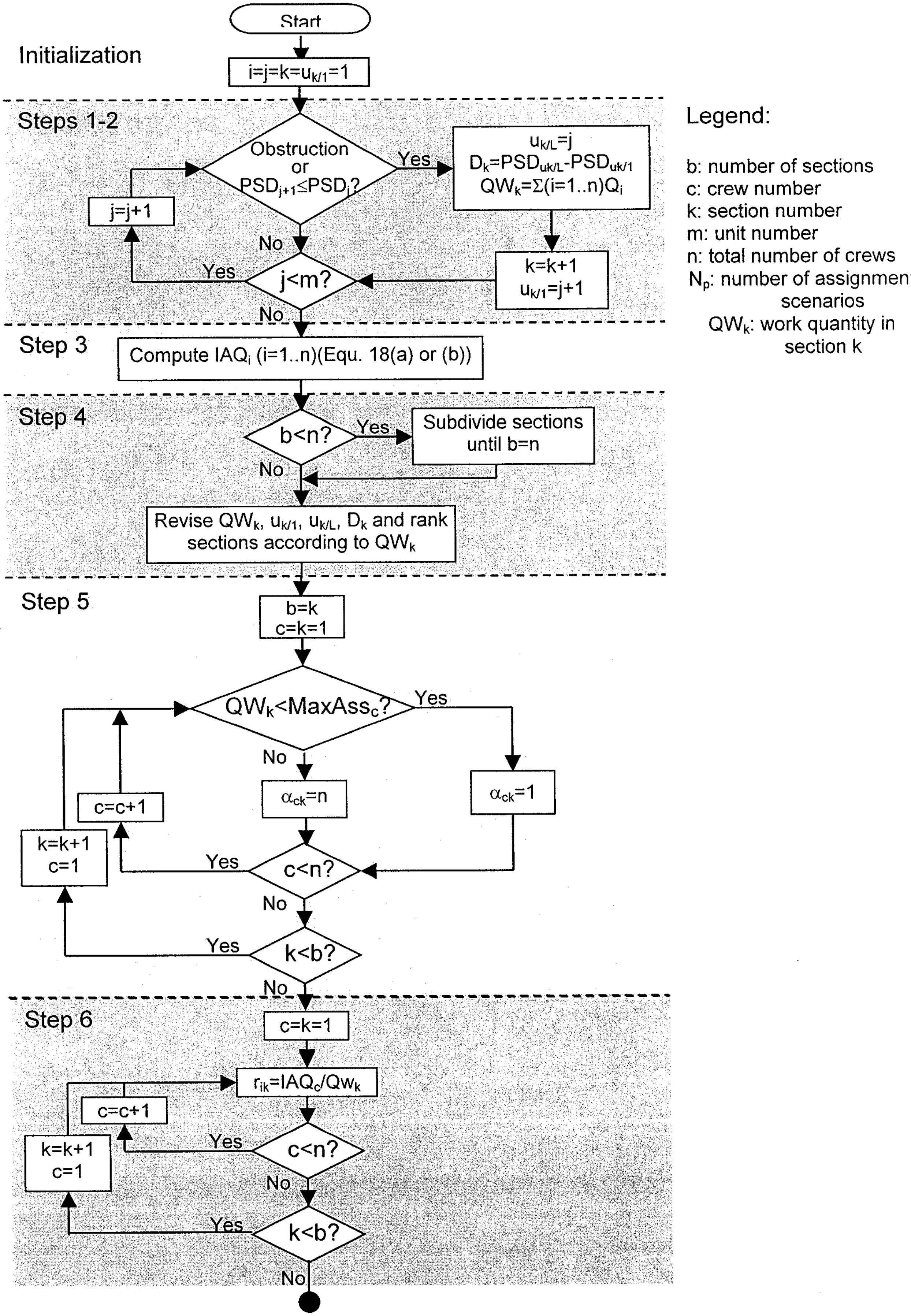
For any crew formation assigned to an activity, the objective is to identify the optimum crew assignments (i.e. which crews work on which units). Clearly, crew formations composed of a single crew are not considered at the activity level; that crew is directly assigned to all units. Non-repetitive activities, being executed at one location by a single crew, are not considered at the activity level either. The crew assignment scenario that satisfies the stated optimization objective is determined by following the procedure described below, and shown in Figure 5.1.

Step 1:

The project is divided into sections based on: 1) locations of transverse obstructions; and 2) possible start dates in all units of the activity being considered, respecting job logic and the required buffers between succeeding activities. The locations where discontinuities (in the possible start times of the activity) occur are determined by inspecting the possible start dates, PSD_j, of all units of that activity (see Figure 5.2), i.e.

$$PSD_{j+1} \leq PSD_j \qquad (j=1..m) \tag{5.3}$$

The stations at which the above discontinuities occur, along with the locations of transverse obstructions, define the boundaries between project sections. The total number of sections, "b", is determined, along with the number of insurmountable obstructions "N_{ins}".


Start
Initialization
i=j=k=uk/1=1
Steps 1-2
Obstruction or PSDj+1≤PSDj?
Yes
No
uk/L=j
Dk=PSDuk/L-PSDuk/1
QWk=Σ(i=1..n)Qi
j=j+1
j<m?
k=k+1
uk/1=j+1
Step 3
Compute IAQi (i=1..n)(Equ. 18(a) or (b))
Step 4
b<n?
Subdivide sections until b=n
Revise QWk, uk/1, uk/L, Dk and rank sections according to QWk
Step 5
b=k
c=k=1
QWk<MaxAssc?
αck=n
αck=1
c=c+1
k=k+1
c=1
c<n?
k<b?
Step 6
c=k=1
rik=IAQc/Qwk
Legend:
b: number of sections
c: crew number
k: section number
m: unit number
n: total number of crews
Np: number of assignment scenarios
QWk: work quantity in section k

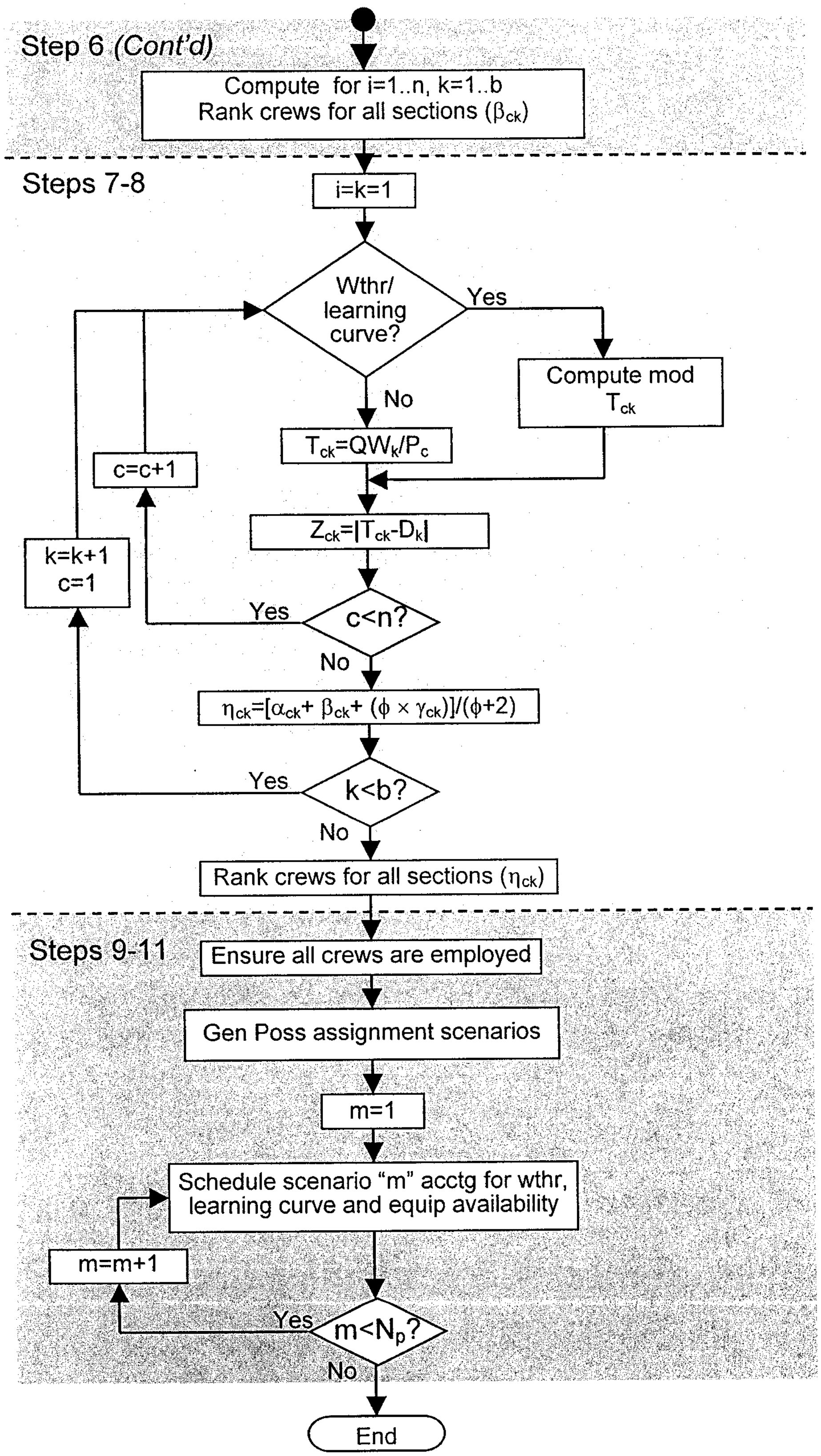


Figure 5.1: Optimization procedure

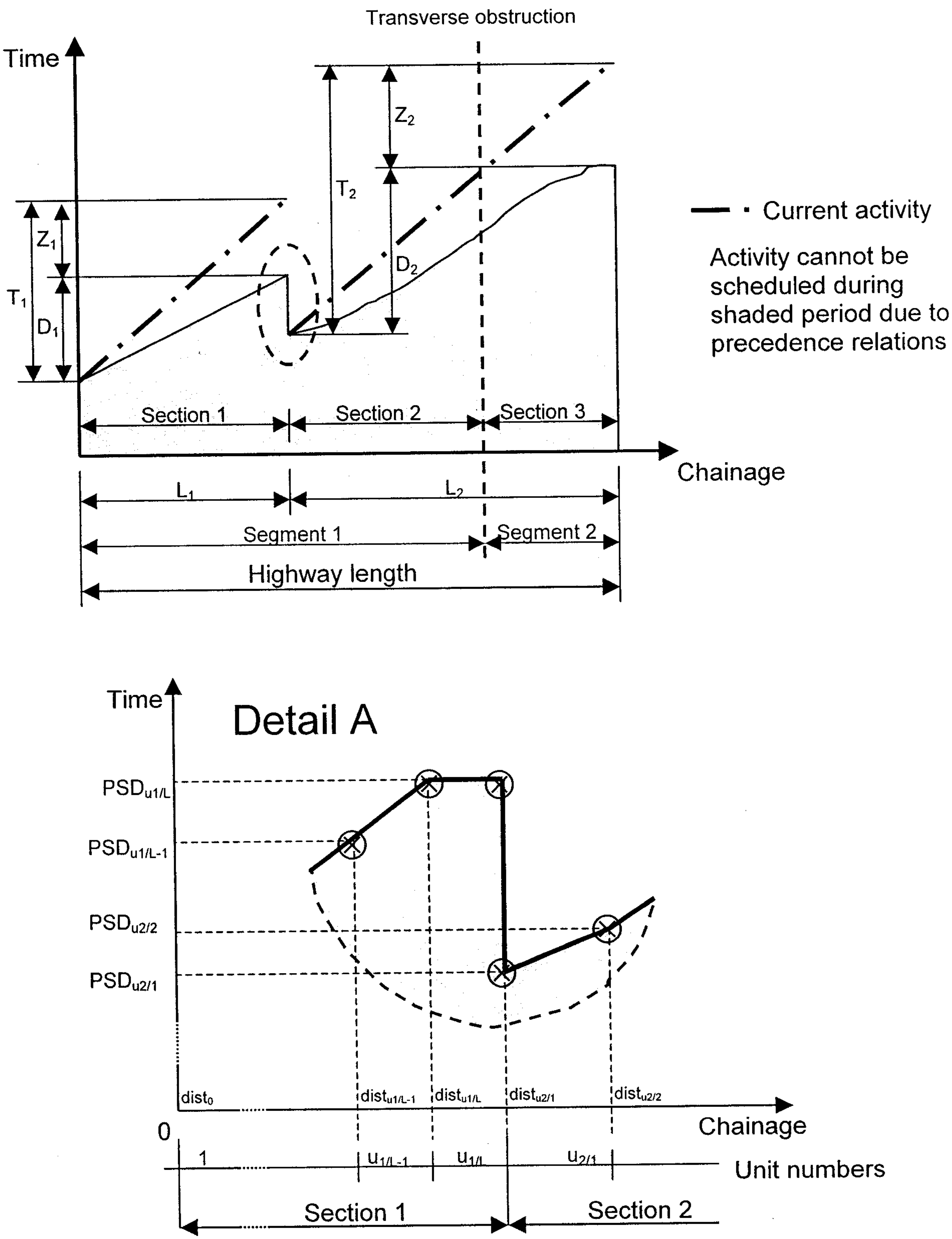


Figure 5.2: Variables used in the crew assignment procedure

Step 2:

The quantity of work for the activity under consideration in section "k", "QW_k", is determined from:

$$QW_k = \sum_{j=u_{k/1}}^{j=u_{k/L}} Q_j \tag{5.4}$$

where QW_k is the quantity of work in section k,

$u_{k/1}$ and $u_{k/L}$ are the numbers of the first and last units in section k and

Q_j is as defined in Equation (5.1).

Step 3:

The total quantity of work in the activity under consideration is initially subdivided among the crews comprising the current crew formation. The quantity of work assigned to crew "c" (c=1..n, where "n" is the total number of crews in the formation), "IAQ_c", is based on the performance of that crew in relation to that of other crews in the formation, as discussed in Section 5.2. Depending on the optimization objective, either Equation (5.1) or (5.2) is used to define the initially assigned quantities to all crews (IAQ_c).

Step 4:

In order to ensure that all crews are employed, the number of sections "b" determined in step (1) is compared to the number of crews comprising the crew formation under consideration "n". If ($b \geq n$), then the number of sections is sufficient to employ all crews, and the computation proceeds with step (5). Otherwise, sections need to be further divided until (b=n) enabling the employment of all crews. If (b=1), the highway needs to be divided into a number of sections equal to the number of crews in the formation. This division is carried out such that the quantity of work in segment "k" is equal to the initial quantity of work assigned to crew "c" ($QW_k=IAQ_c$, c=1..n). On the other hand, if (n>b>1), then the quantity of work in the smallest section (section "x") (QW_x=Min (QW_k), k=1..b) is compared to the initial quantities assigned to all crews. If ($QW_x \leq IAQ_c$, c=1..n), then crew (c) is assigned to the section, and both are discarded from future consideration. This procedure is repeated until no section can be assigned. At this stage, the largest remaining unassigned section (section "y") (QW_y=Max (QW_k)) is divided into two portions, (y_1) and (y_2). The quantities of work in sections "y_1" and "y_2" are set equal to "IAQ_c", and "Q_y-IAQ_c", respectively, and crew "c" (unassigned crew with largest IAQ_c) is assigned to section "y_1". Next, the chainage of the boundary between those two sections is determined. This is achieved by inspecting the location of section "y" with respect to the remaining unassigned length of the highway. Crew "c" and its associated section "y_1" are removed from further consideration, and the above procedure is repeated for the remaining sections and crews, until only one section remains, to which multiple crews are to be assigned. The assignment process for the last section is similar to that when a project is comprised of a single section, as described above. Upon completion of the planning process, including the identification of the length and location of each segment, the scope of work (quantity of work, "QW_k", k=1..b) is calculated.

Step 5:

The time span between start times of the first and last units of immediately preceding activity(ies) in section "k", D_k (k=1..b, where "b" is the total number of sections) (see Figure 5,2), is expressed as:

$$D_k = PSD_{uk/L} - PSD_{uk/1} \tag{5.5}$$

where D_k is the duration of works at section k for the immediately preceding activity(ies),

$u_{k/1}$ and $u_{k/L}$ are as defined in Equation (5.4) and

$PSD_{uk/L}$ and $PSD_{uk/1}$ are the possible start dates for units $u_{k/L}$ and $u_{k/1}$, respectively.

Step 6:

A ratio of the quantity of work of the section being assigned and that expressed by the performance of the crew is calculated as

$$r_{ck} = {}^{IAQ_c}\!\big/_{QW_k} \tag{5.6}$$

where IAQ_c and QW_k are as defined in equations (5.1) and (5.4), respectively.

The closer "r_{ck}" is to unity, the higher the priority of assigning crew "c" to section "k" based on crew performance.

Step 7:

The time required for crew "c" to complete the work at section "k" can be expressed as:

$$T_{ck}=QW_k/P_c \tag{5.7}$$

where T_{ck} is the time required for crew "c" to complete work at section "k" and

P_c and QW_k are as defined in equations (5.1) and (5.4), respectively.

Crews are then ranked in ascending order of "Z_{ck}" (c=1..n), based on the absolute difference between "T_{ck}" and "D_k" ($Z_{ck}=|T_{ck} - D_k|$) (see Figure 5.2).

Step 8:

Four performance indices (α, β, γ and η) have been introduced to aid in the crew assignment process. These indices are assigned a value between unity and "n", where "n" is the total number of crews in the crew formation under study. Their application reduces the solution space, while ensuring that an optimum or near-optimum solution can be achieved. The first index, "α_{ck}", provides a measure as to how close the capacity of the assigned crew "c" is to the scope of work of the designated section "k". i.e. if the scope of work (QW_k) is within the limits of max. and min. capacities specified for crew "c" ($maxAss_c$ and $minAss_c$), then "α_{ck}" is set equal to unity. Otherwise, it is set equal to "n". Unity indicates a ranking of first choice, as opposed to "n", least desirable. The next performance index, "β_{ck}", provides a measure as to how close the initially assigned quantity (IAQ_c) of crew "c" is to the scope of work of the designated section (QW_k). i.e. "β_{ck}" is the order of crews when ranked in ascending order of "r_{ck}", as computed in step (6) above. The third index, "γ_{ck}", provides a measure as to how close the rate of progress of crew "c" if assigned the scope of work of the designated section "k". i.e. "γ_{ck}" is the order of crews when ranked in ascending order of "Z_{ck}", as discussed in Step (7) above. A composite index of the three indices, "η_{ck}", is also considered as described in Equation (5.8), which is applicable except if ($n \neq b$):

$$\eta_{ck} = \frac{\alpha_{ck} + \beta_{ck} + (\varphi \times \gamma_{ck})}{\varphi + 2} \tag{5.8}$$

where η_{ck} is the composite index for crew c to be assigned section k,

α_{ck}, β_{ck} and γ_{ck} are the performance indices of crew c to be assigned to section k based on its capacity, relative performance within the crew formation and balancing with preceding activity(ies), respectively, and

ϕ is a weight factor to adjust the relative weight of balancing the crew vs. crew capacity and performance.

If ($n \neq b$):

$$\eta_{ck} = \gamma_{ck} \tag{5.9}$$

where η_{ck} and γ_{ck} are as defined in Equation (5.8).

"ϕ" is a factor employed to control the relative significance of generating a balanced schedule vs. the crew capacity and performance (default = 1). If the scheduling objective is to minimise duration, "ϕ" should be assigned a value larger than unity. A sensitivity analysis could be carried out to determine the optimum value of "ϕ" for each activity to achieve the optimization objective. For section "k", crews are ranked in an ascending order of "η_{ck}".

Step 9:

The optimum assignment recommendations for all sections are investigated to determine whether all crews are employed. The project sections are then ranked in a descending order of their respective quantity of work (QW_k). The possible assignment scenarios are generated according to the relative values of "b" and "n" as described below. Note that the total number of sections "b" cannot be less than the number of crews (n), as described in step (4) above.

Case 1: (b=n)

In this case, each crew can only be assigned to one section. The goal is to generate assignment scenarios such that each section is, at least once, assigned its optimum crew. A maximum of "n" assignment scenarios is generated, where one section is assigned its optimum crew (crew with lowest "η_{1k}" (k=1..b)). The remaining sections are assigned a priority based on their respective scope of work (satisfy larger sections first).

Case 2: (b>n)

In this case, crews (at least one) will be assigned to work on more than one section. The approach adopted in this case depends on the number of insurmountable obstructions (N_{ins}) defined in the project. Three scenarios are considered: i) $N_{ins}=0$; ii) $N_{ins}=n-1$; and iii) $n>N_{ins}>1$. As mentioned earlier, the number of crews must exceed the number of insurmountable obstructions by at least unity to allow for at least one crew to work on each work zone.

Scenario i: ($N_{ins}=0$)

In this case, crews are free to relocate from any project segment to another. A maximum of "n" assignment scenarios are generated, where the largest "n" sections are allocated to crews in a manner similar to case (1) above. In each of these scenarios, the quantities of work assigned to each crew are computed, and compared to the initially assigned quantities (IAQ_c). A crew is declared unavailable once it is assigned a quantity of work equal to, or greater than (IAQ_c). The optimum crews for the remaining sections are assigned based on crew availability.

Scenario ii: (N_{ins}=n-1)

In this case, the only transverse obstructions that would impact the assignment scenario are the insurmountable ones. Only the largest section in each of the work zones are considered, and are assigned to crews in a manner similar to case (1) above. In this case, "n" possible assignment scenarios are generated. It should be noted that in each assignment scenario, the crew assigned to the largest section within a work zone executes the remainder of the work within the work zone.

Scenario iii: ($n>N_{ins}>1$)

A procedure similar to that in scenario (ii) above is employed to assign crews to each of the largest sections of the project work zones. A total of "N_{ins}+1" assignment scenarios are thus generated, ensuring that each of the work zones is assigned a crew. In each of the generated scenarios, the quantity of work in the work zone is assigned to the crew working on its largest section (Q_{Ind_Seg}). These quantities are compared with the initially-assigned quantities, "IAQ_c", and the segment that has the highest value of "Q_{Ind_Seg}/IAQ_c" is assigned one of the available crews. This process is repeated until all crews are assigned. Sections that did not receive crews at this stage are listed and queued for crew assignment pending availability and the above stated criteria.

Step 10:

The assignment scenarios are investigated to remove any duplicates. For each assignment scenario, the finish times of all units are determined accounting for factors such as weather and the learning curve effect, while maintaining crew work continuity. Periods during which each crew would be required are determined, and the availability of each crew during that period is determined employing the assignment algorithm discussed in Section 4.4.2. If necessary, a revised activity schedule accounting for equipment availability is developed. Activity total cost is then computed using Equation (4.16).

Step 11:

The assignment scenario that satisfies the stated optimization objective is identified as the local optimum solution. For minimising cost, the optimum solution is that which would yield min. total cost. For minimising duration, the local optimum solution is the one that minimises the shaded area shown in Figure 5.3. The methodology is analogous to the minimum moment algorithm (Hiyassat 2001) applied to level resources in that both attempt to minimise the total energy expended.

Figure 5.3: Area to be minimised to expedite construction

For minimising the combined impact of time and cost, the total combined cost, "TCB", is expressed as:

$$TCB = A + B \times RUC \qquad (5.10)$$

WhereTCB is the total combined bid,

A is the project cost (including current activity),

B is the project duration (including current activity) and

RUC is the daily road user cost.

The local optimum solution in this case would be the one with the lowest value of "TCB".

5.3.2 Project Level

At the project level, the goal is identifying the optimum crew formation for each activity in the project, and consequently the global optimum solution. This is achieved in two paths; forward and backward. The forward path starts with the first activity, and propagates through all the activities, investigating all crew formations, and crew assignments, as described above. The local optimum solution for the last activity is identified as the global optimum solution, and the backward path is initiated. The backward path propagates through the project activities, starting from the last activity. Its objective is to scan the local optimum solutions that were identified in the forward path, i.e. identify the optimum crew formation and crew assignments for each activity, along with the optimum crew formation and assignment scenario for the preceding activity(ies). The above procedure is repeated for all activities, until the optimum crew formation and assignment scenario for the first activity are identified.

5.4 Satisfying a Specified Deadline

Developing a schedule to satisfy a specified deadline is an iterative process, where the formulation described above is repeatedly applied to the project at hand. Initially, the procedure described above is applied, and the minimum duration is determined. If the specified duration is equal to or greater than the minimum duration, then the project could be scheduled with crews operating at normal capacity (i.e. without having to expedite any activities). The total duration of all generated schedules are then compared to that specified, and the schedules with total duration less than or equal to that specified are compared to determine the schedule with the least total cost. If, on the other hand, the minimum computed duration is longer than that specified, then the project needs to be expedited. A methodology was developed to identify the most critical activity, or segment thereof. As mentioned in Chapter Two, several models have been proposed to identify critical activities in linear projects (Handa *et al* 1992; Suh 1993; Harmelink and Rowings 1998). The proposed method is mainly graphical, and is based on attempting to balance successive crews to maintain a balanced production that expedites construction. The methodology is analogous to the minimum moment algorithm (Hiyassat 2001) applied to level resources in that both attempt to minimise the total energy expended.

Consider the linear schedule showing the progress of three typical activities, "A", "B" and "C" through a section shown in Figure 5.4. During scheduling, the planning and scheduling module computes the shaded areas, and the eccentricities of their centroids, "e_1" and "e_2" (see Figure 5.4). For example, upon scheduling activity "B" (see Figure 5.4), areas "$A_{1/1....m}$", where m is the number of units in activity "B", are calculated. Area $A_{1/i}$ (i=1..m) is expressed as:

$$A_{1/i} = L_i \times \frac{ES_{(i+1)} - PES_{(i+1)} + ES_{(i)} - PES_{(i)}}{2} \tag{5.11}$$

where ES_i and ES_{i+1} are the scheduled start times for units i and i+1, respectively,

PES_i and PES_{i+1} are the possible start times for units i and i+1, respectively and

L_i is the length of unit i.

