University of Alberta

Scenario-Based Planning for Tunnelling Construction

by

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DEDICATION

This thesis is detected with love to my Father, Mother, and Family.