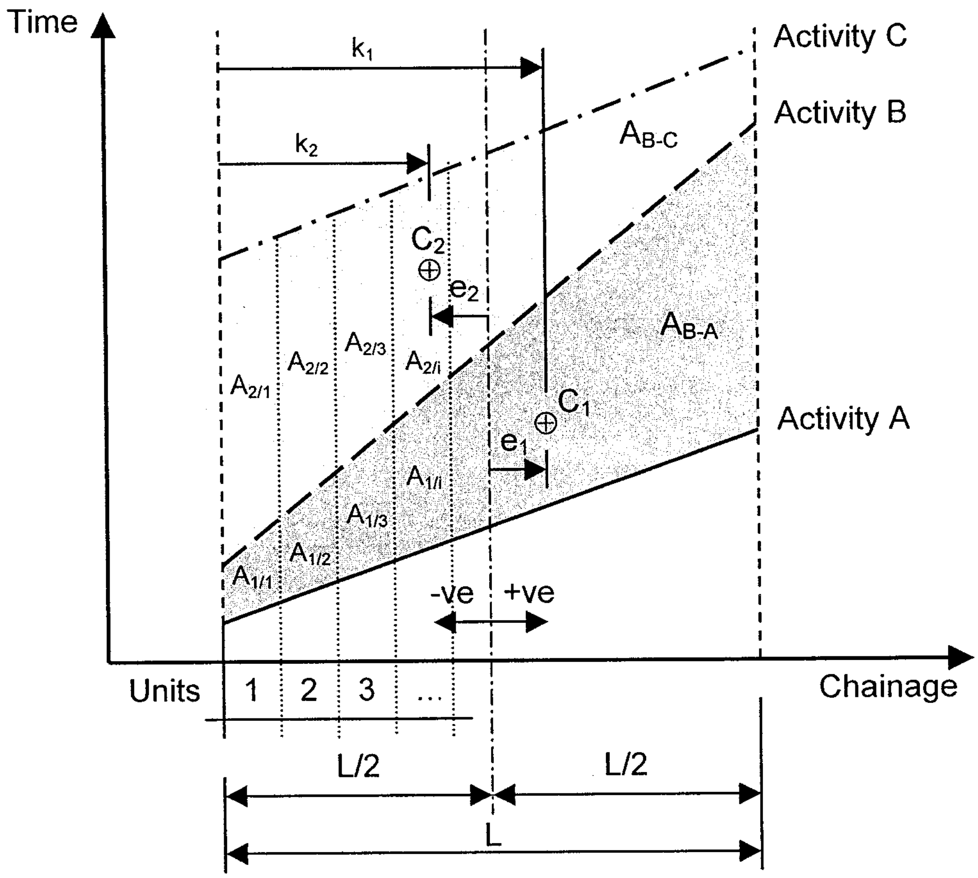


Figure 5.4: Sample project segment

The shape of any area "$A_{1/i}$" is generally a trapezium whose centroid is located at a known distance from its base. The distance from the section's start to the centroid, "k_1", is expressed as:

$$k_1 = \frac{\sum_{i=1}^{i=m} d_i \times A_{1/i}}{\sum_{i=1}^{i=m} A_{1/i}} \qquad (5.12)$$

where d_i is the distance from the start of the section to the centroid of Area $A_{1/i}$.

The eccentricity "e_1" is then computed as:

$$e_1=k_1-L/2 \qquad (5.13)$$

where L is the length of the section (see Figure 5.4).

The above calculations are carried out for all project activities. Maintaining a balanced rate of progress to minimise project duration has been recommended by previous researchers (e.g. Popescu *et al* 1995). The approach adopted to identify the most critical activity (or segment of an activity) is based on identifying the activity (or segment thereof) that is least balanced with its predecessor and/or successor. This is achieved by inspecting all project activities to identify the one with the highest value "Ω_I", where "Ω_i" is expressed as:

$$\Omega_i=A_1\times e_1 - A_2\times e_2 \qquad (5.14)$$

It is worth noting that the bottom envelope of area "A_1" (see Figure 5.4) may be formed as the result of more than one preceding activity, since "PES_i" is the possible start time of unit "i" considering all precedence relations. Consider the sample linear schedule of successive activities "A", "B", "C", "D" and "E" shown in Figure 5.5. Areas "A_1" through "A_5" are computed, as well as their eccentricities ("e_1" through "e_5"). Table 5.1 lists the values of "Ω" for all activities.

Table 5.1: Values of "Ω" for activities shown in Figure 5.5

Activity	Ω
A	$A_1 \times e_1 - A_2 \times e_2$
B	$A_2 \times e_2 + A_3 \times e_3$
C	$-A_3 \times e_3 - A_4 \times e_4$
D	$A_4 \times e_4$
E	0

Based on the repetitive activities shown in the figure, the relative areas 1 through 4 and eccentricities 1 through 5, one can conclude that activity "B" is the most critical, based on its relatively high "Ω". The time required to complete the scope of work in section "k" when adopting various expediting techniques are compared, and the expediting strategy that results in a balanced crew with the previous activity is selected. Figure 5.6 shows the revised schedule, where activity "B" is expedited, and the project duration is reduced from "dur_1" to "dur_2".

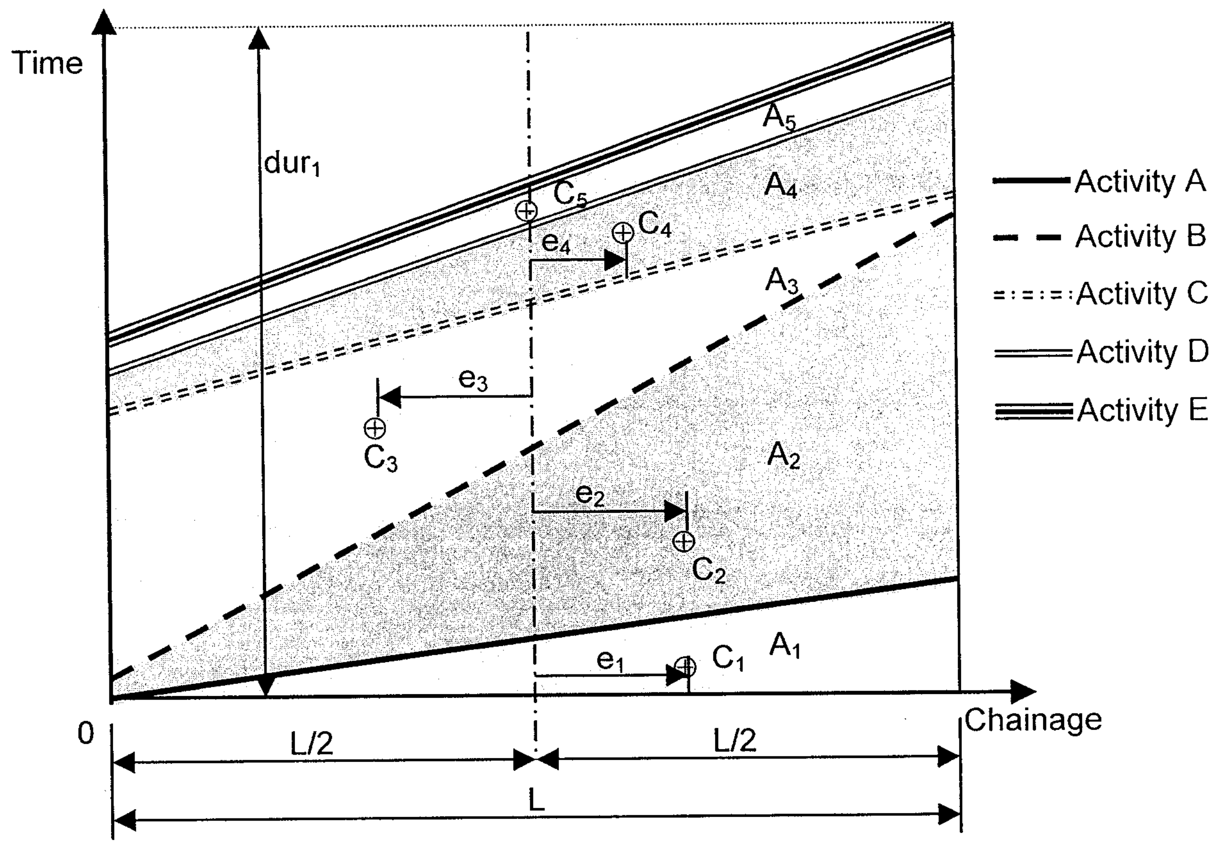


Figure 5.5: Sample linear schedule composed of five activities

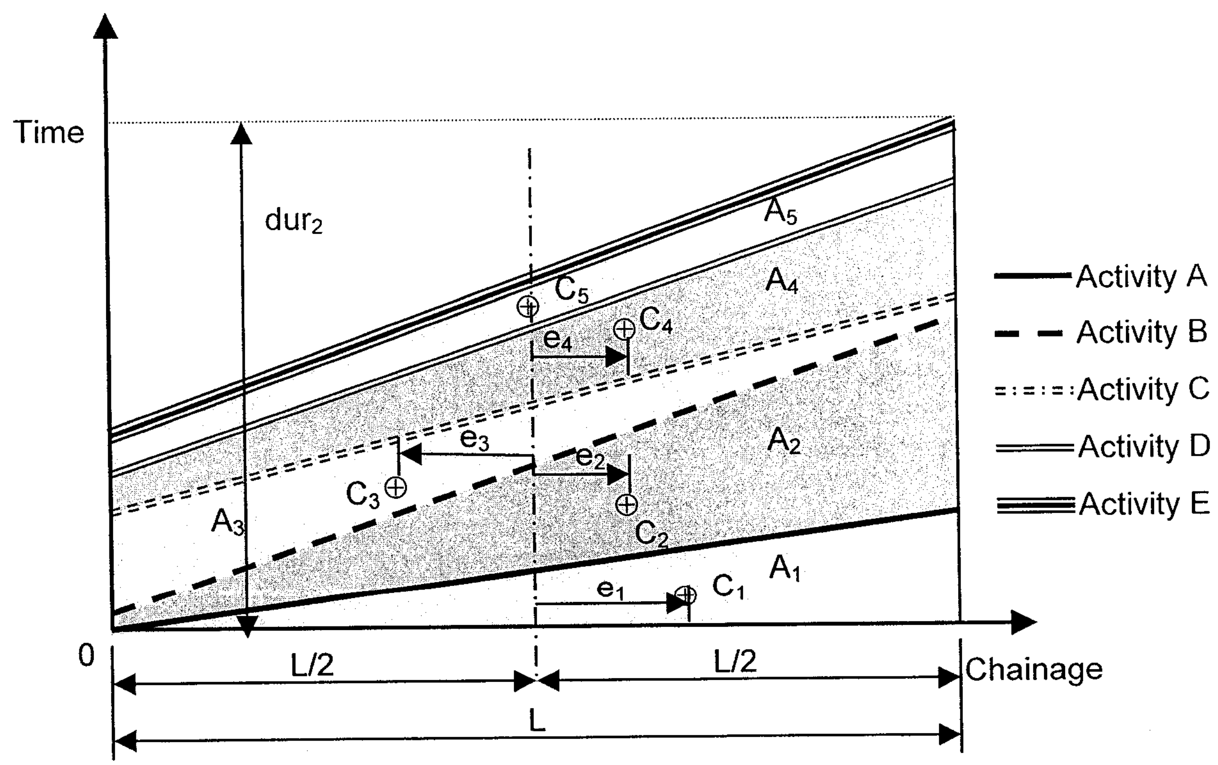


Figure 5.6: Revised schedule after expediting activity “B”

The resulting duration is then compared to the specified duration, and the process of identifying the most critical activity and expediting it is repeated until either: 1) the specified duration is achieved; or 2) "m" iterations have been carried out without a reduction in duration, where "m" is the total number of project activities. Once an activity is expedited to its highest production rate, it is disregarded from future consideration. For example, if the schedule shown in Figure 5.6 is expedited, then activity "B" would not be considered for expediting (once an activity is operating at maximum production, "Ω" of that activity is set equal to zero). It is worth noting that "Ω_C" above has a negative value (see Table 5.1). A negative value indicates that any expediting strategy applied would result in further delays. "Ω_E", on the other hand, has a value of zero, indicating that the activity is perfectly balanced with its predecessor. If the model exhausts all expediting attempts and the specified deadline is not met, then the model indicates that no solution is found, and the schedule with shortest duration is reported.

An interesting feature of linear schedules is that more resources does not necessarily result in faster construction for the project. Consider the linear schedule shown in Figure 5.7 (Moselhi and El-Rayes 1993(b)). Part (a) of the figure shows the schedule when all crews are working at normal productivity. Expediting "Beams" activity resulted in a prolonged schedule, as shown in part (b) of the figure. On the other hand, relaxing "Foundation" activity resulted in a shorter construction schedule, as shown in part (c) of the figure. This somewhat unexpected behaviour is because of adherence to work continuity for all crews. Consequently, relaxing some activities can result in a shorter project duration. This possibility is also considered by the proposed model. Activities that would result in a shorter overall duration are those with negative value of "Ω". A good example would be activity "C" in Figure 5.6, where the result of relaxing the activity is shown in Figure 5.8.

Figure 5.7: Minimising duration of repetitive projects

(Moselhi and El-Rayes 1993(b))

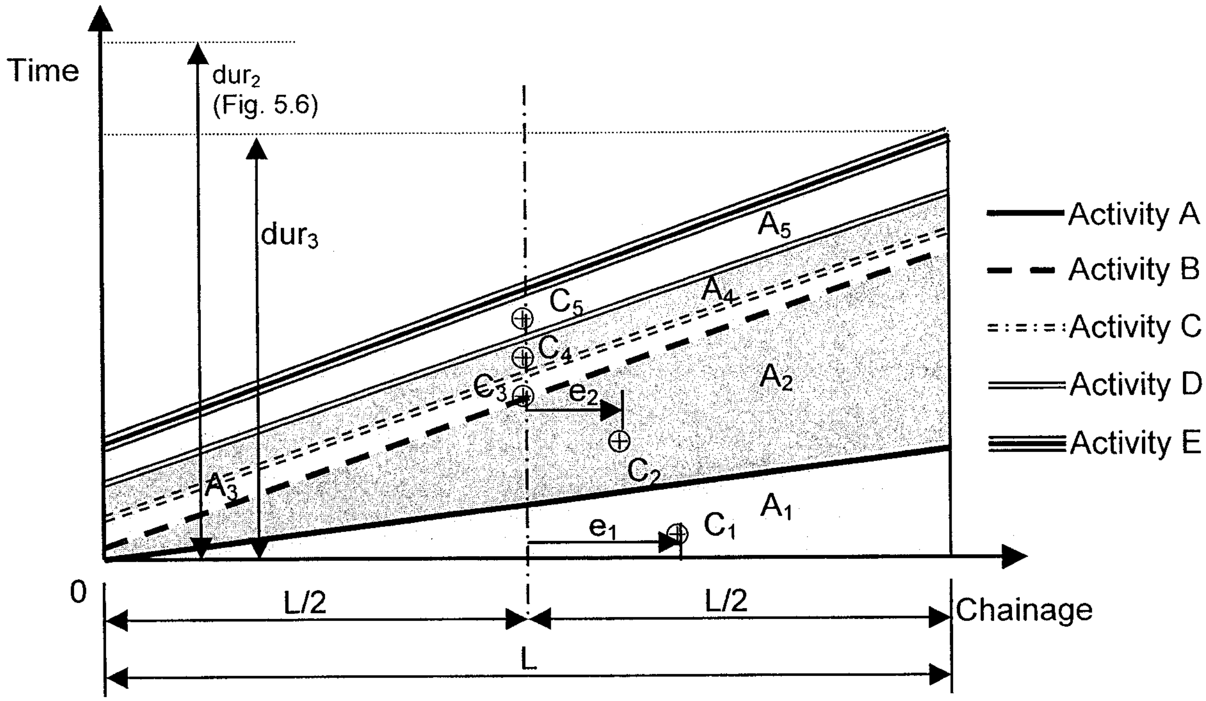


Figure 5.8: Revised schedule after relaxing activity "C"

The project schedule shown in Figure 5.8 shows that project duration has been reduced from "dur_2" to "dur_3". It should be noted that relaxing an activity incurs additional costs for that activity. This is due to the prolonged stay of work crews executing it. These additional costs could be compared to the cost savings resulting from shorter project duration. In order to enhance the practicality of the proposed model, the user can select activities to which relaxation is allowed. By default, none of the activities are allowed to be relaxed.

5.5 Satisfying a Specified Budget

Generating a schedule to satisfy a certain budget is a task that is encountered in the initial planning stage of a project. In order to increase the practicality of the model, a provision was made to enable generating schedules to meet specific budgetary constraints. It should be noted this process might require minimising the project scope of work. In this study, satisfying these budgetary limitations is within the same scope, and aims at determining minimum cost. Generating a schedule to satisfy a certain budget is carried out by first carrying out the optimization process with the objective of minimising total construction cost, and plotting the time-cost curve for the project. If no schedules are generated with total cost less than that specified, then the model reports this finding, along with the minimum possible total cost. If, on the other hand, one or more schedules are generated that satisfy the stated budget, then these schedules are stored and ranked in ascending order of total cost or overall duration. Preference of one schedule over another is left to the user's discretion.

5.6 Summary

This chapter presented the proposed optimization procedure, and introduced the optimization criteria addressed by the proposed model. Optimization of total cost, construction duration and their combined impact for cost-plus-time bidding were introduced, and the dynamic programming formulation for all three optimization objectives was presented. The methodology adopted to identify critical activities, or segments thereof, was presented, and the approach adopted to generate schedules to meet specified deadlines and budgetary constraints, if possible, were presented.

CHAPTER SIX

COMPUTER IMPLEMENTATION

6.1 Introduction

This chapter describes the implementation of the proposed model. First, the prototype software developed to automate data acquisition and analysis, "Analyser", is presented. Next, the software developed to carry out the planning, scheduling, tracking and control functions, "HWPlanner" is presented. Both software systems operate in Windows® environment, and "HWPlanner" employs Microsoft Foundation Classes (MFC). Each software can operate independently, but "Analyser" produces output in a format acceptable to "HWPlanner" so as to automate data entry for the scheduling engine. "Analyser" represents the GIS sub-module used for acquiring and analysing spatial data, while all other modules are included within "HWPlanner". The following sections present the developed implementation. Figure 6.1 shows input and output of the model. An outline of the proposed software system was shown earlier in Figure 3.1.

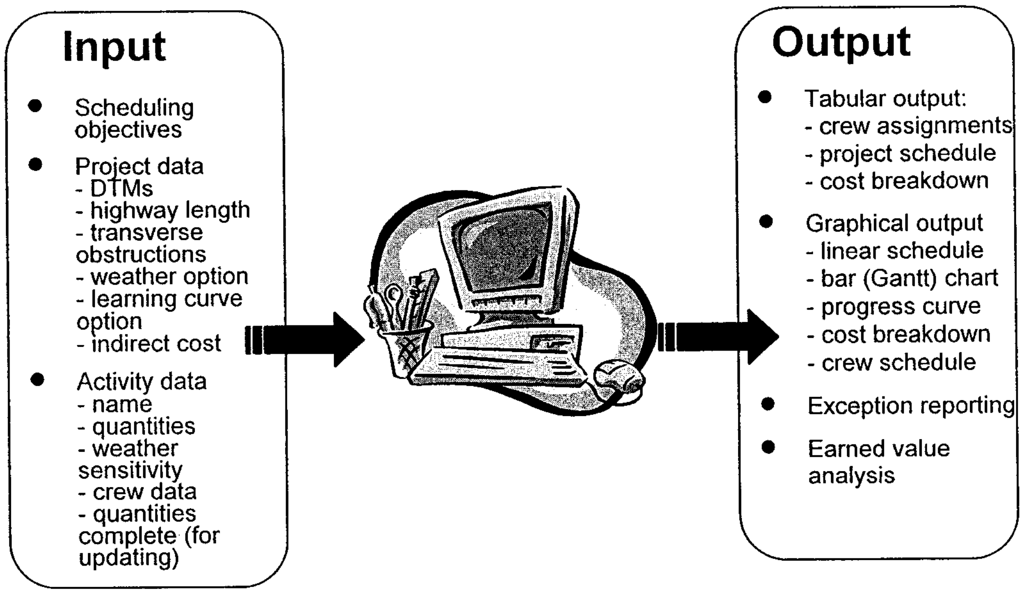


Figure 6.1: Input and output of the developed software

6.2 GIS Sub-Module

The GIS sub-module described in Chapter Three is implemented in a prototype software using object-oriented programming. The software is coded using *Avenue* (ESRI 1996b), as supported by the widely used GIS software ArcView® Version 3.1 (ESRI 1996a). Avenue is a script language that enables object-oriented programming. The software operates in Microsoft Windows® environment and operates on Windows® 95, 98, 2000, NT, ME and XP. Toolbars, menus and dialog windows simplify data input, minimise the possibility of erroneous input and constitute part of a user-friendly graphical interface designed to simplify data input and retrieval. In order to enable three-dimensional analysis, the extension *3D Analyst* of ArcView (ESRI 1997) is employed. The software is flexible and supports the following input formats: 1) ArcView 3-D themes; 2)

AutoCAD® drawings; 3) digitised images from blueprints; 4) satellite images depicting elevation; and 5) global positioning system (GPS) data points.

Locations of borehole test results can be input in one of the following formats; 1) an ArcView point theme; 2) tab-delimited text files; and 3) Excel spreadsheets. The locations of the borehole tests, and their data log, can also be input interactively. The developed software provides three-dimensional visualisation of the highway embankment, ground terrain and underlying soil strata, aiding the user in obtaining a clear perspective of the job at hand. The software also allows the user to consider the impact of obstructions in developing the mass haul diagram, as discussed in Chapter Three. In view of its popular use as a drawing tool, the model is designed to accept AutoCAD drawings and places each layer in the drawing in a separate two-dimensional theme.

6.3 HWPlanner

"HWPlanner" was implemented in a prototype software, operating in a Windows® environment. The software is coded in Visual C++, utilising object-oriented programming, and employing Microsoft Foundation Classes (MFC). This enables the utilisation of previously defined classes that carry out several functions, including file access, serialisation and graphical interface. The user interface of "HWPlanner" incorporates menus, toolbars, a status bar, dialog windows and

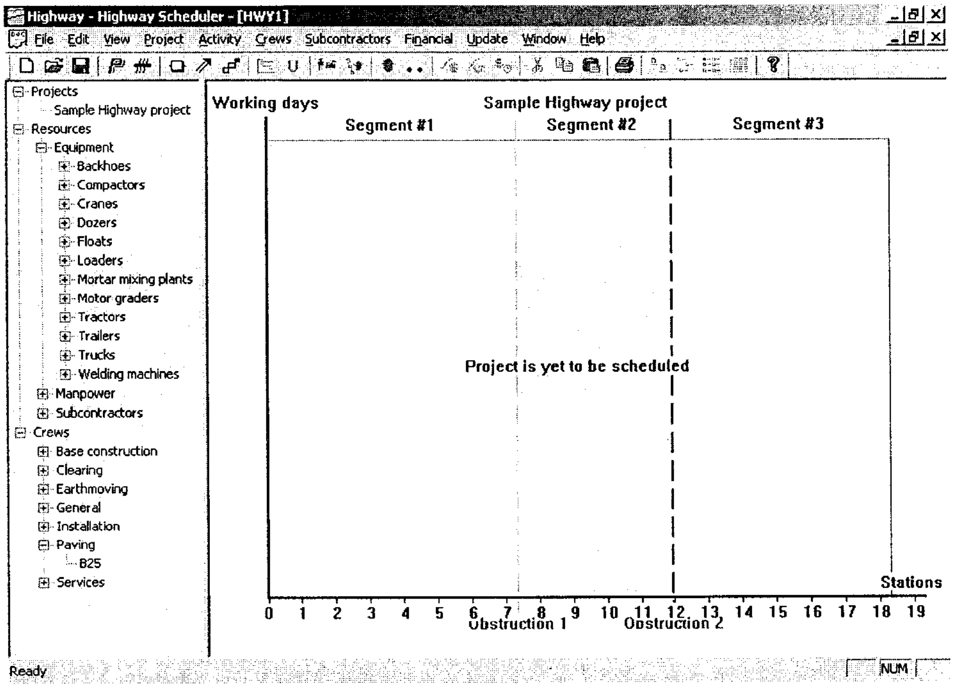


Figure 6.2: Main screen of "HWPlanner"

multiple document interfaces windows. The software is implemented as a Microsoft Windows® application, and can run on Microsoft Windows® 95 , 98, 2000, ME and XP. A user-friendly graphical interface facilitates data entry and retrieval.

Reports are generated at varying levels of detail to suit the requirements of the various members of the project team. Bar (Gantt) charts can be generated, depicting working and calendar days, as well as assignment dates of all crews. The software also prepares plots of linear schedules in the format adopted for highway construction (Harmelink 2001), where the vertical and horizontal axes represent time and chainage, respectively. Microsoft Access® was employed as the database management system (DBMS). In addition, the developed software has a number of interesting features: 1) it enables the definition of as many as needed work calendars (default is the Gregorian calendar); 2) it accepts several input file formats (Microsoft Excel® and tab-delimited text files); and 3) it enables editing of defined activities and crews.

The various features of the proposed model were shared with the 407 ETR project team, who were generally appreciative of some of the model's features, and expressed particular interest in several of them, such as: 1) accounting for the presence of transverse obstructions when developing the earthmoving plan; 2) accounting for variations in swell and shrinkage factors for various soil types; and 3) the mobilization matrix and its updating capabilities to reflect recent changes in accessibility across transverse obstructions. Various practical features that could be incorporated in the model were also proposed by the project team, such as accounting for permits.

6.3.1 Graphical User Interface

The implementation of the graphical user interface sub-module is carried out in a fashion that facilitates data entry and minimises redundant data input. The main screen of "HWPlanner" is shown in Figure 6.2. It is composed of two views; the left view displays a hierarchical tree-view of projects, resources, and crew templates. Activities defined in any project are listed under that project, and crew formations defined for any activity are also shown stemming from that activity. Crews used in a crew formation are also listed under that crew formation, enabling a complete and detailed view of project particulars. Data regarding crew templates, activities and resources can be obtained by right-clicking the item's name shown in the left view. By double-clicking any of the project items its data is displayed in a dialog window, as shown in Figure 6.3 which depicts the dialog window displaying crew data. The window is composed of three tabs: 1) general; 2) equipment; and 3) manpower. The "general" tab displays the data shown in the figure, while "equipment" and "manpower" tabs display a list of equipment and labour comprising the crew, respectively.

The right view, on the other hand, displays a multitude of graphs, such as Gantt and linear charts, progress curves, crew calendars and graphical displays of project cost breakdown. If multiple projects are defined, the right view displays data regarding the active project only. It should be noted that the developed software does not enable multiple project management, but does enable the definition of several projects that utilise resources from the defined pool. Optimizing resource utilisation across a number of projects is, however, beyond the scope of this study. It is worth noting that the software is designed to scale graphs and schedules to fit the dimensions of the computer screen.

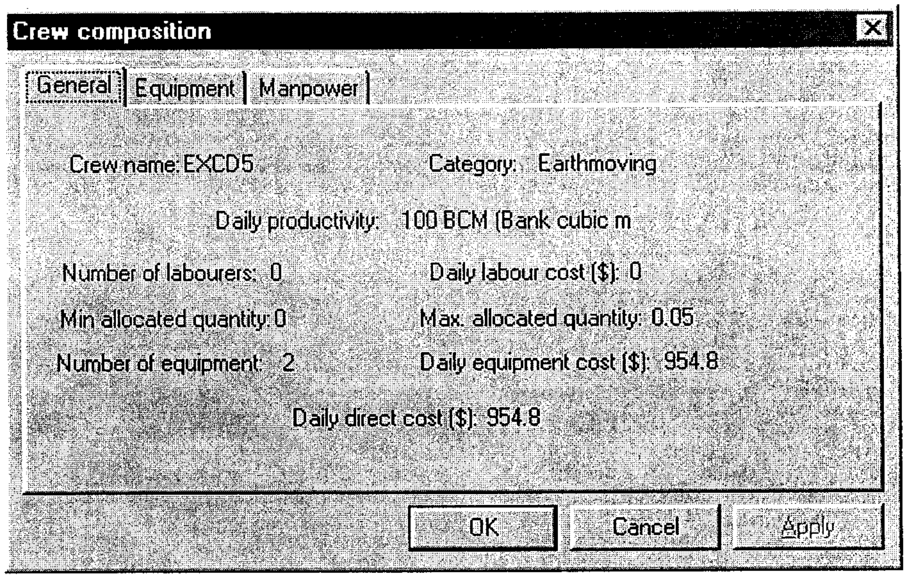


Figure 6.3: Dialog window displaying crew data

Figure 6.4 shows the dialog window employed to acquire the optimization objectives, while Figure 6.5 shows the dialog window designed to display scheduling results. As shown in Figure 6.4, the user can select from one of many scheduling options. Option "Segment" in the optimization portion of the window allows specifying a completion date for a particular work zone in the project. Scheduling options such as: 1) start date; 2) consideration of weather impact; and 3) consideration of the learning curve effect, are also input using this dialog window.

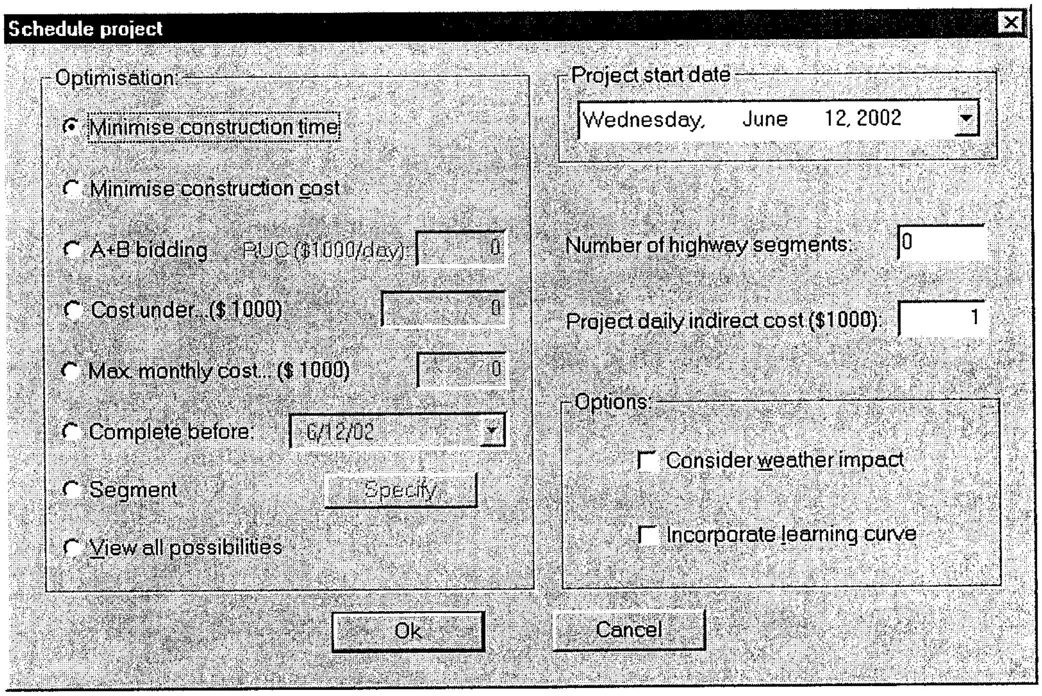


Figure 6.4: Dialog window designed to acquire optimization objectives

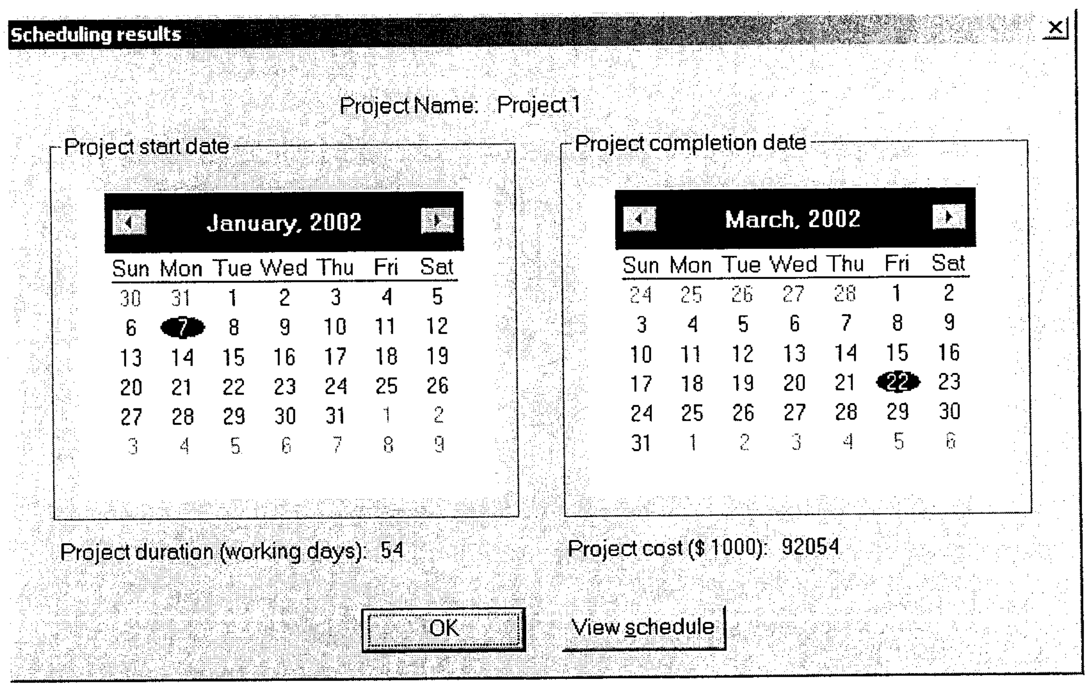


Figure 6.5: Dialog window displaying scheduling results

In order to minimise the possibility of erroneous data entry, menu and toolbar items are only enabled if and when it is possible. For example, menu and toolbar items for adding an activity are not enabled until a project is defined. Similarly, menu and toolbar items for adding a crew formation to an activity are not enabled until that activity has been defined. Right-clicking on any of the defined groups (projects, resources and pre-defined crew formations) activates floating menus designed to facilitate and expedite data entry, as shown in Figure 6.6, which shows the floating menu designed for activity objects.

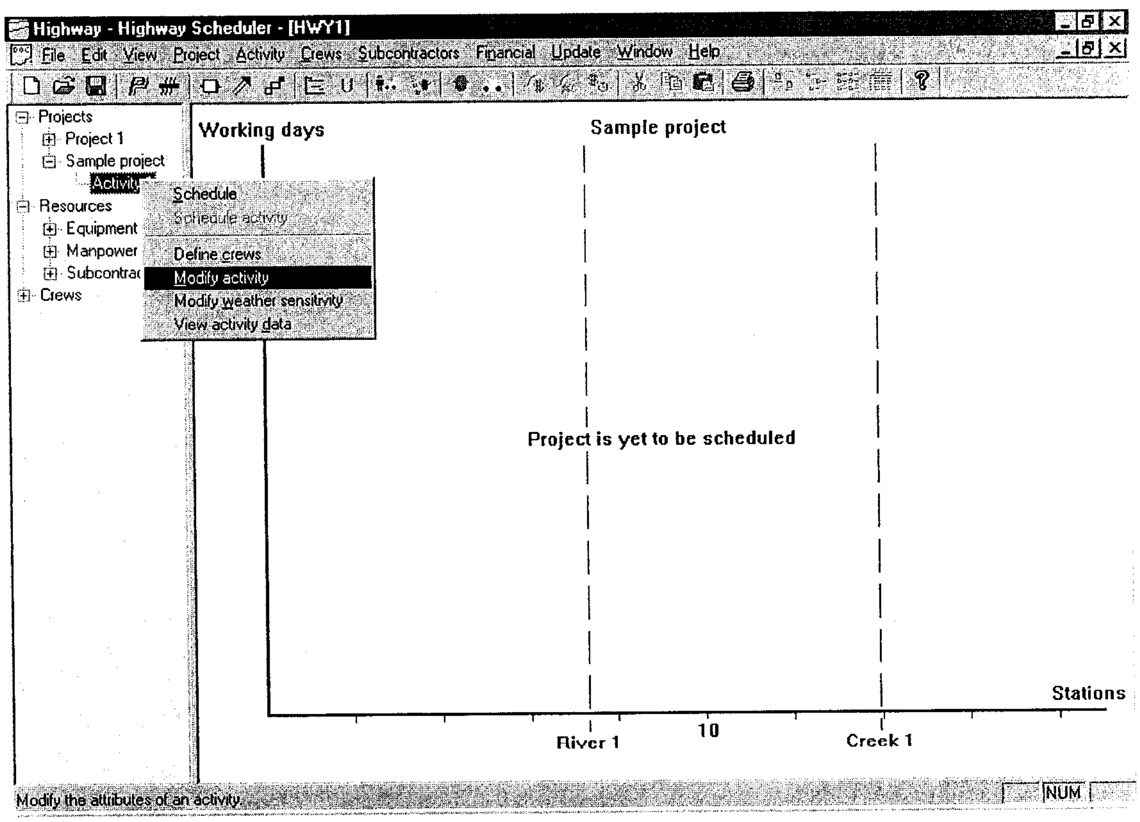


Figure 6.6: Floating menu for activities

6.3.2 Data Input

"HWPlanner" enables interactive input of project and activity data, as well as tab-delimited text files. The developed software is designed to facilitate definition of various project entities. The dialog window for inputting project data, shown in Figure 6.7, enables users to define most of the project specifications in a simple and efficient manner. As the figure shows, inputting data from a GIS file is allowed, providing the interface with "Analyser". If project data is not available in digital format, then project data such as highway length are input using the same dialog window.

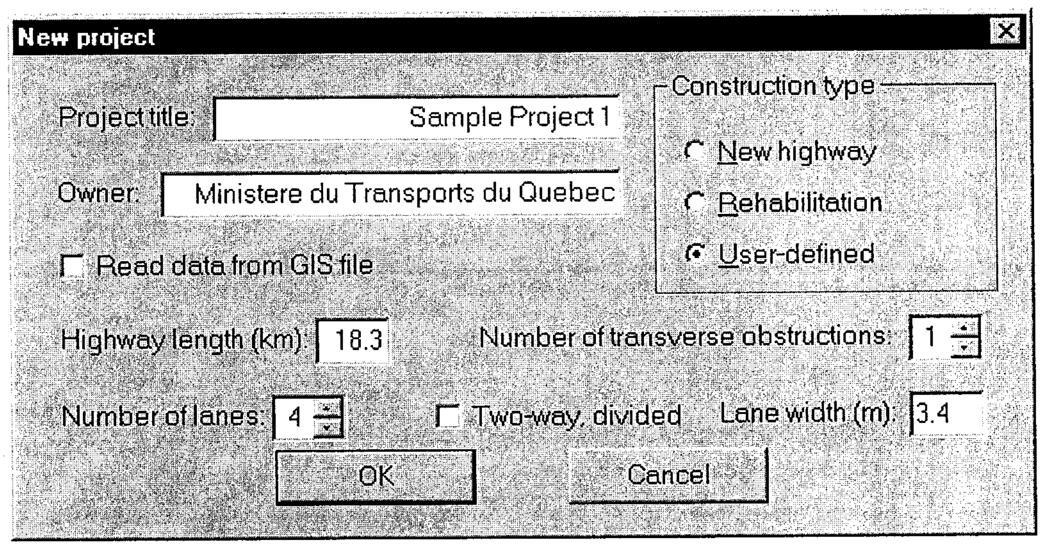


Figure 6.7: Dialog window designed to acquire project data

The definition of the project's mobilization matrix is carried out through the dialog window shown in Figure 6.8. A project can be further divided into segments by the user, and borders between segments can also be user-defined. Figure 6.9

shows the dialog window designed to define the boundaries separating project segments. The dialog window keeps re-appearing until the input station is equal to the total project length.

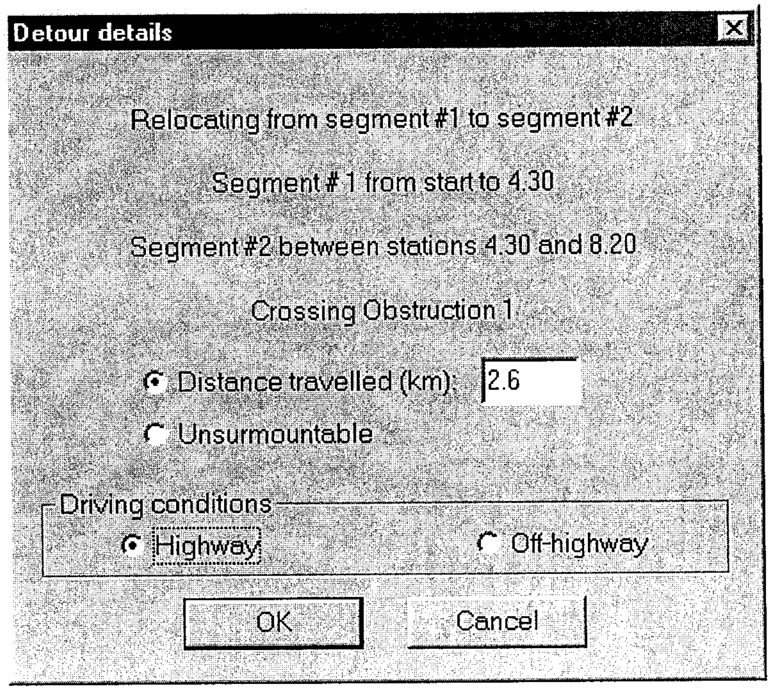


Figure 6.8: Dialog window designed to input travel distances between segments

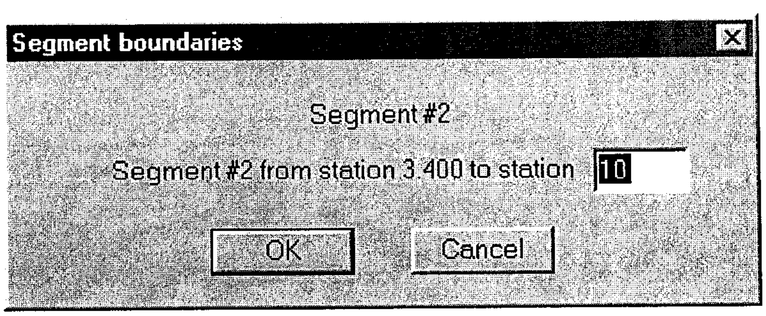
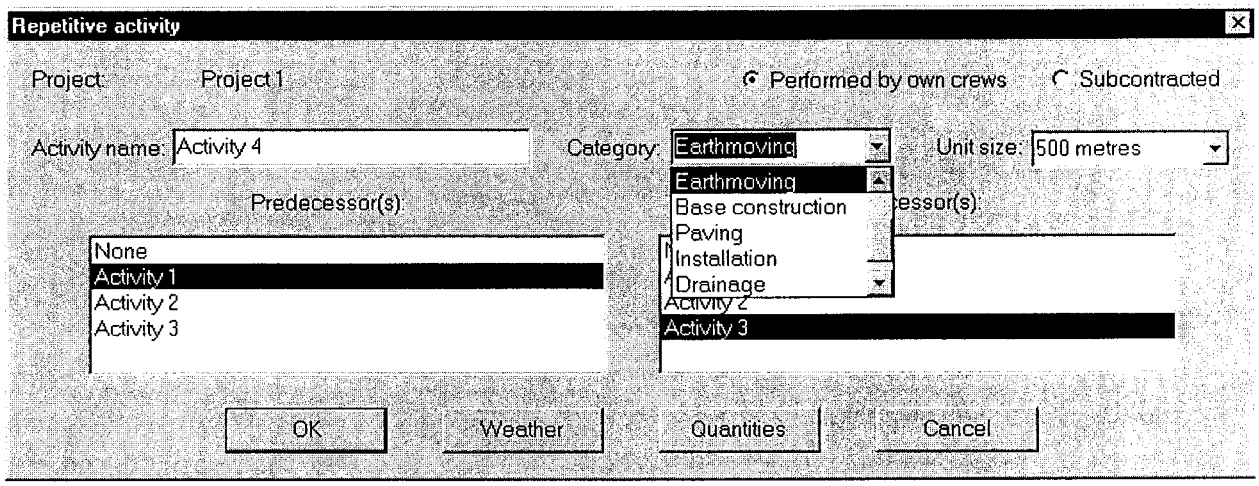
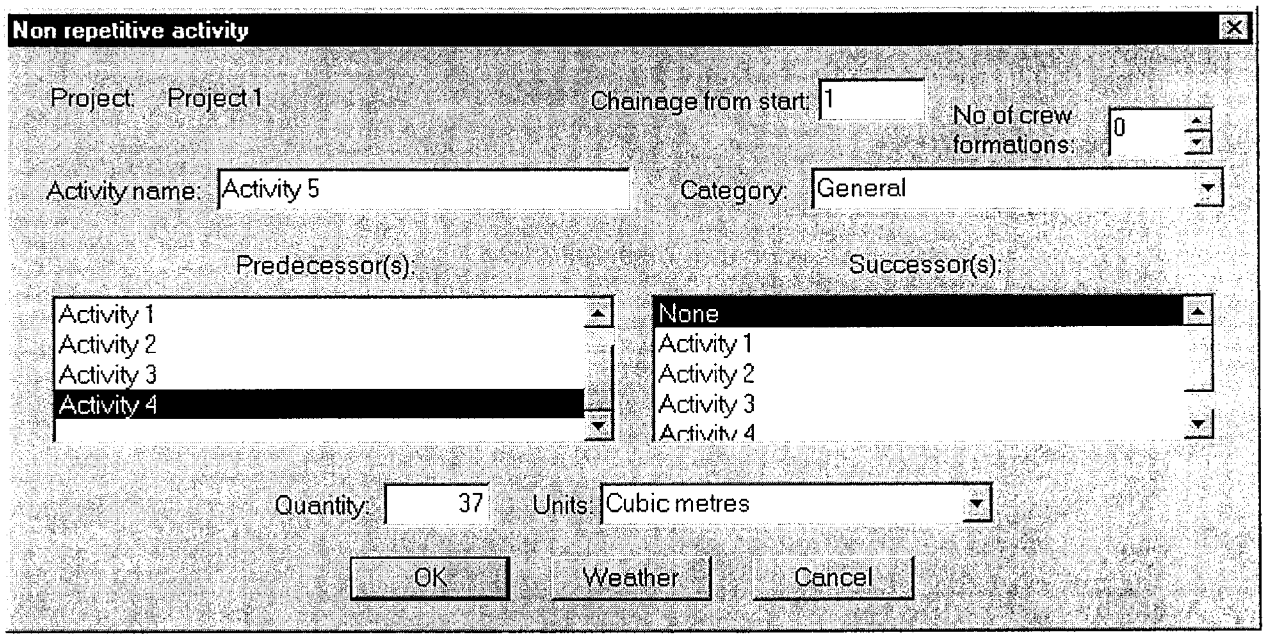


Figure 6.9: Dialog window designed to define segment boundaries

Figures 6.10(a) and (b) show dialog windows designed to input repetitive and non-repetitive activity data, respectively. As the figures show, list boxes are included depicting project activities to enable defining the precedence network. Multiple predecessors and successors can be defined. Upon updating the list of preceding activities, the list of potential succeeding activities is updated to avoid any logical errors (e.g. closed loops) in the network. The dialog window also contains a drop down list containing pre-defined categories. Figure 6.10(b) shows that a location needs to be defined for any non-repetitive activity. Figure 6.11 shows the dialog window employed to define quantities of work involved in repetitive activities. As mentioned earlier, measurement units (See Fig. 6.11) applicable to an activity depend on the category of that activity. The figure also shows that for the case of non-typical activities, quantities can either be input interactively or through a tab-delimited text file. The radio button "Same locations as" (See Fig. 6.11) enables defining quantities of work at locations where another activity has been defined, and setting the quantity of work in all other units to zero. This feature expedites data entry for sequential activities that are not carried out throughout the project. An example is the case where, certain locations are defined where a wearing surface is to be stripped. In this case, replacing the stripped asphalt need only be carried out at locations defined in the earlier activity (stripping wearing surface).



(a) Repetitive activity



(b) Non-Repetitive activity

Figure 6.10: Dialog windows designed to acquire activity data

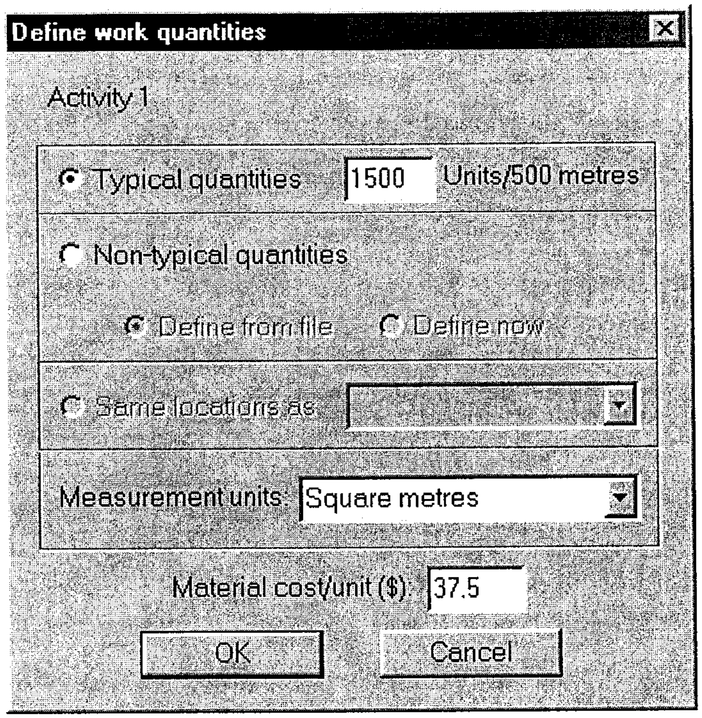


Figure 6.11: Dialog window designed to acquire quantities for repetitive activities

Upon clicking the "Weather" button in either of the dialog boxes shown in Figure 6.10, the dialog window shown in Figure 6.12 is activated. The window is designed to define the activity's sensitivity to various weather elements. The default values depend upon the selected category of the activity (Chapter Four), and are defined based on the findings of the survey discussed in Section 2.5, as well as the findings of earlier studies (NCHRP 1995; El-Rayes and Moselhi 2001(b)). A working range of temperature for each activity can be defined. Also upper limits for precipitation and wind speed can be defined. If any of the elements exceeds the working range, operation is halted altogether. Within the working range for the activity, crew productivity depends on the deviation from optimum weather conditions and to what degree the activity is sensitive to weather.

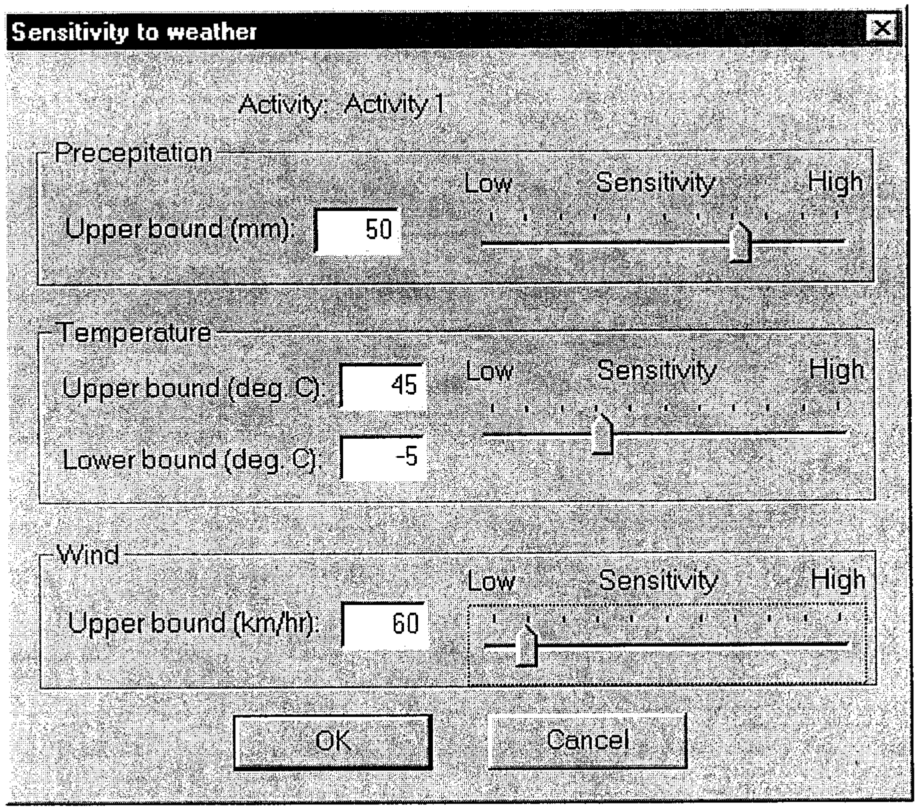


Figure 6.12: Dialog window designed to define activity sensitivity to weather

Figure 6.13 shows the dialog box designed to define crews. Two panes list available equipment and labour for the crew being defined. It is worth noting that the list of equipment and labour reflects the category of activities the crew is capable of performing ("Discipline" in Figure 6.13). Upon selecting a resource, a dialog window such as the one shown in Figure 6.14 is employed to define the selection criterion. To facilitate equipment selection the dialog window enables selecting a piece of equipment based on its model. If “Model” is selected in the list shown in the figure, the comparative radio buttons (“at least”, “at most” and “between”) are disabled, and a dropdown list containing all stored models is enabled.

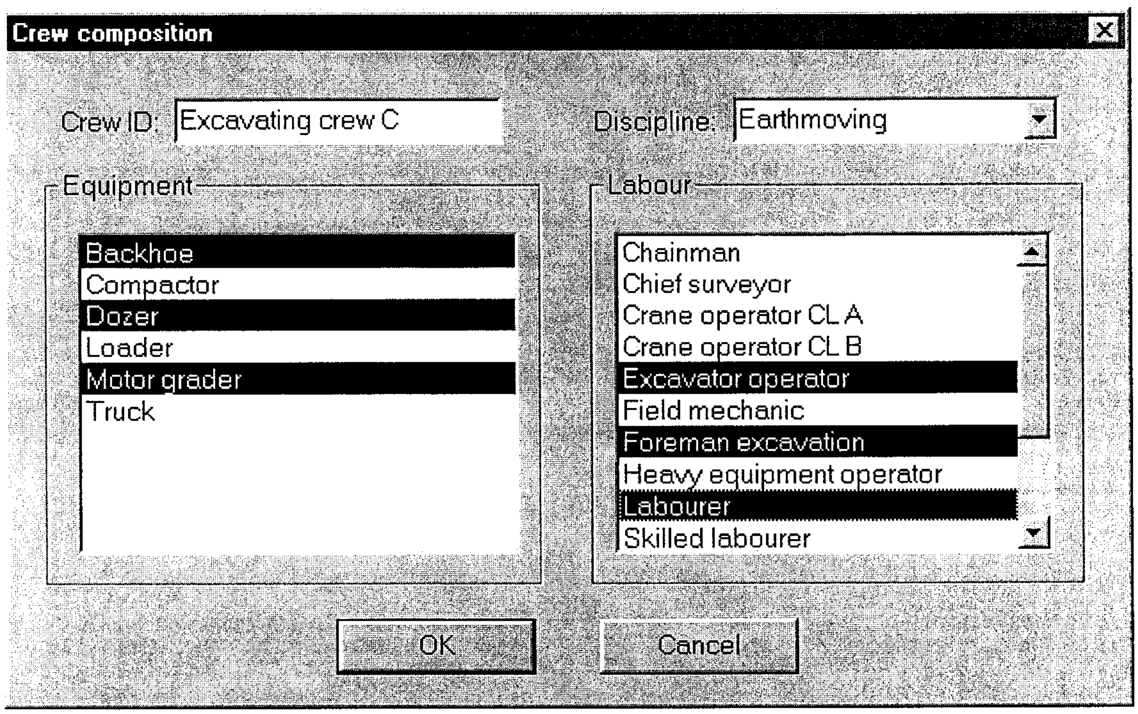


Figure 6.13: Dialog window designed to build crews

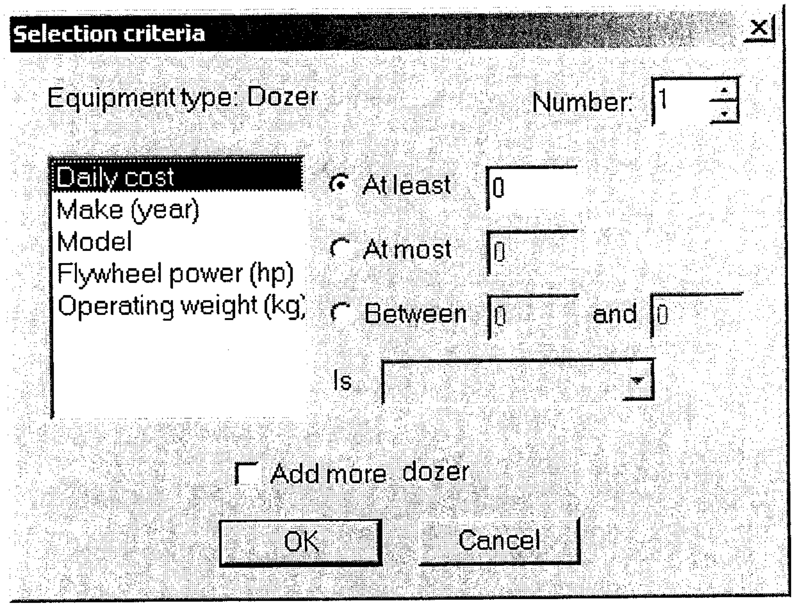


Figure 6.14: Dialog window to set selection criterion for dozers

Having defined the crew in terms of its components, the last step is to define its overall properties. Figure 6.15 shows the dialog window designed for this purpose. Daily equipment and labour cost, as well as mobilization data, are estimated by the software based on the selected resources, and can be updated by the user. Equipment and labour costs cannot be set to values less than those estimated by the model. Travel speed is evaluated based on the slowest crew component. The software, however, does not estimate the daily productivity of a crew based on its components. Minimum and maximum quantities of work that can be allotted to the crew are also defined using this window.

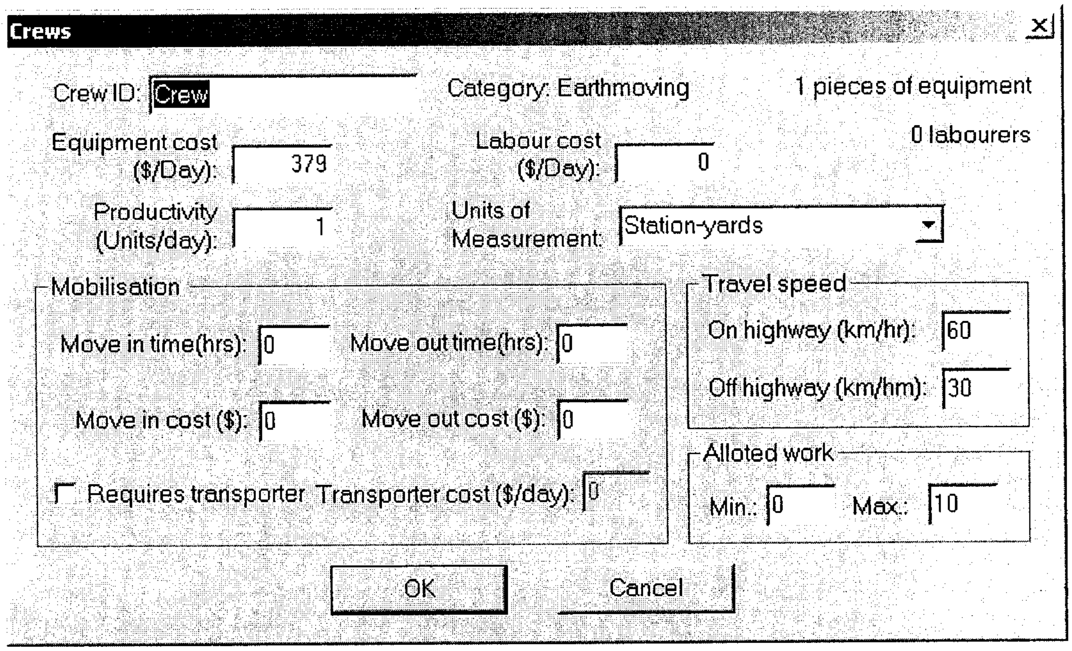


Figure 6.15: Dialog window designed to input crew data

As mentioned above, the units of measurement are limited to those typically used in that category. For example, the units of measurement defined for base construction are tons, square metres and longitudinal metres, while the measurement units defined for earthmoving operations are station-yards, tons, and loose, bank and compacted cubic metres. As discussed in Chapter Four, weather impact on an activity varies depending on the category of that activity, i.e. type of work performed in that activity.

6.3.3 Editing Project Entities

Project data is updateable, as are activity and crew data. Figures 6.16 and 6.17 show the dialog windows designed to report data of repetitive and non-repetitive activities, respectively. Upon selecting the "Modify" button, the dialog window designed to input activity data appears, and required modifications can be made. The size of a crew formation (number of crews comprising the formation) can be modified, as can particulars such as daily productivity. Modifications made to resources are immediately reflected in all crews employing that resource, minimising potential inconsistencies in data entry. For example, if the daily cost of a particular piece of equipment is modified, that modification is reflected automatically in all crews utilising that piece of equipment. It is worth noting that none of these editing features were available in the software developed earlier by El-Rayes (1997).

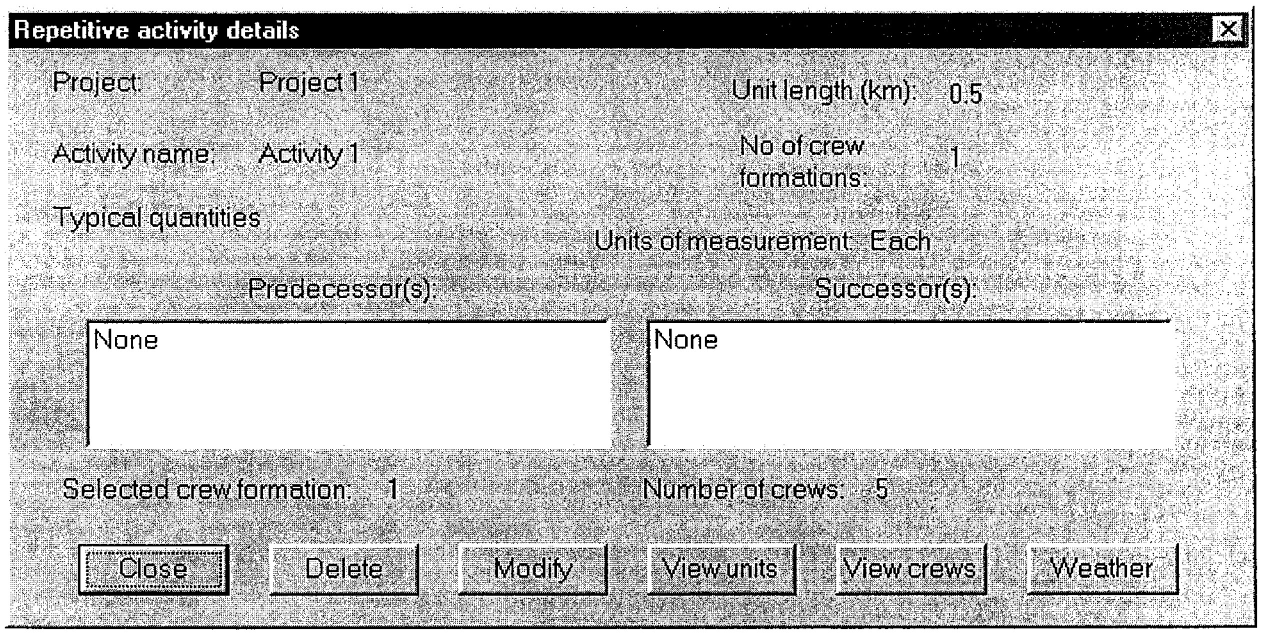


Figure 6.16: Dialog window reporting repetitive activity data

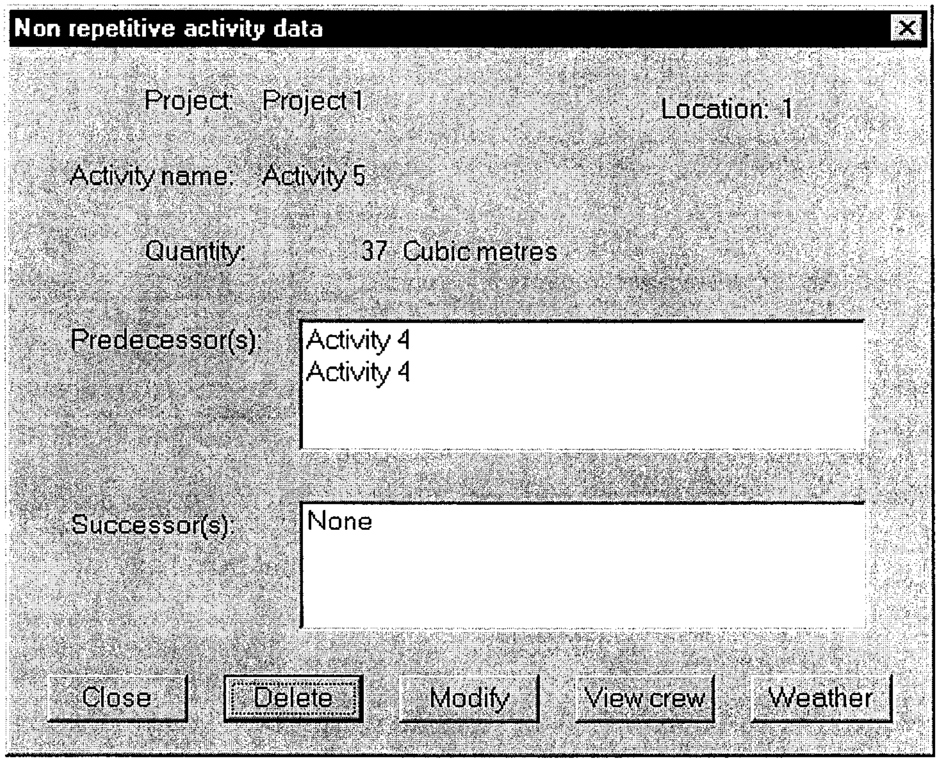


Figure 6.17: Dialog window reporting non-repetitive activity data

6.3.4 Updating Database

The developed software is fully integrated with a Microsoft Access 2000 database management system, facilitating adding and removing items to and from the database and editing entities already defined in the database. Figures 6.18 through 6.20 illustrate the process of adding a new piece of equipment (compactor) to the database. Upon selecting "*Add item to database*" under "*Crews*" menu, for example, the dialog window shown in Figure 6.18 is employed to select the type of item (equipment or labour) to be added. Upon selecting the type, the user is queried for the model of the new piece of equipment. Models defined in the database are listed along with the possibility of adding a new model, as shown in Figure 6.19. If a new model is to be added to the database, then particulars of that model need to be defined. The dialog window shown in Figure 6.20 is employed to acquire data of a new model of compactors. Other dialog windows were developed to acquire data regarding other equipment types, such as shown in Figure 6.21, which illustrates the dialog window designed to acquire data regarding a new backhoe. It is worth noting that the Microsoft Foundation Class, CRecordset, is employed in the developed software. This enables new entries or updates in the database to be instantly accessible to the software.

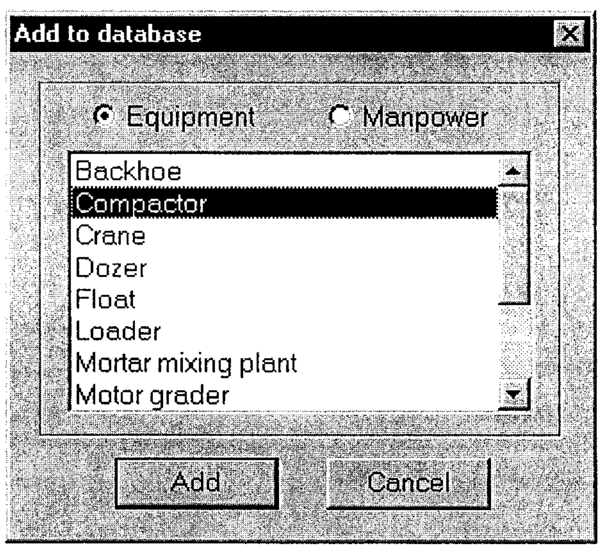


Figure 6.18: Dialog window designed to add item to database

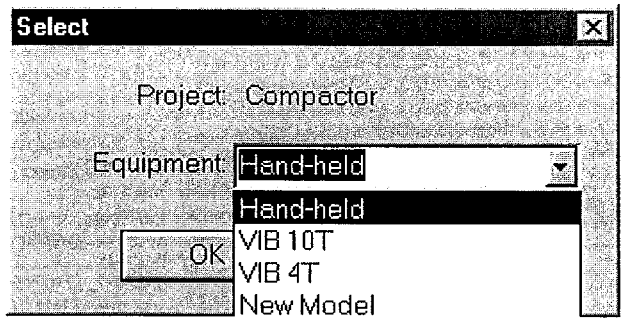


Figure 6.19: Selecting model type to add

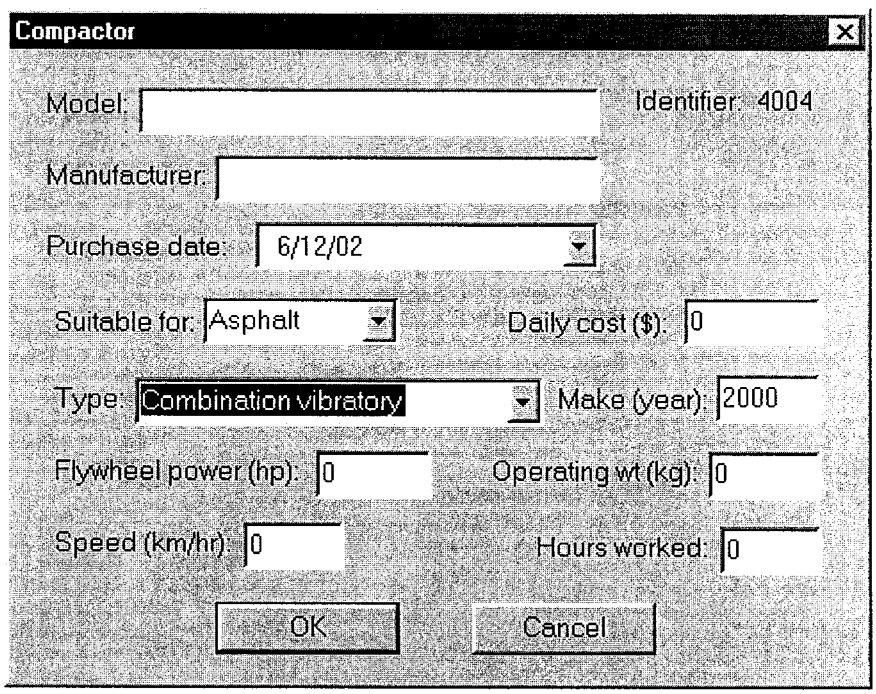


Figure 6.20: Dialog window designed to acquire new compactor model data

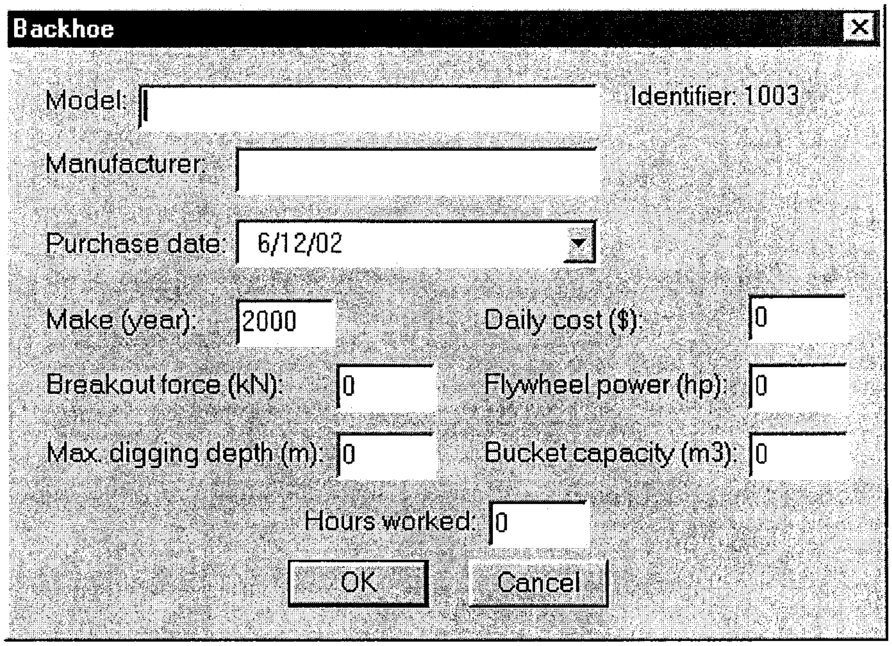


Figure 6.21: Dialog window designed to acquire new backhoe model data

In addition to own crews, the database is designed to store data regarding subcontractors. The dialog window designed to acquire subcontractor data is shown in Figure 6.22. In order to increase the flexibility of the software, multiple trades can be selected from the list at the bottom of the window. For each selected trade, expected productivity rate(s) and corresponding unit cost(s) should be defined. These can be obtained from previous experience with the subcontractor, industry averages from Means Construction Cost Data (1993), or consultations with known subcontractors.

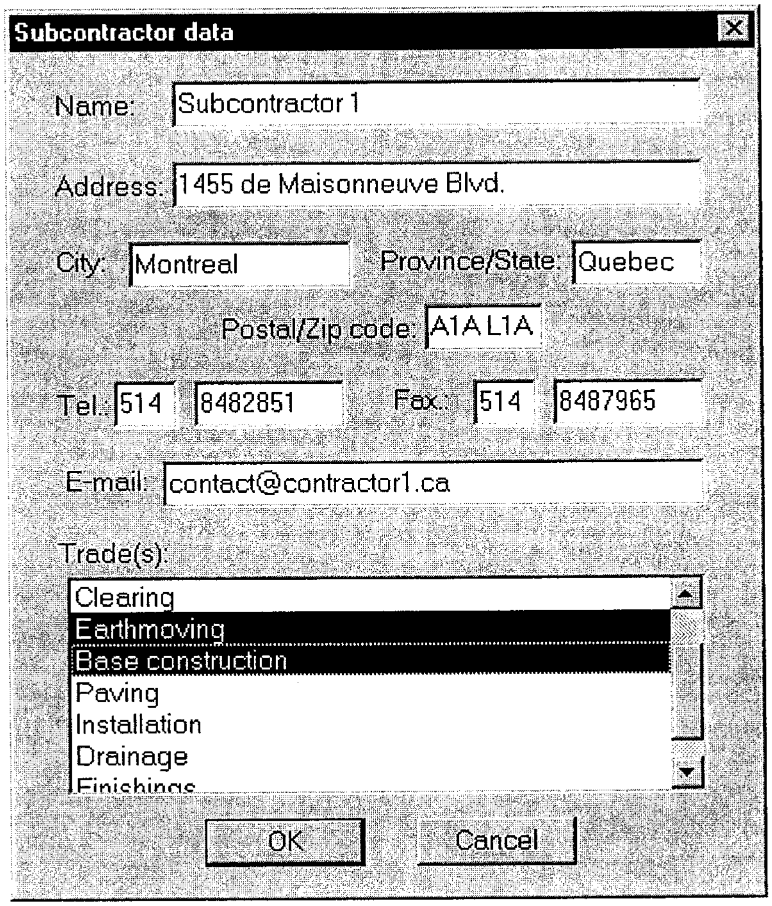


Figure 6.22: Dialog window designed to acquire subcontractor data

6.3.5 Progress Reporting

Chapter Three described the tracking and control module, and presented the methodology adopted to forecast future productivity rates. This methodology is implemented in the developed software in a user-friendly manner. Figure 6.23 shows the planned complete quantities at a reporting date for a sample project. The horizontal dashed line is drawn at the reporting date, and the schedule beyond it is shown in dashed lines. The table at the bottom of the figure lists quantities planned to be complete at the reporting date for each activity. Sixty percent of "Activity 1" is planned to be complete, while 46 % of "Activity 2" is planned to be complete. "Activity 3" is planned to commence on the reporting date. As the figure shows, zero percent is planned to be completed, while some costs have already been incurred. These are the mobilization and setup (if any) costs for the crew that is to perform the activity. It is worth noting that the second activity in the schedule shown in the latter figure is a time space activity (Stradal and Cacha 1982), and is therefore represented as a series of rectangles, indicating that the activity occupies significant portions of the project over relatively prolonged periods. Shaded portions of the rectangles indicate planned completion.

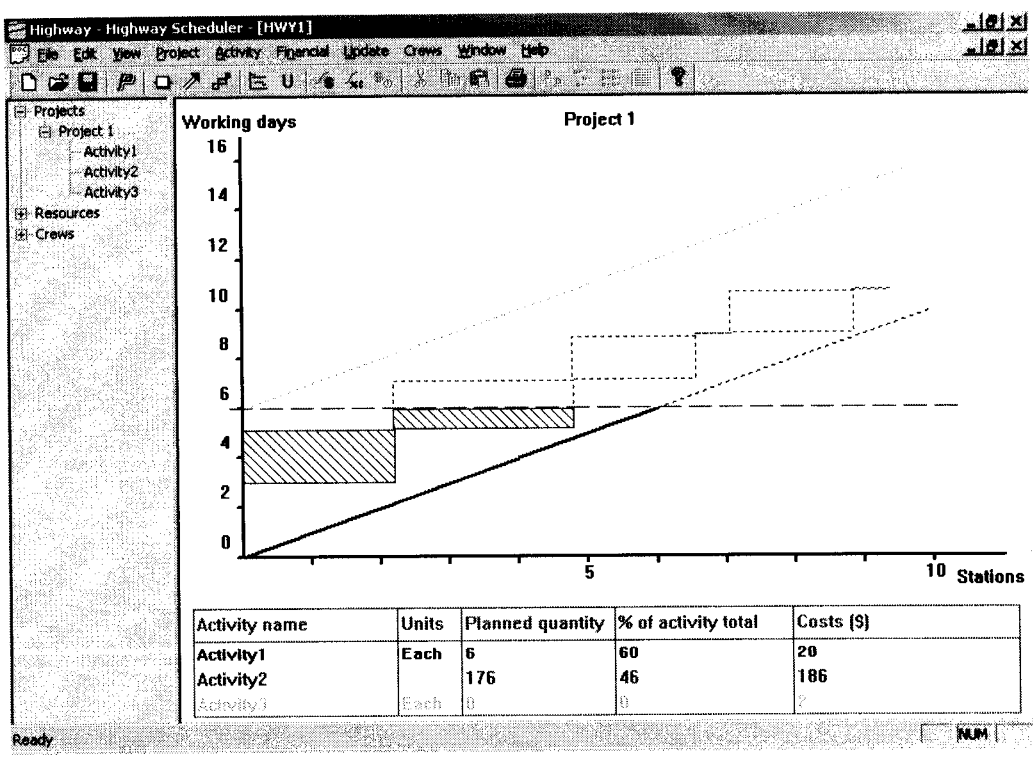


Figure 6.23: Planned progress at reporting date

6.4 System Validation

In order to validate the proposed system, three numerical examples are presented. The first is employed to validate "Analyser", as topographic data was available enabling the generation of DTMs representing ground terrain. The second and third are employed to validate the scheduling and optimization features of "HWPlanner".

6.4.1 Numerical Example I

In order to demonstrate the features of "Analyser", a 957-meter stretch of a recently constructed two-lane highway was analysed. The project involved the construction of a bridge and its east approach on Highway 364 across the Riviére Rouge at Huberdeau, near Arundel, Québec. The original topography and highway profile were input as AutoCAD drawings. Figure 6.24 depicts the original ground topography and the proposed highway route, while Figure 6.25 shows the highway profile. Borehole test results for this project were not available, therefore hypothetical soil data was used to demonstrate the model's ability to consider varying soil strata, as listed in Table 6.1.

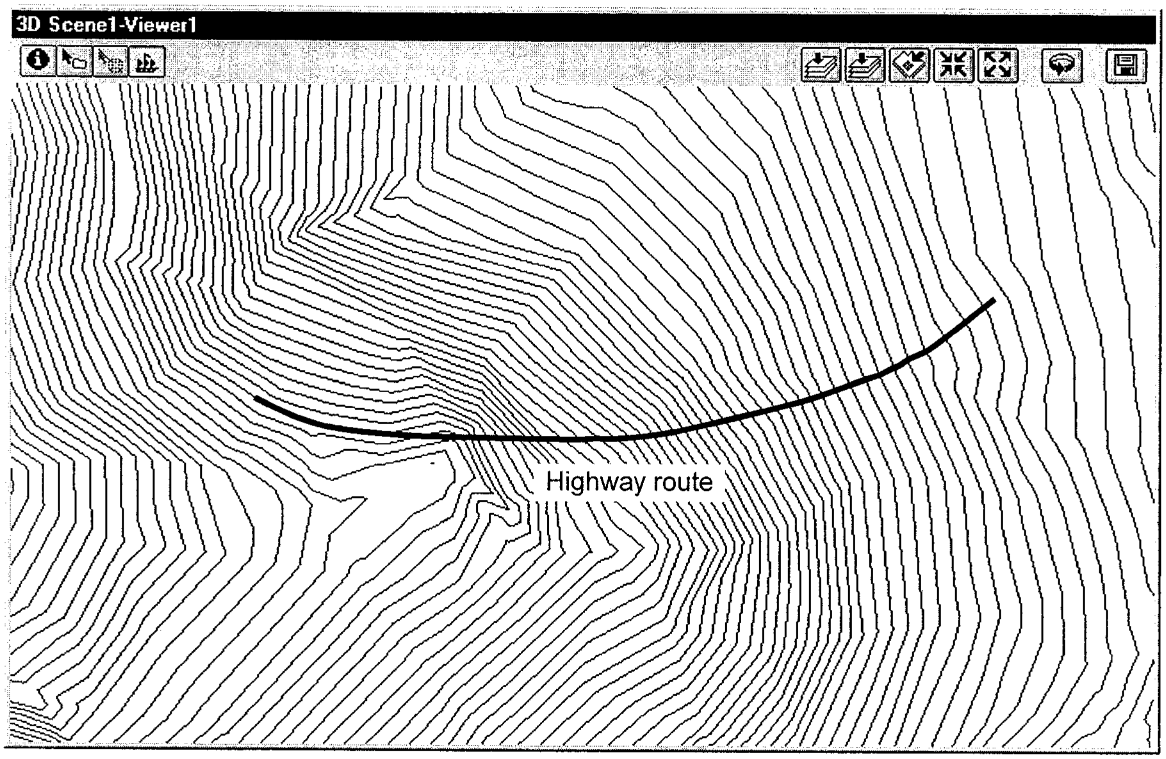


Figure 6.24: Original topography and highway route

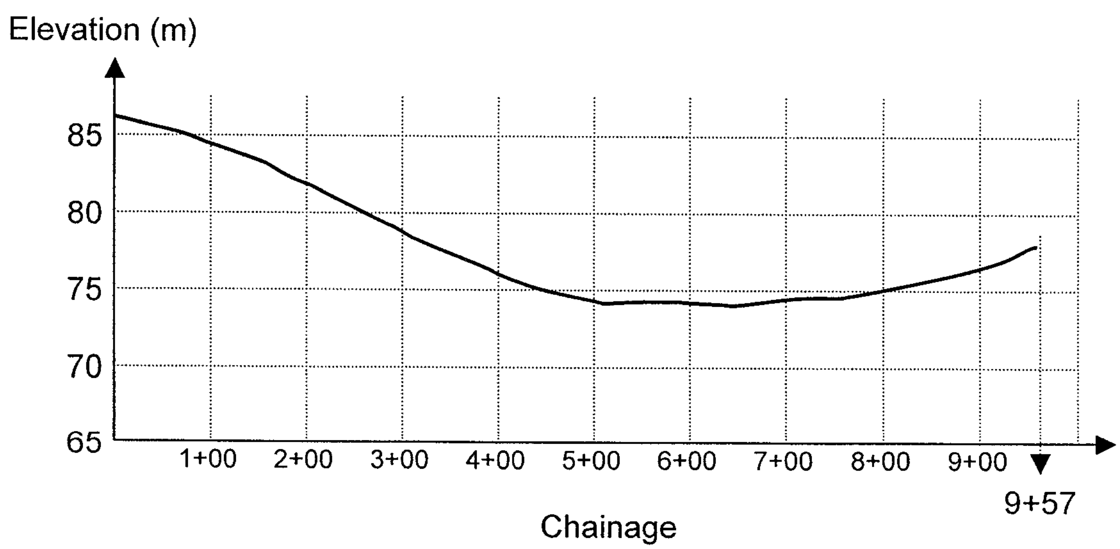


Figure 6.25: Highway profile

The developed model was employed to generate the strata profiles between boreholes as shown in Figure 6.26, and the resulting highway embankment (see Figure 6.27). It should be noted that the vertical scale in these two figures has been distorted to enhance visualisation. The calculated cut and fill quantities are displayed in three tables arranged as shown in Figure 6.28. The table entitled *"Statistics"* provides a summary of the total quantities of cut and fill in both loose and bank states, and reports the maximum cut and fill depths. The *"By Soil Types"* table reports the quantities of cut of each soil type in bank and loose states. The *"Earthmoving Summary"* table lists the quantities of cut or fill for each section along the highway route, individually and cumulatively. A detailed report of cut and fill quantities at each section is shown in Figure 6.29. The last column includes the net earthmoving quantities in loose cubic meters (LCM) for haul calculations. The proposed model also provides information regarding the location(s) at which a particular soil type is to be excavated. The data reported in the above-mentioned figures is expected to assist the user in selecting the appropriate excavation equipment and methods.

Table 6.1: Borehole test results

Borehole #	Dist from start (m)	Stratum #	Soil type	Thickness (m)
1	15	1	Silt	0.6
		2	Clay	0.9
		3	Silt	1.1
2	210	1	Sand	0.2
		2	Silt	0.8
		3	Clay	0.8
		4	Silt	0.6
3	350	1	Sand	0.2
		2	Silt	0.4
		3	Common earth	0.4
		4	Clay	0.6
		5	Silt	0.8
4	530	1	Silt	0.8
		2	Common earth	0.2
		3	Clay	0.6
		4	Silt	0.7
5	620	1	Silt	0.8
		2	Clay	0.7
		3	Silt	0.5
6	731	1	Silt	0.4
		2	Clay	1.0
		3	Sand	0.4
		4	Silt	0.6
7	948	1	Clay	1.0
		2	Sand	0.6
		3	Silt	0.8

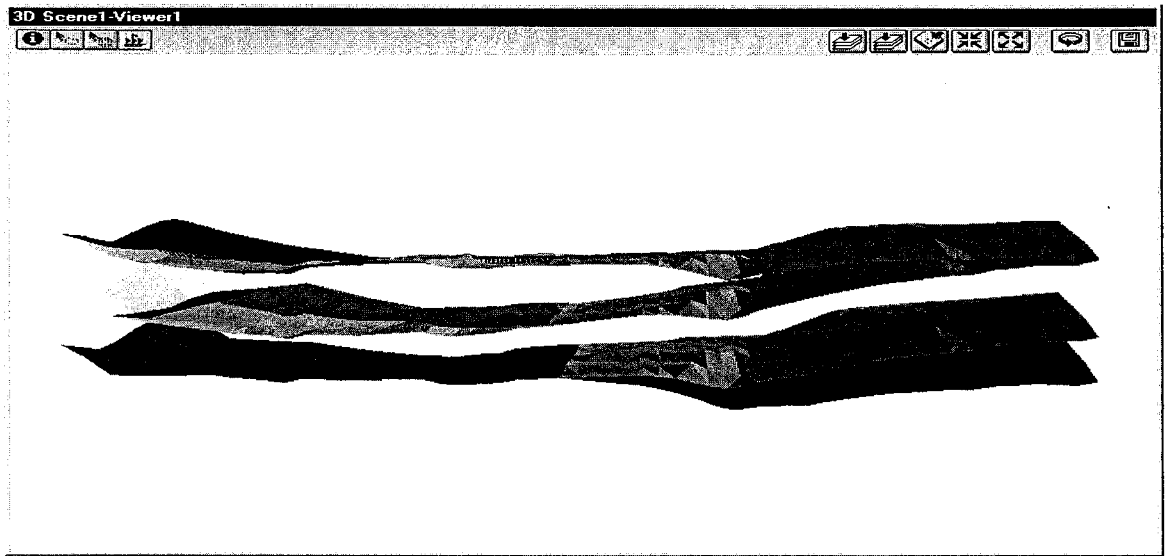


Figure 6.26: Generated strata profiles

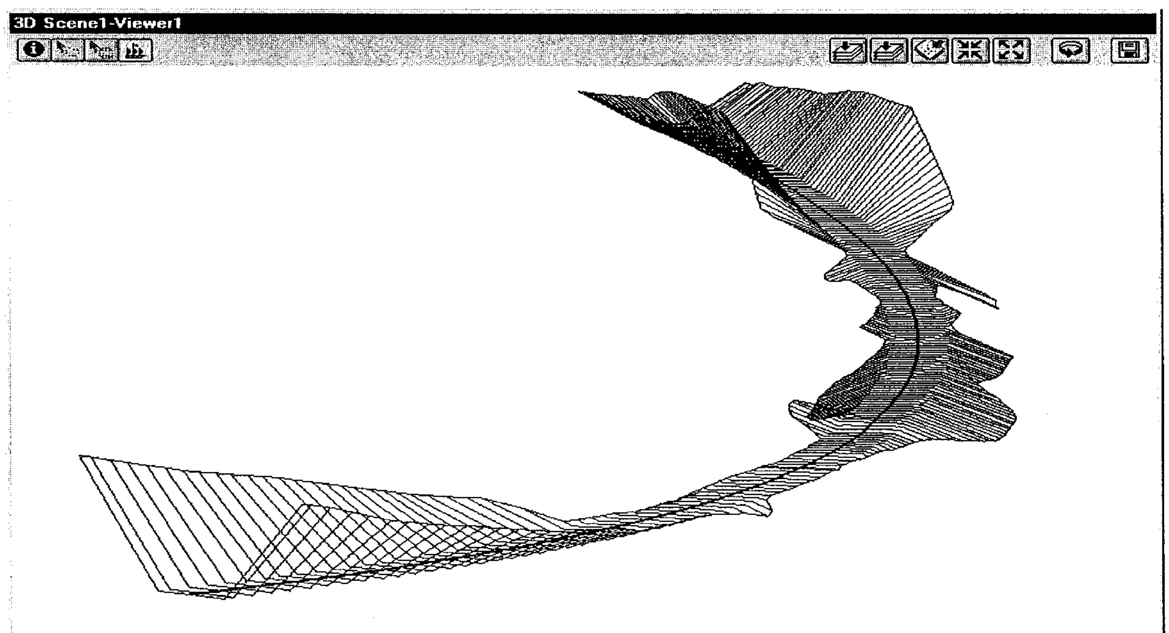


Figure 6.27: Generated highway embankment

The generated three-dimensional visualisation enhances the perception of the project, and can aid in determining the locations where different soil types are encountered. This could prove to be valuable information at the crew assignment stage. For example, crews responsible for excavating rock can be dispatched to the location(s) they are needed.

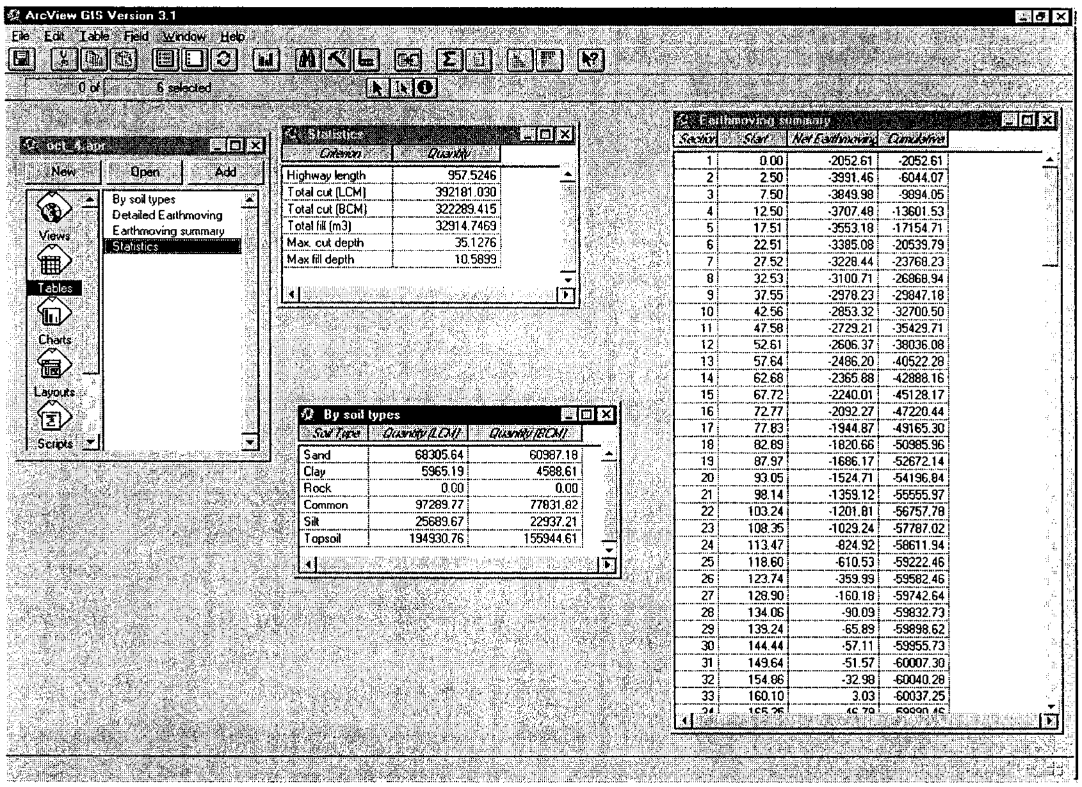


Figure 6.28: Earthmoving summary reports

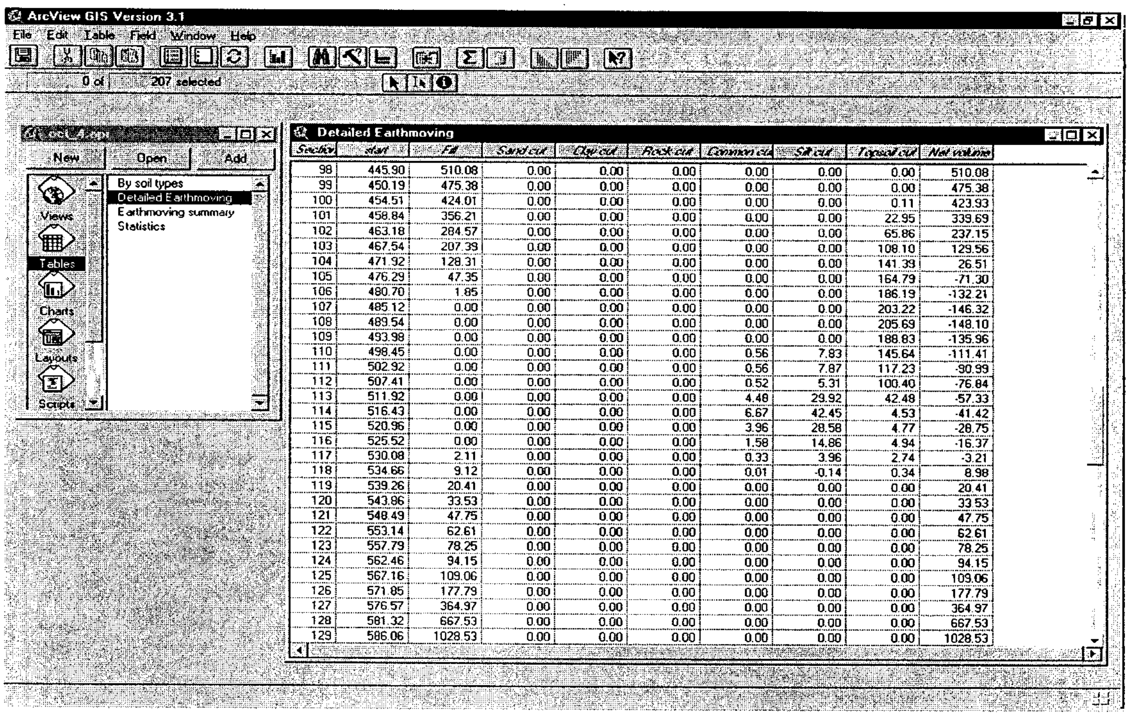


Figure 6.29: Detailed earthmoving report

6.4.2 Numerical Example II

In order to illustrate the use of the proposed scheduling algorithm and demonstrate its capabilities, an example highway project, drawn from the literature (El-Rayes 1997), is analysed. Five serial repetitive activities are considered in the construction of the 15-km stretch of the highway. These activities, in their order of precedence, are: 1) cut and chip trees; 2) grub and remove stumps; 3) excavation; 4) base; and 5) paving. All precedence relations are finish to start, with no lag time. The unit size of all activities is set to one (1.0) km, and the quantities associated with all activities are as shown in Table 6.2. Crews obtained from Means Construction Cost Data (1993) are assigned to the activities, and are summarized in Table 6.3.

Table 6.2: Quantities of work for numerical example II

Unit (km)	Cut and chip trees (m^3)	Grub and remove stumps (m^3)	Earthmoving (m^3)	Base (m^2)	Paving (m^2)
1	12,000	12,000	6,000	32,000	32,000
2	12,000	12,000	6,000	32,000	32,000
3	18,000	18,000	6,000	32,000	32,000
4	12,000	12,000	7,000	32,000	32,000
5	18,000	18,000	8,600	32,000	32,000
6	30,000	30,000	7,000	32,000	32,000
7	36,000	36,000	6,500	32,000	32,000
8	30,000	30,000	6,000	32,000	32,000
9	24,000	24,000	6,000	32,000	32,000
10	24,000	24,000	6,000	32,000	32,000
11	18,000	18,000	6,000	32,000	32,000
12	12,000	12,000	6,000	32,000	32,000
13	12,000	12,000	6,000	32,000	32,000
14	12,000	12,000	6,000	32,000	32,000
15	12,000	12,000	6,000	32,000	32,000

Table 6.3: Crew data for numerical example II

Activity	Crew #	Crew ID (Means)	Daily productivity (units/day)	Earliest available date	Latest available date
Cut and chip trees	1	B-7	3,000	0	*
	2	B-7	3,000	0	*
	3	B-7	3,000	0	18
	3	B-7	3,000	24	40
Grub and remove stumps	1	B-30	4,000	0	*
	2	B-30	4,000	0	*
Earthmoving	1	2 × B33-F	1,200	10	70
	2	2 × B33-F	800	10	70
Base	1	B-36	3,200	26	*
	2	B-36	3,200	26	*
	3	B-36	3,200	26	*
	4	B-36	3,200	26	*
Paving	1	B-25	4,000	0	*
	2	B-25	4,000	0	*
	3	B-25	4,000	0	*

* crew is available till project completion

The generated schedule is shown in Figure 6.30. It can be reproduced in the commonly used bar chart format for easier reference. The developed software generates bar (Gantt) charts and crew assignments in calendar dates as shown in Figures 6.31 and 6.32, respectively.

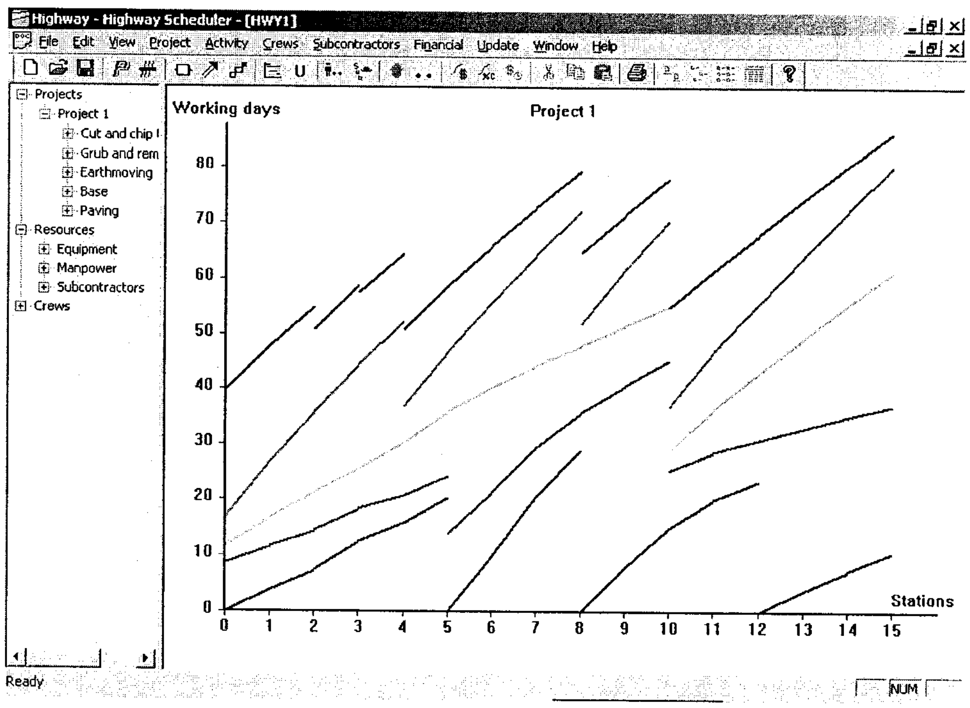


Figure 6.30: Linear schedule for numerical example II

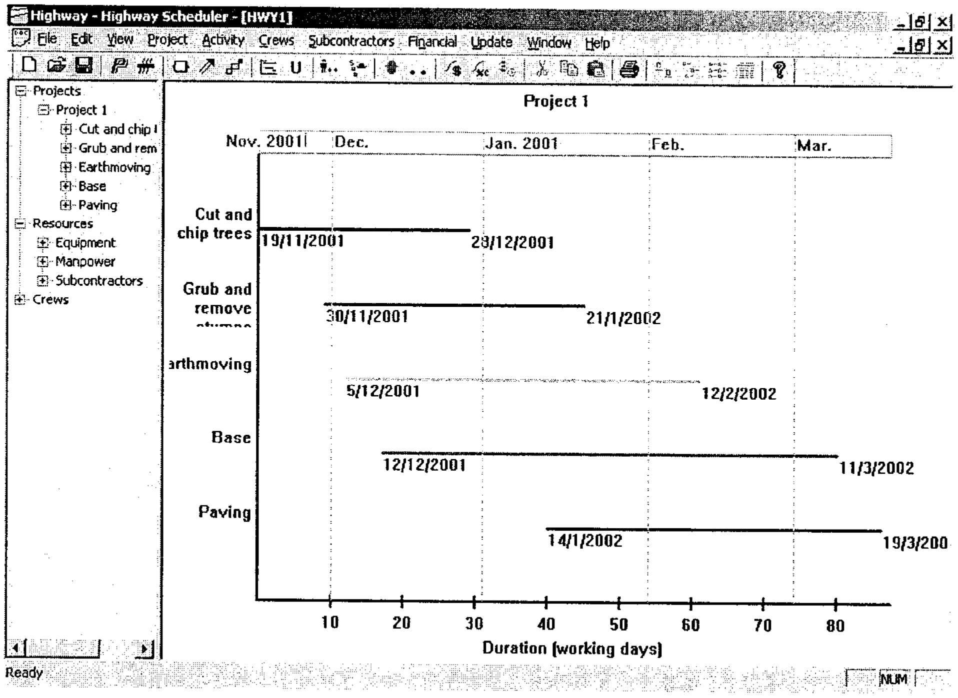


Figure 6.31: Bar (Gantt) chart for numerical example II

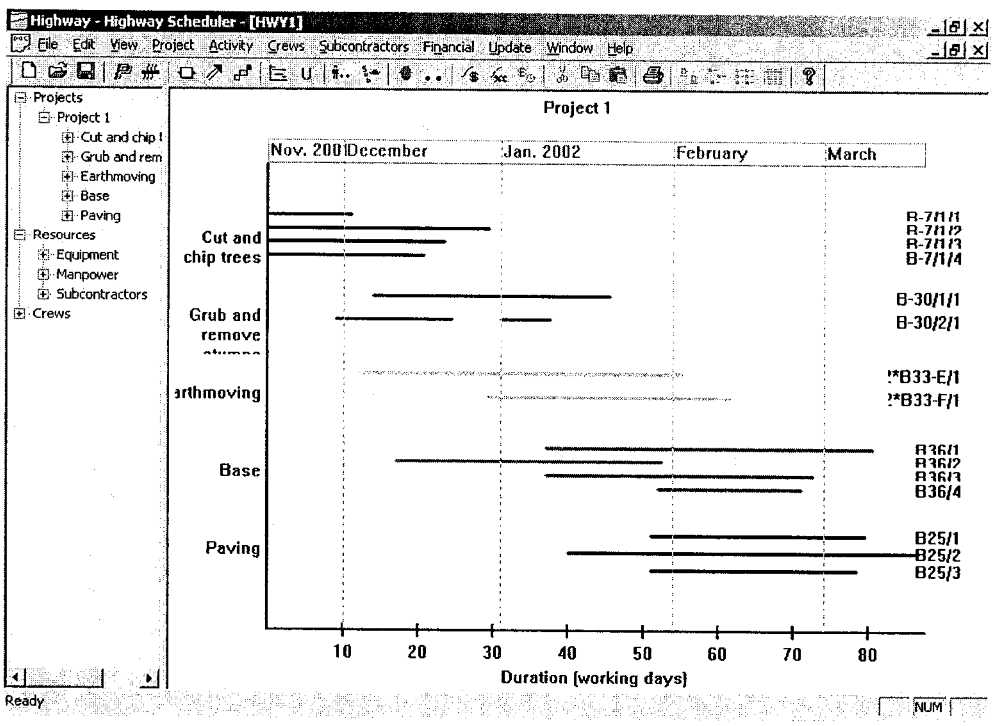


Figure 6.32: Crew assignment schedule for numerical example II

The overall project duration was estimated to be 87 working days, a slight increase over that reported in the original example (83 days). This is attributed to the use of interruption vectors in the original example, which are not considered in the proposed model. However, the developed schedule has two practical advantages over its predecessor, which are:

1. The developed schedule assigns each crew a group of adjacent units. As mentioned earlier, assigning crews in an alternating manner is an impractical assignment scheme for linear projects. This is due to the additional travel time and cost, along with the losses in the learning process due to frequent interruptions.
2. The developed schedule maintains work continuity of all employed crews. In order to reduce the overall project duration, the previous study had allowed a total of four days interruption for the "grub and remove stumps" activity. As mentioned earlier, work interruption results in inefficient resource utilization, idle costs, additional mobilization/demobilization costs, and not fully benefit from the learning curve effect.

In order to illustrate the impact of transverse obstructions on crew assignments and overall project duration, three transverse obstructions were introduced at stations 4, 7.2 and 10.3. The second obstruction (station 7.2) is considered insurmountable, and additional travel distances to overcome the first and third obstructions are 4.8 and 3.2 km, respectively. The mobilization matrix is thus expressed as:

$$M_{(4\times4)} = \left\{ \begin{matrix} 100 & 4.8 & -1 & -1 \\ 0 & 100 & -1 & -1 \\ -1 & -1 & 100 & 3.2 \\ -1 & -1 & 1 & 100 \end{matrix} \right\} \qquad (6.1)$$

The project duration considering obstructions was found to be 89 working days, based on the schedule shown in Figure 6.33. The figure shows that crew assignments have been altered to minimize mobilization/demobilization time and cost, at the cost of a slight increase in total project duration. For example, activity "grub and remove stumps" was divided into three segments in the first scenario, and work was equally shared by identical crews. When transverse obstructions were introduced one crew was assigned to each of the work zones, resulting in a prolonged construction schedule.

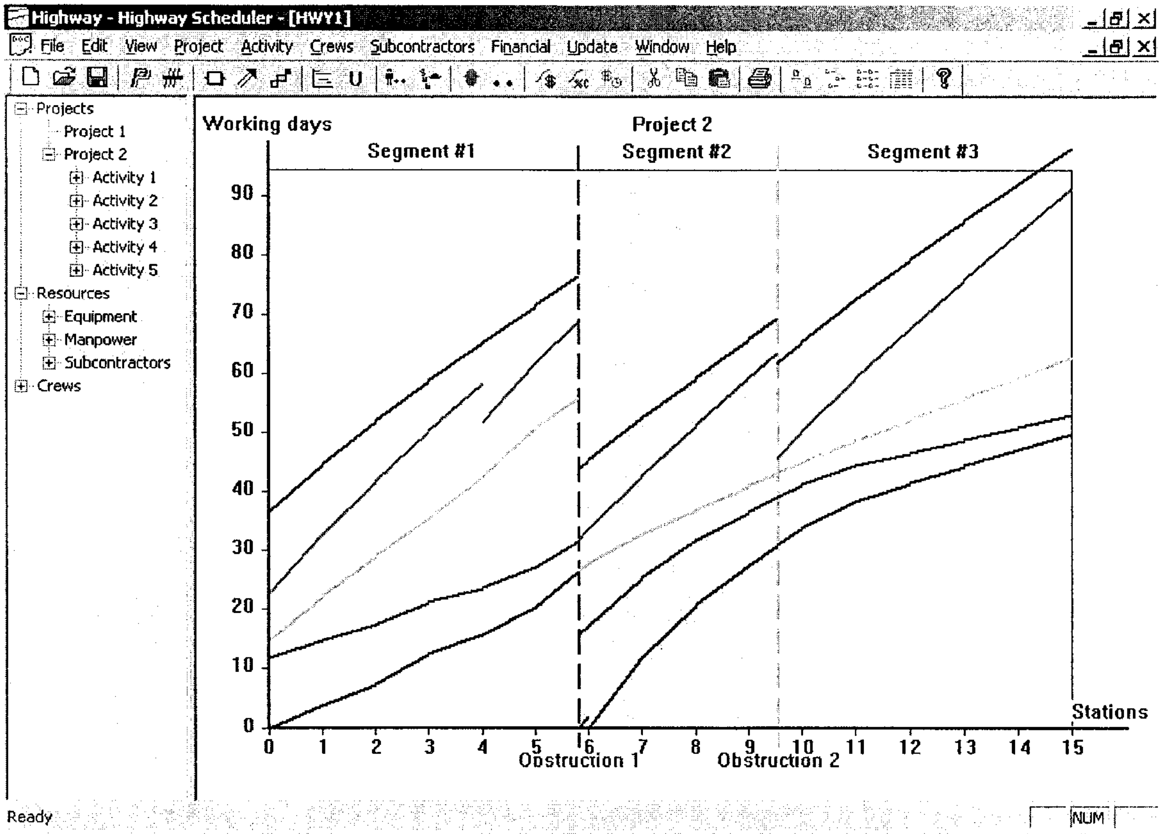


Figure 6.33: Linear schedule considering two transverse obstructions

6.4.3 Numerical Example III

This example is a pipeline rehabilitation project undertaken by a major Canadian contractor (SNC-Lavalin), still under construction in the Middle East. The total project length is approximately 310 km, with an estimated 1,500 pipe segments to be replaced (each has a length of 7.5 m). Construction equipment was to be provided according to a pre-set timetable, as shown in Table 6.4. The developed model was used to schedule the project, which had the precedence network shown in Figure 6.34.

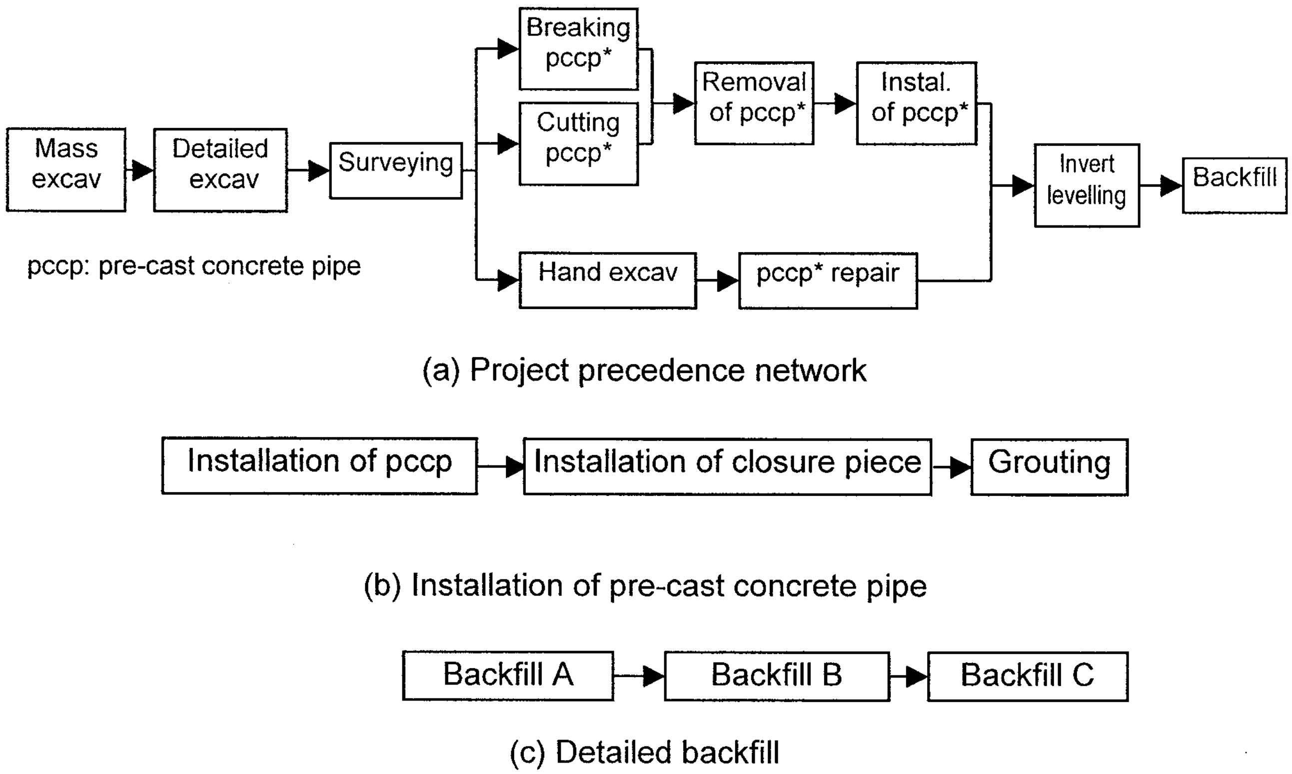


Figure 6.34: Precedence networks for numerical example III

Upon exposing a pipe, the decision was then made to either replace or apply a layer of paint, based on the condition of that pipe. Upon replacing defected pipes, a closure piece is installed. Due to confidentiality, no cost data is presented in this example. The main objective of the contractor was to complete construction within nine (9) months, respecting the equipment delivery schedule given in Table 6.4. Work was to progress seven days a week, working single shifts, enabling multiple crews to be working simultaneously on any repetitive activity. Particulars of crews assigned to each activity are shown in Table 6.5. Weather impact on productivity was not considered, but the effect of the learning curve was accounted for in preparing the project schedule.

Table 6.4: Equipment delivery dates for numerical example III

Description	Qty	Make	Model	ETA at port
Hydraulic Excavator Long Reach	1	Caterpillar	325B/L	20-Aug-00
Hydraulic Excavator Long Reach	3	Caterpillar	325B/L	30-Sep-00
Hydraulic Excavator Long Reach	4	Caterpillar	325B/L	30-Oct-00
Hydraulic Excavator	10	Caterpillar	330B/L	20-Jul-00
Hydraulic Excavator	2	Caterpillar	330B/L	20-Aug-00
Hydraulic Excavator	1	Caterpillar	330B/L	30-Sep-00
Mass Excavator	2	Caterpillar	375ME	20-Aug-00
Low Bed Trailer	1	Doll	3DSAT64	30-Dec-00
Wheel Loader	10	Caterpillar	972G	20-Jul-00
AT Crane	1	Tadano	ATF120-5	30-Oct-00
Clamshell Bucket for 325B/L	1	Caterpillar	Clamshell	20-Aug-00
Clamshell Bucket for 325B/L	2	Caterpillar	Clamshell	30-Oct-00
Hand Held Compactor	16	Dynapac	Compactor	20-Jul-00
Vibratory Compactor 10t	4	Bomag	Compactor	20-Jul-00
Vibratory Compactor 4t	2	Bomag	Compactor	20-Jul-00
Dozer	6	Komatsu	D155A-5	30-Sep-00
Float	5	Renault	Float	25-Dec-00
Grader	4	Komatsu	GD705A-4	30-Sep-00
Hammer for 330B/L	2	Caterpillar	Hammer	20-Jul-00
Mortar Mixing Plant	2	KYC	Mortar	25-Aug-00
Dump Trucks	6	MAN	Trucks	30-Dec-00
Vibro plate for 325B/L	2	Caterpillar	Vibro	30-Sep-00
Vibro plate for 325B/L	4	Caterpillar	Vibro	30-Oct-00
Water Tanker	4	Renault	Water	25-Dec-00
Welding Machine	16	Genset PLC	Welding	20-Aug-00

Table 6.5: Crew data for numerical example III

Activity	Number of crews	Productivity (of each crew)
Mass excavation	1	1000 m^3/hr
Detailed excavation	4	200 m^3/hr
Surveying	3	N/A
Hand excavation	3	4 m^3/hr
Repair	1	40 units/hr
Breaking pccp	1	1 pipe/day
Cutting pccp	1	1 pipe/day
Removal of pccp	1	2 pipes/hr
Installation of pccp	1	2 pipes/hr
Installation of closure piece	1	1 pipe/day
Grouting	2	2 pipes/hr
Invert levelling	2	1 pipe/hr
Backfill A	2	150 m^3/hr
Backfill B	2	280 m^3/hr
Backfill C	2	480 m^3/hr

The proposed software was employed to generate a schedule satisfying the above-stated objective and Figure 6.35 shows the generated linear schedule. As the figure shows, the overall duration is 279 working days, meeting the scheduling objectives (7-day work week). Figure 6.36 shows the generated bar (Gantt) chart along with calendar dates, showing that project would be completed on July 11.

6.5 Summary

This chapter presented the computer implementation and validation stages of the developed system. Object-oriented programming is employed and the system operates in Windows 95, 98, 2000 and NT environments. The GIS sub-module, "Analyser", is implemented in ArcView Version 3.1 and coded using the computer language “Avenue” (ESRI 1997). Three-dimensional data analysis is carried out employing ArcView® 3D Analyst. All other modules are contained within “HWPlanner”, which is coded in Visual C++ utilising Microsoft foundation classes. The user interface incorporates menus, toolbars, a status bar and dialog windows, and supports multiple document interface. Microsoft Access 2000 is employed as the database management system. Three numerical examples were introduced to validate the system and illustrate its use and capabilities.

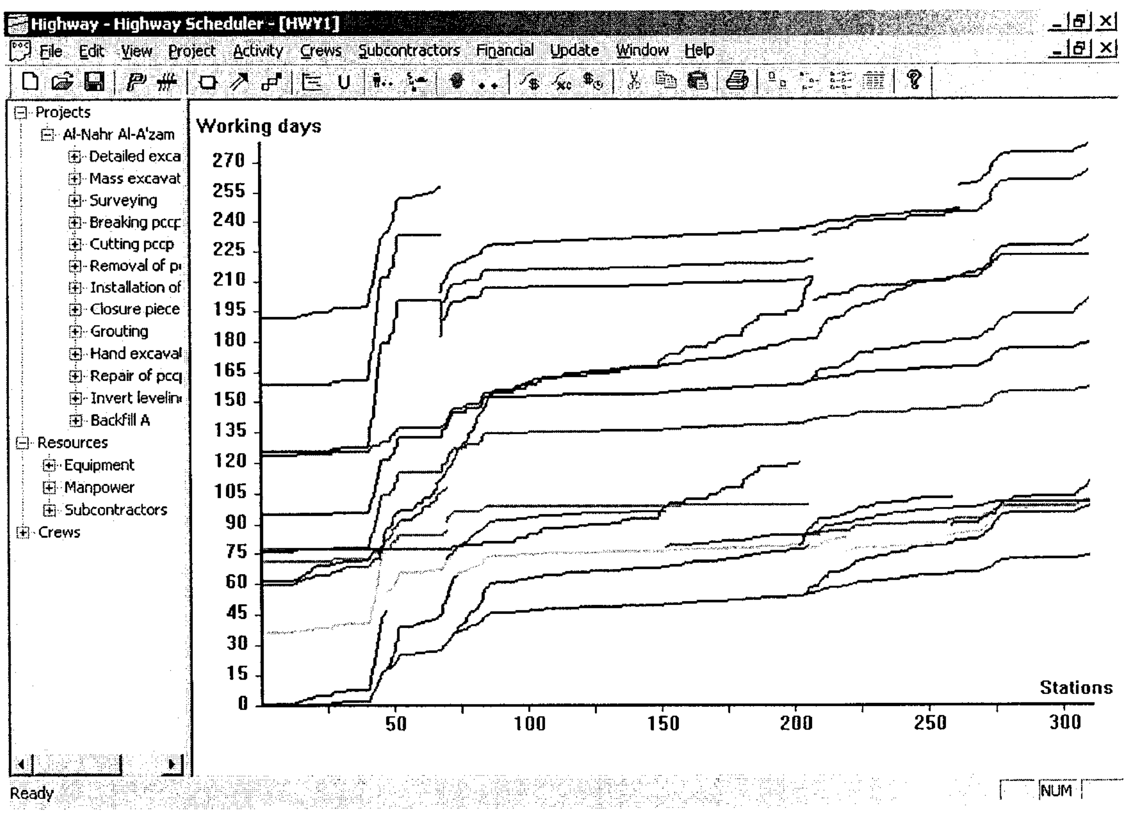


Figure 6.35: Generated linear schedule for numerical example III

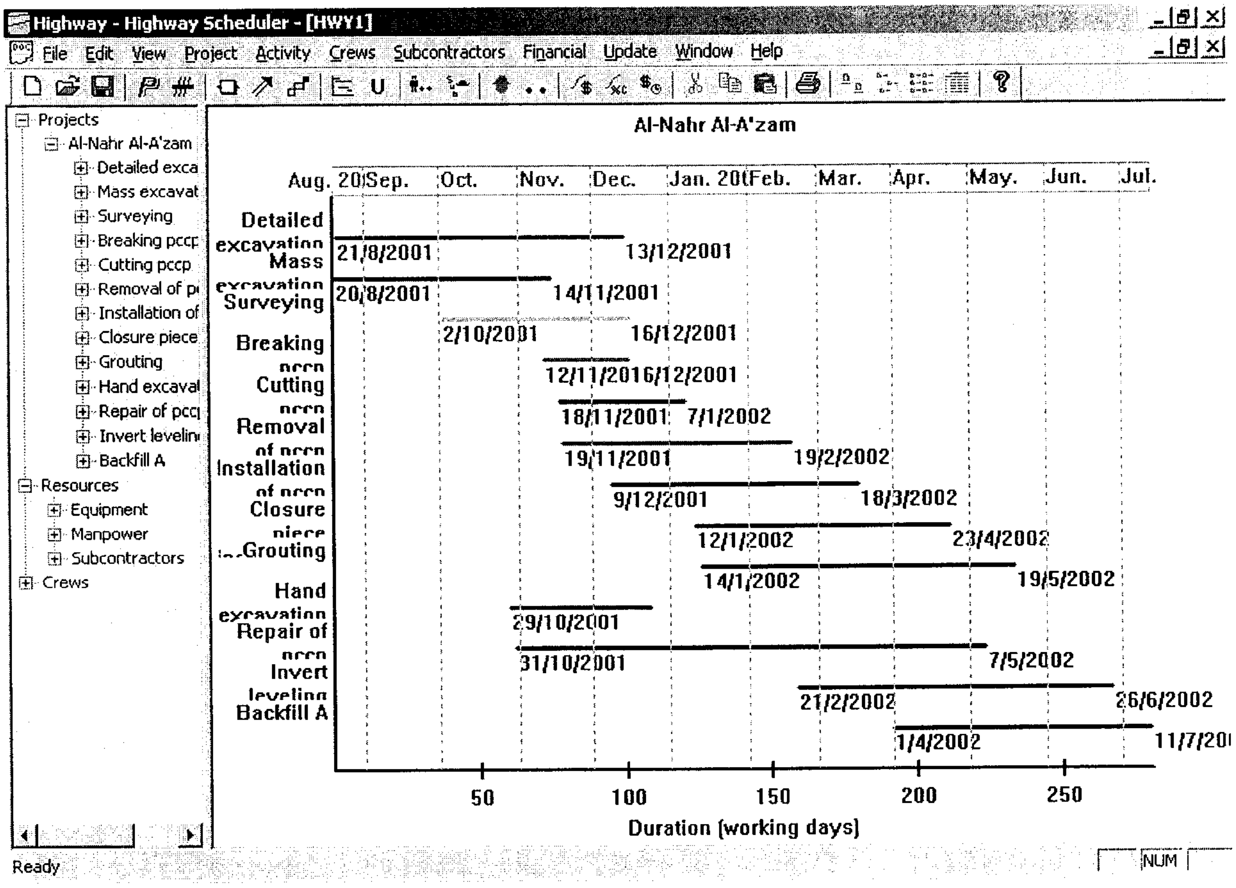


Figure 6.36: Bar (Gantt) chart for numerical example III

CHAPTER SEVEN

SUMMARY AND CONCLUDING REMARKS

7.1 Summary

This study presents an object-oriented model, designed to aid highway construction personnel in planning and scheduling highway construction projects. The model estimates the quantities of cut and fill for earthmoving operations, and employs a two-state-variable, N-stage, dynamic programming formulation, coupled with a set of heuristic rules, to generate practical, near-optimal schedules. At the core of the model is a relational database storing data regarding: 1) available resources; 2) local weather conditions; and 3) soil swell and shrinkage factors. The model optimizes either: 1) project construction duration; 2) total cost; or 3) their combined impact for what is known as cost-plus-time bidding, also referred to as A+B bidding (Herbsman 1995). It can also generate schedules that satisfy budget or duration constraints, if feasible. The model proposes a methodology identify critical activities, and identify the expediting strategy that would best expedite construction. A new methodology to forecast project time and cost at completion is proposed, enabling the assignment of higher weights to recent crew performance when forecasting future productivity.

The model is composed of five modules: 1) data acquisition; 2) database; 3) planning and scheduling; 4) tracking and control; and 5) reporting modules. The data acquisition module is composed of the GIS and GUI sub-modules. The former is responsible of acquiring and analysing spatial data, and generating optimized earthmoving plans using the mass haul diagram. It accounts for the presence of different soil strata, as well as natural and/or man-made obstructions affecting earthmoving plans. The latter, on the other hand, is responsible for acquiring non-graphic data. The planning and scheduling enables automated generation of the precedence network for highway construction. The scheduling methodology extends on the work carried out earlier by El-Rayes (1997). It is resource-driven, and incorporates both repetitive and non-repetitive activities in the optimization procedure. It accounts for: 1) the impact of transverse obstructions on crew assignments; 2) resource availability; 3) multiple predecessor and successor activities with specified lead and lag times; 4) the effect of inclement weather and learning curve on crew productivity; 5) variations in quantity of work in repetitive activities from one unit to another; and 6) multiple crew assignment scenarios.

The model is implemented in a computer system operating in Windows® environment, providing a friendly user interface with menus, toolbars, status bars and dialog windows. ArcView is employed as the GIS engine, and the GIS sub-module is implemented in “Analyser”, which is coded in the computer language “Avenue” (ESRI 1997). All other modules are implemented in “HWPlanner”. It is coded in Visual C++, employs Microsoft Foundation Classes (MFC). The model generates schedules in both graphical and tabular formats at varying levels of detail to suit all management levels. Three numerical examples were presented to illustrate the use of the developed system and highlight its capabilities.

7.2 Research Contributions

This study presents a model designed to automate the data acquisition and planning stages of highway construction projects. The contributions of this study can be summarised as:

1) The development of an object-oriented model for scheduling linear construction projects in general, and highway projects in particular.
2) The employment of GIS to acquire and analyse spatial data, and automatic computation of cut and fill quantities and the development of the mass haul diagram.
3) The development of a methodology to account for the impact of transverse obstructions on earthmoving operations. The date of completion of an overpass across that obstruction is integrated in the methodology, updating travel time between the two segments.
4) The development of a practical database model, enabling tracking own resources for contractors. The design of the database, along with crew templates, enables assessing the availability of equipment during the scheduling process.

5) The development of a practical WBS for linear projects while accounting for transverse obstructions.
6) The development of a dynamic programming formulation for generating schedules while minimising total cost, duration, or their combined impact for "A+B" bidding (Herbsman 1995).
7) The development of a procedure to identify the most critical activity or section thereof to expedite construction.
8) The development of a methodology to forecast project time and cost at completion.

7.3 Recommendations for Future Research

This study presents a model designed to automate the data acquisition and analysis processes for highway construction, and optimize the scheduling of this class of projects. The model can also generate precedence network respecting job logic for: 1) construction of new highways; and 2) rehabilitating existing highways. The following recommendations are suggested for future research:

i. Regarding spatial data acquisition and analysis:

1) Expanding the GIS sub-module to enable the generation of digital terrain models representing interim stages in the earthmoving process. This could be done with updated work progress either manually or using global positioning system receivers.

2) Expanding the GIS sub-module to enable the automatic generation of the mobilization matrix, and automatically determine the shortest travel route between project segments.

3) Expanding the GIS sub-module to highlight any potential conflicts with any existing utilities, such as phone and power lines and water and sewage pipes.

4) Expanding the GIS sub-module by developing a more realistic methodology to interpolate strata transition between borehole locations. The Kriging model has been identified as the model that best represents elevation data (ESRI 1997; Taylor *et al* 2000).

5) Expanding the GIS sub-module by enabling real-time tracking of equipment using GPS. This would enable thorough studies of equipment productivity and idle times, enabling timely identification of problem areas.

ii. Regarding highway planning and scheduling:

1) Expanding the scheduling and optimization procedure to account for uncertainty in resource availability and rates of crew productivity. Use of fuzzy sets theory has been proven to be capable of achieving that objective for network scheduling (Lorterapong 1995). The main obstacle in this regard is that schedules generated using resource-driven scheduling are particularly sensitive to variations in productivity rates.

2) Expanding the scheduling algorithm to account for several factors including:

   a) Productivity loss due to site congestion (Thabet and Beliveau 1994) and working prolonged hours.

b) Time restrictions in certain locations as dictated by permits.

c) Incorporating time of day in determining travel time across transverse obstructions. This feature would prove particularly useful in cases where the transverse obstruction is an existing highway, and volume of traffic varies throughout the day, and road can only be blocked at specified times.

3) Expanding the model's knowledge-base to enable the automatic generation of precedence networks describing:

a) The detailed construction of foundations and superstructure of overpasses.

b) The construction of other linear projects, such as railroad construction (laying tracks), pipe laying and power line construction.

4) Expanding the model to aid in equipment selection for various crews for earthmoving operations. If-then type rules can be generated to aid in equipment selection, and geographic information systems can used to provide various criteria such as soil type and average haul distances.

5) Expanding the scheduling algorithm to optimize resource sharing among projects. This feature would prove particularly useful to highway contractors, whose resources are typically shared among multiple projects.

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APPENDIX I

Industry Practices Survey

SECTION I THE COMPANY

- Years of experience
  □ < 5 □ 5-10 □ 10-15 □ > 15 *(please specify)* ____

- Typical job size *($ millions)*
  □ < 1 □ 1-10 □ 10-50 □ > 50 *(please specify)* ____

- Average volume of operations per year *($ millions/year)*
  □ <1 □ 1-10 □ 10-50 □ > 50 *(please specify)* ____

- Typical number of projects in progress concurrently
  □ 1 □ 2 □ 3 □ 4 □ > 5 *(please specify)* ____

- Owned equipment *(please indicate number of equipment in the space provided)*
  (For example: *14* Trucks *8* Dozers *2* Scrapers)

  ___ Trucks ___ Dozers ___ Scrapers
  ___ Water trucks ___ Cranes ___ Crushers
  ___ Bituminous distributors ___ Motor graders ___ Soil Stabilizers
  ___ Loaders ___ Backhoes ___ Road reclaimers

  Compactors ___ Pneumatic ___ Steel-wheel
  ___ Vibratory ___ Sheepsfoot
  Pavers ___ Slip-form pavers ___ Paving trains
  ___ Floating screeds ___ Asphalt finishing machines
  Plants ___ Asphalt plant ___ Concrete plant
  ___ Other *(please specify)* ______________ *(use additional sheet if necessary)*

- Indirect cost on a typical job *(expressed as % of direct cost)*
  Accessible in-province projects
  □ <10 □ 10-15 □ 15-20% □ 20-25% □ >25 *(please specify)* ___
  Remote, in-province projects
  □ <10 □ 10-15 □ 15-20% □ 20-25% □ >25 *(please specify)* ___
  Accessible, out-of-province but within Canada projects
  □ <10 □ 10-15 □ 15-20% □ 20-25% □ >25 *(please specify)* ___
  Remote, out-of-province but within Canada projects
  □ <10 □ 10-15 □ 15-20% □ 20-25% □ >25 *(please specify)* ___

- Expected profit on a typical job *(expressed as % of total cost)*
  □ < 5% □ 5-10% □ 10-15% □15-20% □ > 20%

- Scheduling tools employed *(please check all that apply)*
  □ Network techniques (e.g. critical path method – CPM) □ Bar chart
  □ Other *(please specify)* ______________________________

- Accounting for uncertainty in scheduling
  □ Frequently (>80%) □ Regularly (20-80%)
  □ Seldom(<20%) □ Only considered for projects larger than $__ million

- Tools employed to quantify uncertainty associated with project cost (contingency)
  □ As a percentage of the total cost allocated, based on experience.
  □ Computer simulation (e.g. MonteCarlo) □ Other *(please specify)*________

- Typical value of works subcontracted *(as % of contract value)*
  □ <15% □ 15-25% □ 25-50% □ >50 *(please specify)* _____

- Work packages subcontracted on a typical job *(please check (√) appropriate box)*

	Frequently (>80%)	Regularly (20-80%)	Seldom (<20%)
- Camp and infrastructure construction	□	□	□
- Pioneer road construction	□	□	□
- Clearing	□	□	□
- Earthmoving	□	□	□
- Subgrade preparation	□	□	□
- Culvert installation	□	□	□
- Aggregate base course	□	□	□
- Paving	□	□	□
- Supply of asphalt	□	□	□
- Supply of concrete	□	□	□
- Surface course application	□	□	□
- Landscaping and highway finishing	□	□	□

- Equipment typically rented *(please check (√) appropriate box)*

		Frequently (>70%)	Regularly (30-70%)	Seldom (<30%)
- Dozers		☐	☐	☐
- Forestry equipment		☐	☐	☐
- Loaders		☐	☐	☐
- Trucks		☐	☐	☐
- Water trucks		☐	☐	☐
- Crushers		☐	☐	☐
- Scrapers		☐	☐	☐
- Motor graders		☐	☐	☐
- Stabilizers		☐	☐	☐
- Compactors	- Tandem steel wheel	☐	☐	☐
	- Vibratory	☐	☐	☐
	- Sheepsfoot	☐	☐	☐
	- Pneumatic	☐	☐	☐
- Asphalt mix plant		☐	☐	☐
- Asphalt finishing machines		☐	☐	☐
- Bituminous distributors		☐	☐	☐
- Concrete mix plant		☐	☐	☐
- Slip-form pavers		☐	☐	☐
- Dowel placing machines		☐	☐	☐
- Paving trains		☐	☐	☐
- Floating screed pavers		☐	☐	☐
- Road reclaimers		☐	☐	☐

SECTION II INDUSTRY PRACTICES

- Frequency (%) of adopting the following expediting techniques (temporary measures – to accelerate, or reduce project duration by **up to** one week)
  ____ % Working night shift ____ % Work over-time
  ____ % Renting additional equipment ____ % Increasing crew size
  ____ % Assigning multiple crews in various sections ____ % Other *(please specify)* ____________

- Frequency (%) of adopting the following expediting techniques (Long-term measures – to accelerate, or reduce project duration by **more than** one week)
  ____ % Working night shift ____ % Work over-time
  ____ % Renting additional equipment ____ % Increasing crew size
  ____ % Assigning multiple crews in various sections ____ % Other *(please specify)* ____________

- Method employed to plan and estimate the cost of earthmoving operations
  ☐ Mass haul diagram ☐ Other *(please specify)* ____________

- Does the crew size (no. of equipment or manpower) for an activity vary throughout project duration?
  ☐ Frequently (>80%) ☐ Regularly (20-80%)
  ☐ Seldom(<20%) ☐ For certain activities *(please specify)* ____________

- If the project is divided into two segments each with its own crews
  ☐ Crews start from mid-point, working outwards
  ☐ Crews start from end-points, working inwards
  ☐ Other *(please specify)* ____________

- If paving a two-way, four lane highway
  ☐ Two crews are employed, each working in one direction
  ☐ A single crew constructs both pavements
  ☐ Other *(please specify)* ____________

- Frequency of design-build contracts *(expressed as % of total number of contracts awarded)*
  ☐ <1% ☐ 1-5% ☐ 5-10% ☐ >10% *(please specify)* ______

- Frequency of occurrence of the following contracting methods *(expressed as % of total number of contracts awarded)*
  ___% Unit price, fixed rate ___% Lump sum
  ___% Other *(please specify)*______

- Accepted variation in an activity without modifying unit rates stipulated in the contract *(expressed as % of contract original quantity)*
  ☐ < ±5 ☐ ±5-10 ☐ ±10-15 ☐ Over ±15 *(please specify)* ____

- Do rental/leasing companies typically provide operators?
  ☐ Yes ☐ No ☐ For certain equipment *(please specify)*
  ____

- In pricing change orders, estimating impact cost (additional cost over and beyond direct, indirect, overhead and profit) is determined based on
  ☐ Change order amount (variation in scope vs. the original scope of work)
  ☐ Extra working hours required vs. original contract hours
  ☐ Other *(please specify)* __________________

- Typical move-in and setup costs *(expressed as % of project direct cost)* for:
  Accessible in-province projects
  ☐ < 0.5% ☐ 0.5-1% ☐ 1-2% ☐ > 2% *(please specify)* ___
  Remote, in-province projects
  ☐ < 1% ☐ 1-2% ☐ 2-5% ☐ > 5% *(please specify)* ___
  Accessible out-of-province, but within Canada projects
  ☐ < 1% ☐ 1-2% ☐ 2-5% ☐ > 5% *(please specify)* ___
  Remote out-of-province, but within Canada projects
  ☐ < 1% ☐ 1-2% ☐ 2-5% ☐ > 5% *(please specify)* ___

- Typical move-in and setup duration *(working days)*
  Accessible in-province projects
  ☐ < 5 ☐ 5-10 ☐ 10-15 ☐ >15 *(please specify)* ____
  Remote, in-province projects
  ☐ < 5 ☐ 5-10 ☐ 10-15 ☐ >15 *(please specify)* ____
  Accessible out-of-province, but within Canada projects
  ☐ < 5 ☐ 5-10 ☐ 10-15 ☐ >15 *(please specify)* ____
  Remote out-of-province, but within Canada projects
  ☐ < 5 ☐ 5-10 ☐ 10-15 ☐ >15 *(please specify)* ____

- Setup costs mostly affected by
  ☐ Project size ☐ Project Location ☐ Site conditions
  ☐ Other *(please specify)* ____________________

- Activity(ies) typically controlling production rate (i.e. critical activities):
  ☐ Clearing ☐ Earthmoving ☐ Subgrade preparation
  ☐ Aggregate base course ☐ Concrete paving ☐ Asphalt paving

- Is work continuity for the crews commonly enforced?
  ☐ Yes, for all activities
  ☐ Yes, for certain activities *(please specify)* ______________________
  ☐ Not enforced

- Typical work week
  ☐ Five-day work week ☐ Six-day work week

- Typical work day
  ☐ Eight hours ☐ Ten hours ☐ Other *(please specify)* ________

- Minimum space requirements for the crews *(expressed as multiples of 100 metres)*
  (For example: "5 Earthmoving" indicates that earthmoving crew requires 500 m along proposed route to operate without interference with other crews)
  ___ Pioneer road construction
  ___ Clearing
  ___ Earthmoving
  ___ Subgrade preparation
  ___ Culvert installation
  ___ Aggregate base course
  ___ Paving (concrete pavement)
  ___ Paving (asphalt pavement)
  ___ Surface course application
  ___ Landscaping and highway finishing

- Average cost ($/km) of transporting construction equipment along paved routes *(please check appropriate box, and/or specify cost if greater than $2.50/km)*

	Cost ($/km)				
	<0.50	0.50-1	1-1.50	1.50-2.50	>2.50
Short distances *(<500 km)*					
- Light equipment	☐	☐	☐	☐	☐ *(please specify* ___)
- Heavy equipment	☐	☐	☐	☐	☐ *(please specify* ___)
Average distances *(>500 and <1,000 km)*					
- Light equipment	☐	☐	☐	☐	☐ *(please specify* ___)
- Heavy equipment	☐	☐	☐	☐	☐ *(please specify* ___)
Long distances *(>1,000 km)*					
- Light equipment	☐	☐	☐	☐	☐ *(please specify* ___)
- Heavy equipment	☐	☐	☐	☐	☐ *(please specify* ___)

SECTION III CREWS AND EQUIPMENT

- Typical crew compositions

Activity	Crews		Typical productivity (units/hr)	Direct cost ($/hr)
	Equipment	Manpower		
For example: Activity "A"	_1_ loaders _4_ trucks (*1*) *water truck*	(*1*) *foreman* (*5*) *labour* ( ) ______	*17.*^{50} *m*^{3}	*420.*^{00}
Construction of Pioneer road	___ cranes ___ dozers ( ) ________	( ) ______ ( ) ______ ( ) ______		
Clearing	___ dozers ___ forwarders ___ log loaders ___ road builders ( ) ________	( ) ______ ( ) ______ ( ) ______		
Surveying	___ levels ___ transits ( ) ________	( ) ______ ( ) ______ ( ) ______		
Earthmoving (dozer method)	___ dozers ( ) ________	( ) ______ ( ) ______ ( ) ______		
Earthmoving (loader-truck method)	___ dozers ___ loaders ___ trucks ___ backhoes ( ) ________	( ) ______ ( ) ______ ( ) ______ ( ) ______		
Earthmoving (scraper method)	___ scrapers ___ dozers ( ) ________	( ) ______ ( ) ______ ( ) ______		
Compaction	__ tamping foot roller __ sheepsfoot roller __ tandem steel wheel rollers __ water trucks ( ) ________	( ) ______ ( ) ______ ( ) ______ ( ) ______ ( ) ______		

Typical crew compositions
(continued)

Activity	Crews		Typical productivity (units/hr)	Direct cost ($/hr)
	Equipment	Manpower		
Grading	___ motor graders ___ water trucks ( ) __________	( ) _____ ( ) _____ ( ) _____		
Subgrade Preparation	__ tamping foot roller __ sheepsfoot roller __ tandem steel wheel rollers __ water trucks __ crushers __ soil stabilizers ( ) ______________	( ) _____ ( ) _____ ( ) _____		
Aggregate Course Application	__ tamping foot roller __ sheepsfoot roller __ tandem steel wheel rollers __ water trucks __ crushers __ soil stabilizers ( ) ______________	( ) _____ ( ) _____ ( ) _____ ( ) _____		
Concrete paving (slip-form method)	1 Dowel placing Machine 1 slip-form paver ___ trucks ( ) ______________	( ) _____ ( ) _____ ( ) _____ ( ) _____		
Concrete paving (paving train method)	1 paving train __ bituminous distributors __ trucks ( ) ______________	( ) _____ ( ) _____ ( ) _____ ( ) _____		
Asphalt paving	1 Floating screed paver 1 Asphalt finishing Machines __ bituminous distributors __ pneumatic rollers __ vibratory rollers __ trucks ( ) ______________	( ) _____ ( ) _____ ( ) _____ ( ) _____ ( ) _____		

- Equipment productivities and operating costs *(please provide list of equipment owned and their hourly productivity and operating cost – use additional sheets if necessary)*

Equipment type	Manufacturer and model	Productivity (units/hr)	Direct cost ($/hr)
For example:	*Caterpillar 953 C*	*154 BCM*	*$45.^{00}$*
Loaders	*Caterpillar 973*	*189 BCM*	*$75.^{00}$*

APPENDIX II

Survey on Impact of Weather on Productivity

- Listed below are various weather conditions that could potentially affect construction operations. Please indicate their impact on production rate due to adverse weather conditions. Please adopt the following format:
  S – Severe *(work stoppage or more than 50% loss in production rates)*
  M – Moderate *(10-50% loss in hourly production rates)*
  L – Little *(less than 10% loss in hourly production rates)*

Operations	Rainfall				Temperature		Wind speed (km/hr)		
	Very little[A]	Little[B]	Moderate[C]	Heavy[D]	Low (<9°C)	High (>26°C)	0-15 Low	15-45 Med.	>45 High
Pioneer road const.									
Clearing									
Surveying									
Earthmoving (dozers)									
Earthmoving (loader-truck fleets)									
Earthmoving (scrapers)									
Compaction									
Grading									
Subgrade preparation									
Culvert installation									
Aggregate base course									
Concrete paving									
Asphalt paving									

[A] – precipitation rate less than 0.2mm/hr
[B] – precipitation rate between 0.2 and 4.6 mm/hr
[C] – precipitation rate between 4.6 and 7.6 mm/hr
[D] – precipitation rate greater than 7.6 mm/hr

- What are the most adverse conditions (please specify min. temp and max. wind speed) at which the following construction operations can be performed satisfactorily?

Operations	Temperature (°C – min)	Wind speed (km/hr - max)
Pioneer road construction		
Clearing		
Surveying		
Earthmoving (dozers)		
Earthmoving (loader-truck fleets)		
Earthmoving (scrapers)		
Compaction		
Grading		
Subgrade preparation		
Culvert installation		
Aggregate base course		
Concrete paving		
Asphalt paving		

- Work stoppage (lost hours and days due to precipitation)

		Earthmoving (poor drying conditions)		Earthmoving (average drying conditions)		Earthmoving (good drying conditions)		Paving			
								Asphalt		Concrete	
Cumulative rainfall (mm)	Time of day	Total hours lost	Days lost following current day	Total hours lost	Days lost following current day	Total hours lost	Days lost following current day	Total hours lost	Days lost following current day	Total hours lost	Days lost following current day
3	Morning 7:00 am –noon										
3	Afternoon Noon-5:00 pm										
3	Full day										
3	Overnight 5:00 pm-7:00 am										
6	Morning 7:00 am –noon										
6	Afternoon Noon-5:00 pm										
6	Full day										
6	Overnight 5:00 pm-7:00 am										
13	Morning 7:00 am –noon										
13	Afternoon Noon-5:00 pm										
13	Full day										
13	Overnight 5:00 pm-7:00 am										
25	Morning 7:00 am –noon										
25	Afternoon Noon-5:00 pm										
25	Full day										
25	Overnight 5:00 pm-7:00 am										

APPENDIX III

Impact of Transverse Obstructions

On Freehaul and Overhaul

Consider the sample longitudinal section and its corresponding mass haul diagram shown in Figures III-1(a) and (b), respectively. A horizontal line is drawn passing through the point of intersection of the mass haul diagram and the transverse obstruction (line KP in part (b) of the Figure). If KP+$M_{i+1,i}$ (element "i+1", "i" of the mobilization matrix, where "i" and "i+1" are the segments separated by obstruction "i") is greater than the free haul, then the free haul reduces to KP (see Figure III-1(b)). In this case, all the soil in segment "i" will be hauled to segment "i+1" as overhaul. A horizontal line ("HJ" in Figure III-1(b)) is drawn passing through the ordinate "K/2". The length of this line, added to the additional travel distance to overcome the obstruction, $M_{i+1,i}$, provides an accurate estimate of the actual haul distance. Consequently, overhaul cost is expressed as:

$$C_{over} = K \times (HJ + M_{i+1,i} - \text{free haul}) \times c_o \qquad \text{(III.1)}$$

where K is the ordinate at the location of the obstruction,

HJ is the length of the line HJ (see Figure III-1),

$M_{i+1,i}$ is the additional travel distance to overcome the obstruction,

Free haul is the free haul distance as specified in the contract and

c_o is as defined in Equation (3.4).

Otherwise, if KP+$M_{i+1,i}$ is less than the free haul, this indicates that the free haul extends beyond the obstruction, as shown in Figure III-1(c). In this case, overhaul cost is expressed as:

$$C_{over} = F \times (HJ + M_{i+1,i} - \text{free haul}) \times c_o \quad \text{(III.2)}$$

where F is the ordinate of the mass haul diagram (see Fig. 3.10(c)) and

HJ, $M_{i+1,i}$, free haul and c_o are as defined in Equation (3.4).

Figure III-2 shows the potential impact of a transverse obstruction if it is outside the range of the free haul distance. The intercept of the mass haul diagram with the obstruction, "K", provides the quantity of earth to be hauled across the obstruction. A horizontal line, "PL", is drawn passing through "K/2", and its intercept with the mass haul diagram (point "L") provides the location of the centroid of the shape (kk'c'c). In this case, cut is divided into two sections: 1) one that has a quantity of earth equal to "K", and needs to be hauled across the obstruction; and 2) another that has a quantity of earth equal to "G – K", which doesn't. The location of the centroid of the shape (gg'k'k) is determined by drawing a horizontal line at a distance (K+G)/2, and overhaul cost is expressed as:

$$C_{over} = (K \times (HZ + M_{i+1,i} - \text{free haul}) + (G - K) \times (TS + RH - \text{free haul})) \times c_o \quad \text{(III.3)}$$

where K and G are ordinates of the mass haul diagram (see Fig. III-2),

HZ, TS and RH are the distances as shown in the same figure and

c_o is as defined in Equation (3.4).

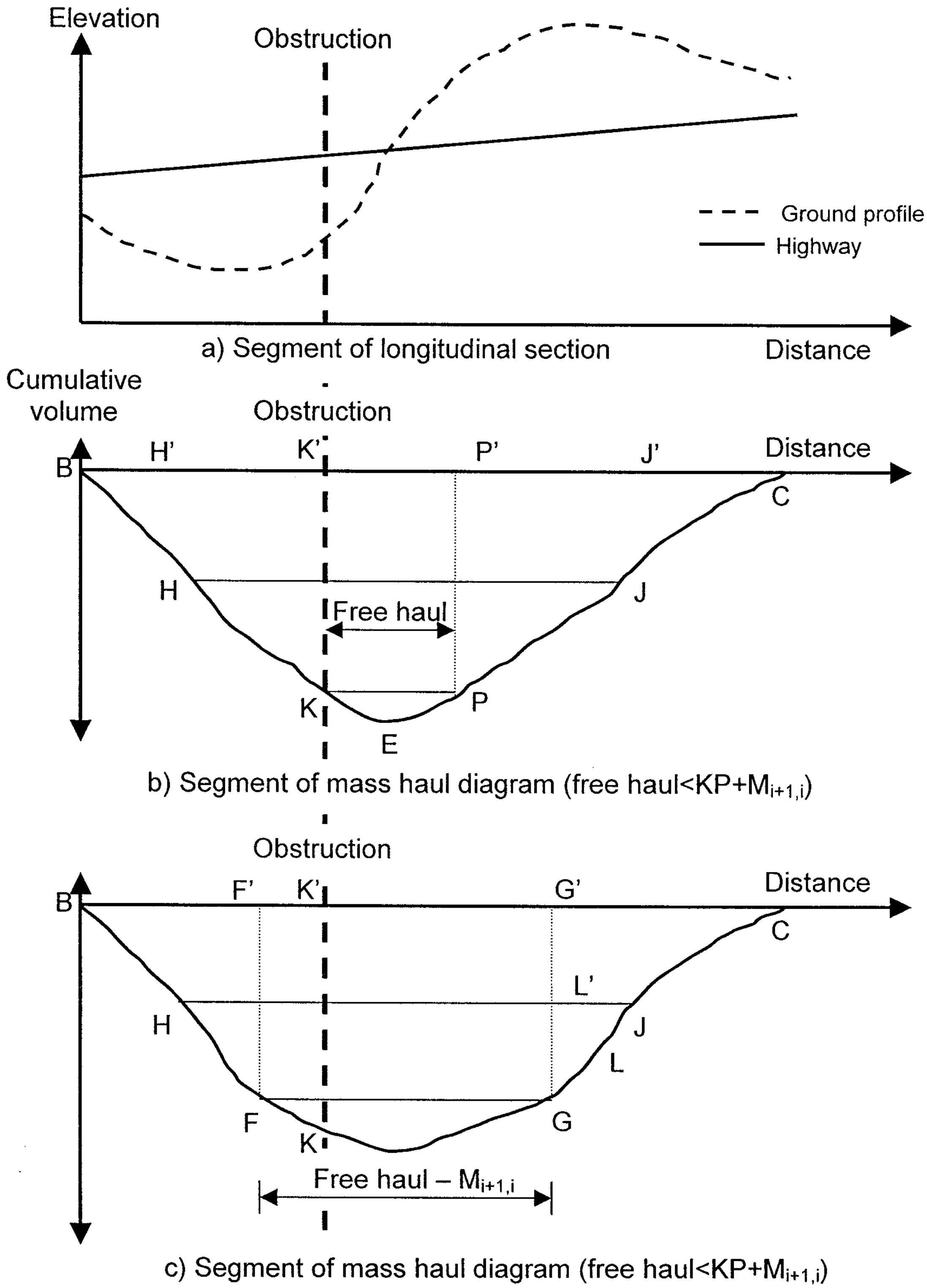

Figure III-1: Impact of transverse obstruction (within free haul) on earthmoving costs

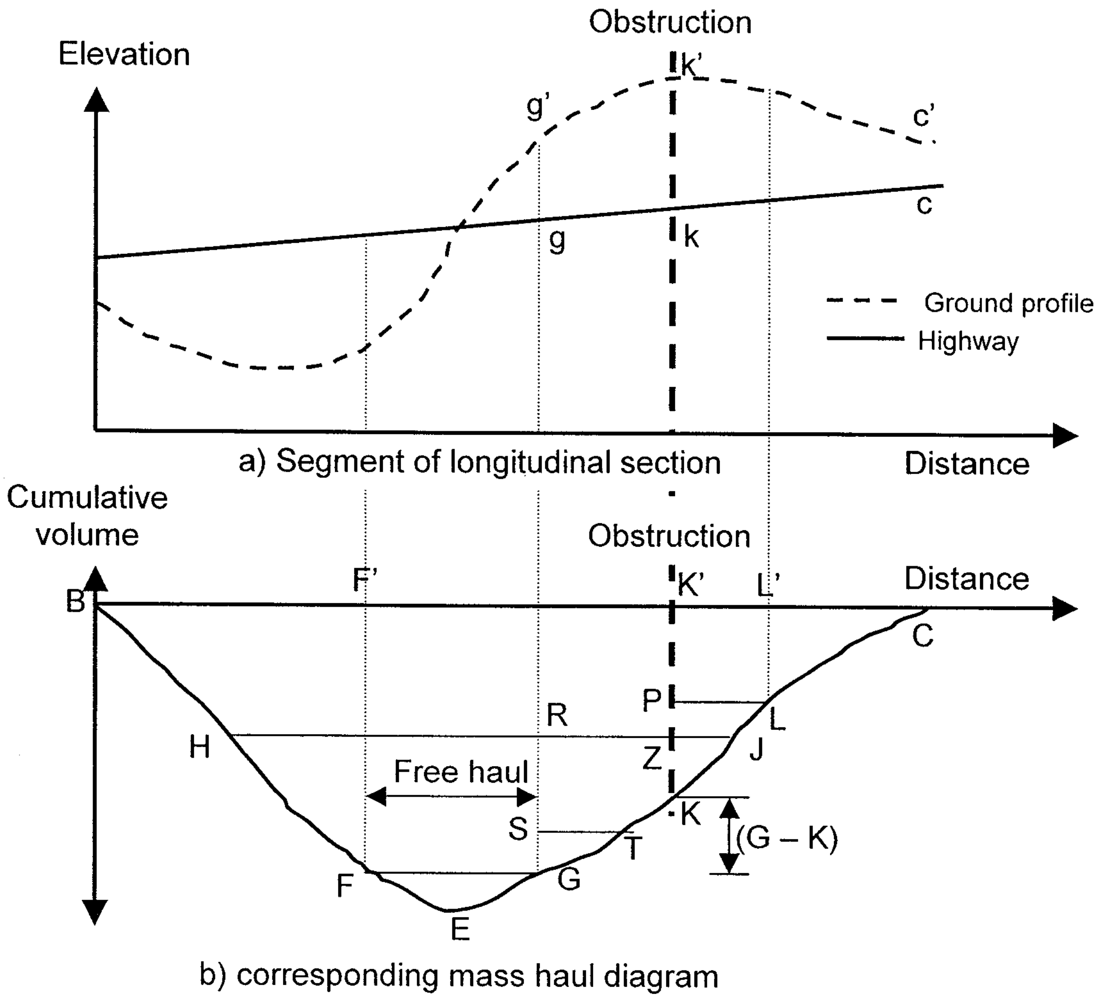

Figure III-2: Impact of transverse obstruction (outside free haul) on earthmoving costs

APPENDIX IV

Equipment Data Stored

In Database

The following data is stored for all equipment types:

- Equipment identifier: unique identifier for each piece of equipment
- Model: identifier for each equipment model
- Hours worked: total number of hours worked by equipment

Equipment	Attribute Stored	Units
Asphalt mix plants*	Mobility (yes/no) Daily productivity Capacity Assembly cost	Binary Ton/hr Tons $
Backhoes**	Flywheel power Max. digging depth Breakout force	Hp m kN
Compactors	Type (vibrating/sheepsfoot/pneumatic) Material (soil/asphalt) Operating weight Flywheel power Speeds (1/2)	Alpha-numeric Alpha-numeric Tons hp Numeric
Cranes	Daily productivity Max. lifting weight	Tons Tons
Crushers	Daily productivity Capacity	Tons m^3
Dozers***	Mounting (track/wheel) Flywheel power Operating weight Ground contact area	Alpha-numeric Hp Tons m^2
Loaders	Mounting (track/wheel) Flywheel power Cycle time Max. travel speed	Alpha-numeric Hp Sec km/hr
Motor graders	Flywheel power (shifts 1-3) Flywheel power (shifts 4-8) Operating weight Travel speed (forward) Travel speed (reverse)	Hp Hp Tons km/hr km/hr
Pavers	Flywheel power Mounting (track/wheel) Paving speed Max. travel speed Max. theoretical capacity Hopper capacity	Hp Alpha-numeric m/min km/hr Ton/hr m^3

Equipment	Attribute Stored	Units
Scrapers	Type (standard/push-pull/elevating)	Alpha-numeric
	Struck capacity	m^3
	Heaped capacity	m^3
	Flywheel power (tractor)	Hp
	Flywheel power (scraper)	Hp
	Rated load	Kg
	Top speed (loaded)	km/hr
	Width of cut	M
	Max. depth of cut	M
	Max. depth of spread	M
Trucks	Type (water/haul/off-highway)	Alpha-numeric
	Flywheel power	Hp
	Gross power	Hp
	Operating weight	Kg
	Max. gross weight	Kg
	Top speed loaded	km/hr
	Max. capacity	m^3
	Struck capacity	m^3
	Heaped capacity	m^3

* linked to screeds table (storing screed widths)
** linked to buckets table (storing bucket capacities)
*** linked to blades table (storing blade widths and heights)

APPENDIX V

Baseline and Earned Value Analysis

The significance of integrating time and cost control to achieve efficient project control was highlighted by Moselhi (1993). The earned value concept has gained wide acceptance in the construction industry, and has been employed to monitor the progress of several construction projects (Barrie and Paulson 1992). The following S-curves are generated: 1) budgeted cost of work scheduled (BCWS); 2) actual cost of work performed (ACWP); and 3) budgeted cost of work performed (BCWP). These curves are superimposed to determine the variances, if any, between planned and scheduled progress. The ACWP is the actual incurred cost to date, while the BCWP represents the costs that, according to the plan, should be incurred in completing the work done to date. Upon determining the above three values (i.e. BCWS, ACWP and BCWP), the following variances and indices can be computed:

$$CV = ACWP - BCWP \tag{V.1}$$

$$SV = BCWP - BCWS \tag{V.2}$$

$$CPI = \frac{BCWP}{ACWP} \tag{V.3}$$

$$SPI = \frac{BCWP}{BCWS} \tag{V.4}$$

where CV is the cost variance, also referred to as the spending variance,

SV is the schedule variance,

CPI is the cost performance index and

SPI is the schedule performance index.

A positive value for the cost variance indicates cost overrun, while a positive value for the schedule variance indicates that the project is ahead of schedule. A cost performance index greater than unity indicates cost savings, while a schedule performance index greater than unity indicates that the project is ahead of schedule.

Assuming performance thus far will prevail till project completion, the estimate at completion is expressed as:

$$EAC = \frac{BAC}{CPI} \tag{V.5}$$

where EAC is the estimate at completion,

BAC is the original budget at completion and

CPI is as defined in Equation (V.3).

Assuming that the planned progress rates will prevail from this point until project completion, the estimate at completion is expressed as:

$$EAC = BAC + CV \tag{V.6}$$

where EAC and BAC are as defined in Equation (V.5) and

CV is as defined in Equation (V.4)

If a revised estimate of the project duration is required, and assuming that current production rates will prevail until project completion, the revised duration is expressed as:

$$DE = \frac{OD \times N_{wd}}{N_{wd} - TV} \qquad (V.7)$$

where DE is the duration estimate (in working days),

OD is the original (planned) duration (in working days),

N_{wd} is the number of working days from project start till reporting date and

TV is the time variance.

On the other hand, if planned progress rates are assumed to prevail from this point onward, the revised duration is expressed as:

$$DE = OD + TV \qquad (V.8)$$

where DE, OD and TV are as defined in Equation (V.7).

APPENDIX VI

Estimating Daily Costs

It is worth noting that, although the following discussion focuses primarily on determining the quantity of work complete in a unit of any repetitive activity, the algorithm also applies to non-repetitive activities. For each day (D) (where $0<D\leq$project duration) units of all repetitive activities and all non-repetitive activities are queried to determine whether any work is scheduled on day (D). For an activity with work scheduled to progress on day (D), four possible scenarios exist, as shown in Figure VI.1. The first possible scenario, shown in part (a) of the figure, represents the case where work on unit (J) of a repetitive activity is progressing in the previous day, and completed on day (D). The period the crews are working on unit (J) is expressed as:

$$T_{D/J} = Finish_J - D \qquad \text{(VI.1)}$$

where $T_{D/J}$ is the fraction of the day that crews are working on unit (J) and

$Finish_J$ is the scheduled completion time of unit (J).

The quantity of work completed by any crew on day (I) is expressed as:

$$Quan_D = \frac{T_{D/J}}{dur_J} \times Q_J \qquad \text{(VI.2)}$$

where $Quan_{D/J}$ is the quantity of work of unit (J) scheduled for day (D),

$T_{D/J}$ is as defined in Equation (VI.1),

dur_J is the duration of work in unit (J) and

Q_J is the quantity of work in unit (J).

The second scenario is shown in Figure VI.1 (b), where work on unit (J) of a repetitive activity is progressing in the previous day, and continues beyond day (D). In this case, crews are occupied for the whole day ($T_{D/J}$=1) and the quantity of work completed in day (D) is expressed as:

$$Quan_{D/J} = \frac{1}{dur_J} \times Q_J \qquad (VI.3)$$

where $Quan_{D/J}$, dur_J and Q_J are as defined in Equation (VI.2).

The third scenario is shown in Figure VI.1 (c), where work on unit (J) of a repetitive activity commences on, and continues beyond, day (D). In this case, the duration that crews work on unit (J) is expressed as:

$$T_{D/J} = D + 1 - Start_J \qquad (VI.4)$$

where $Start_J$ is the scheduled start time of work on unit J.

The quantity of work completed on day (D) is computed using Equation (VI.2). The last scenario is shown in Figure VI.1 (d), where work on unit (J) of a repetitive activity commences, and is completed, on day (D). In this case, the crews are occupied for a duration equal to that of work on the unit, i.e.:

$$T_{D/J} = dur_J \qquad (VI.5)$$

where dur_J is as defined in Equation (VI.2).

The quantity of work completed on day (D) would thus be equal to the quantity of work in unit (J). i.e.:

$$Quan_{D/J}=Q_J \qquad (VI.6)$$

where Q_J is as defined in Equation (VI.2).

Case 1:

$$Quan_{(I)} = \frac{Finish - I}{dur_j} \times Q_j$$

Case 2:

$$Quan_{(I)} = \frac{\mathbf{1}}{\mathbf{dur_j}} \times \mathbf{Q_j}$$

Case 3:

$$Quan_{(I)} = \frac{I+1-Start}{\mathbf{dur_j}} \times Q_j$$

Case 4:

$$Quan_{(I)} = Q_j$$

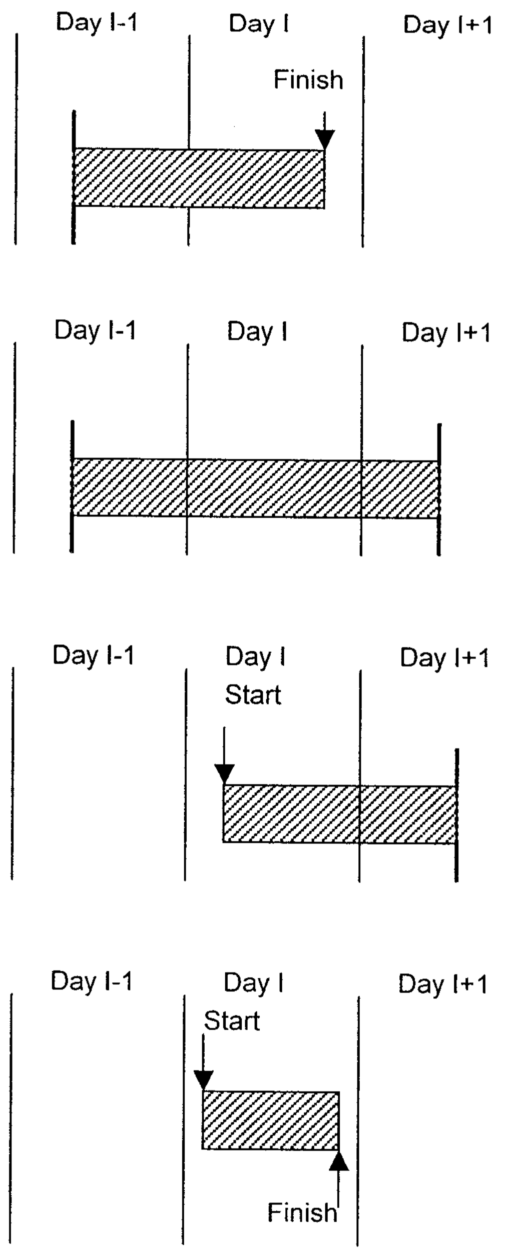

Figure VI.1: Possible scenarios for activity progress

APPENDIX VII

Experts Consulted while Developing Precedence Network

Name	Title	Company
Todd Galliford	Scheduler	SNC-Lavalin
John Mirabelli	Senior scheduler	SNC-Lavalin
Dan Guistini	Manager, const. operations	407-ETR
Ignacio Clopez	Senior scheduler	SLF
Michael Senn	Cost estimator	SNC-Lavalin
Jacques Lafontaine	Senior Scheduler	Les Grands Travaux Soter Inc.,
Richard Poirier	Project Manager	Les Grands Travaux Soter Inc.,

APPENDIX VIII

Map and Schedule

for Zone "W1"

of Highway 407 – ETR

Toronto, Ontario

The 407 Express Toll Route (ETR) is the first all-electronic, open access toll highway in the world. It runs east - west just north of Toronto, Ontario, Canada (see Figure VIII.1), connecting the Queen Elisabeth Way QEW in the west to Highway 7 in the east; a total length of 108 kilometres. The highway was completed in two phases. The first extends from Highway 410 in Brampton to Highway 404 in Markham, and open to the public on June 7, 1997. Phase 2 is composed of two sections; the east extension from Highway 404 to Highway 7, and the West extension from QEW to Highway 410. The project was completed in August 2001.

A total of six site visits were carried out between the periods of June 1999 and July 2002. These visits were mainly to the West extension of Phase 2, a segment approximately 24 km in length. The purposes of these visits was inspect the progress of the work on site, and refine the logic of the proposed precedence network through discussions with site personnel and Mr. John Mirabelli, the project's senior scheduler. These visits helped establish the developed job logic, and enabled a first-hand experience of the subtleties involved in the planning, scheduling and control of highway construction projects. Since there were several interchanges, overpasses and underpasses in the project, these visits also enabled the identification of the differences in the job logic between these various operations. Figures VIII.2 and VIII.3 show the progress of earthmoving operations in the vicinity of a transverse overpass and the installed subdrains, respectively. Figure VIII.4 shows the embankment after rainfall, illustrating the unworkable conditions following precipitation. Figure VIII.5 shows the construction of the barrier wall.

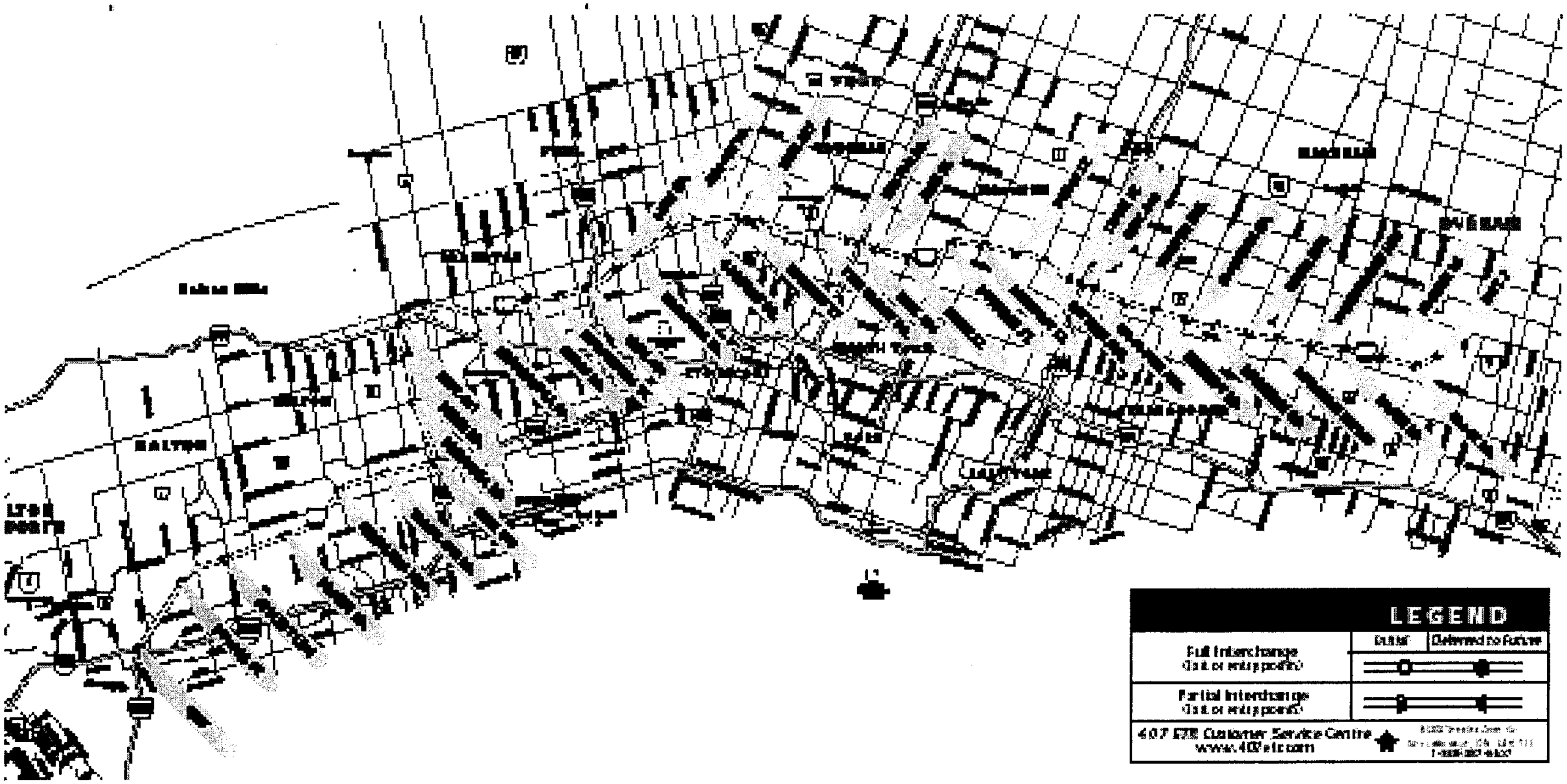

Figure VIII.1: Site map of the 407 ETR project

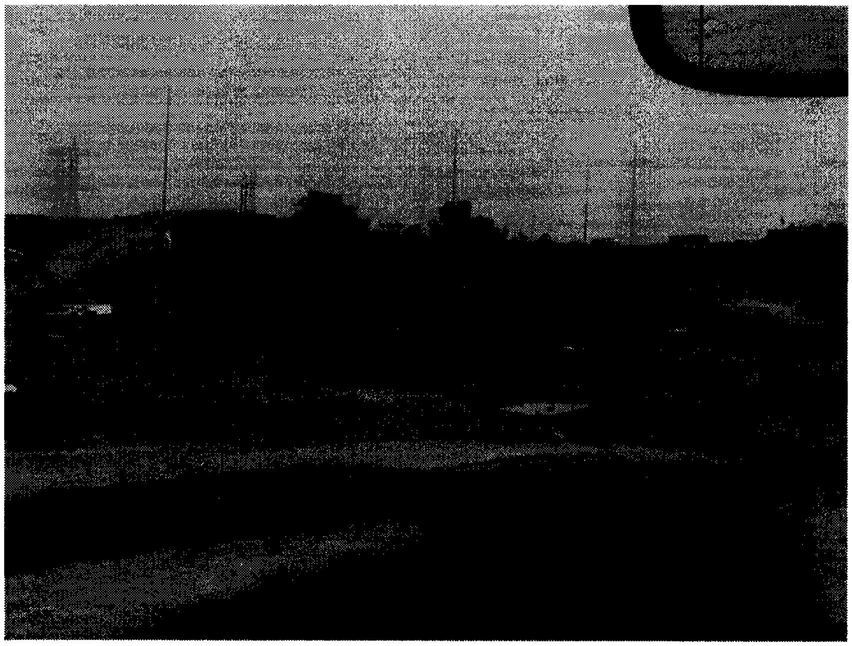

Figure VIII.2: Progress of earthmoving operations

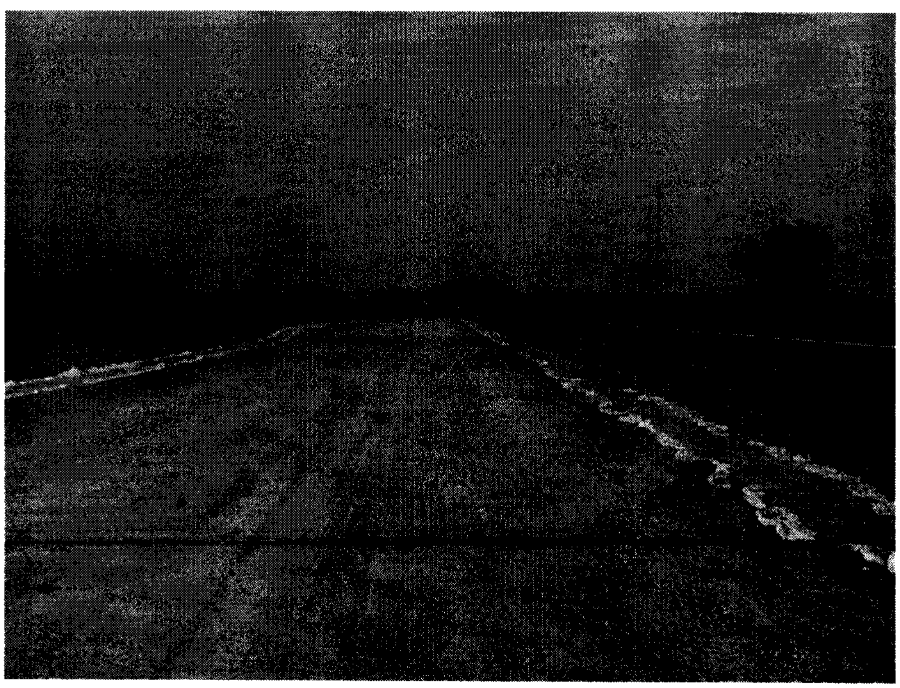

Figure VIII.3: Installed subdrains

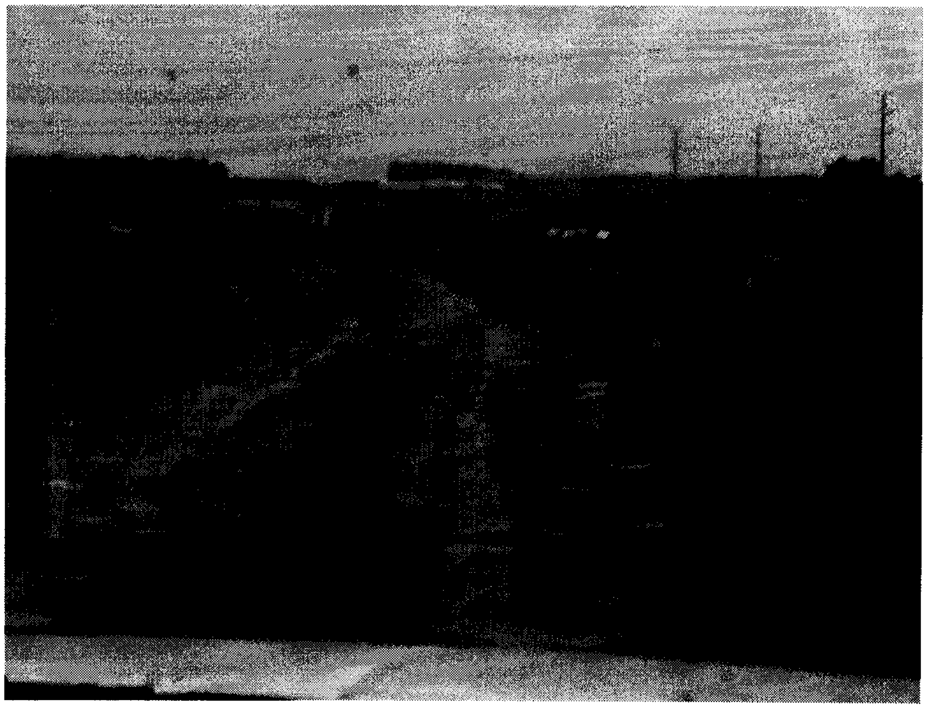

Figure VIII.4: Embankment following rainfall

Figure VIII.5: Construction of median barrier

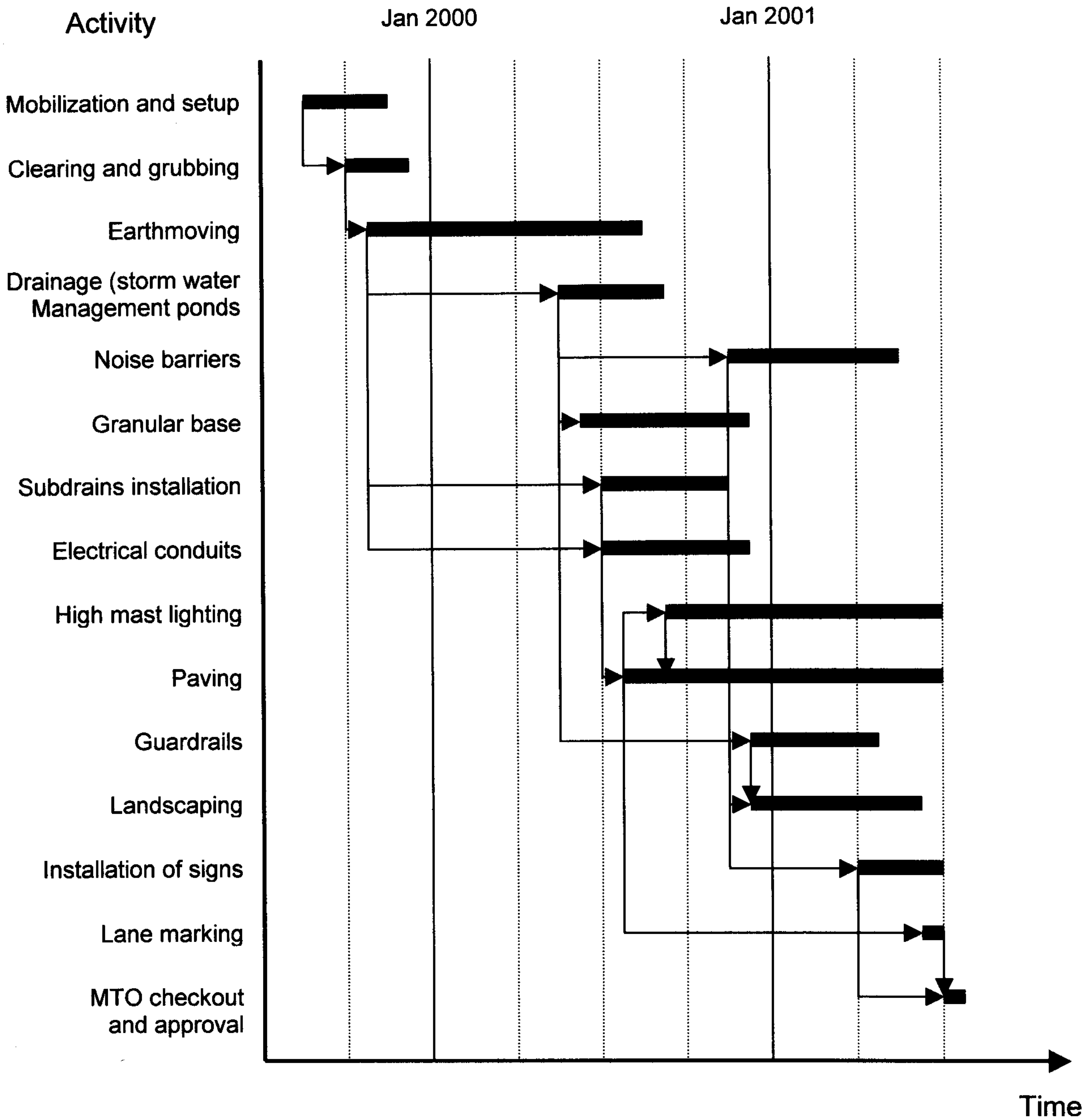

Figure VIII.7: Simplified bar chart for mainline activities of zone W1

The last visit was on July 19, 2002. The purpose of this visit was twofold: 1) to verify and validate the proposed job logic; and 2) to obtain feedback on the developed software and its various features. This was carried out through a brainstorming session with Mr. Todd Galliford, the project scheduler. The schedule is shown in bar chart format in Figure VIII.6. Mainline activities are aggregated and simplified to bar chart shown in Figure VIII.7 in order to bring the bar chart to the same level of detail as the activity definition in the proposed study. Although precedence relations are not depicted on the chart, they can be inferred from the relative start and finish times of the various activities. These have been manually added to the bar chart in Figure VIII.7 for illustrative purposes only.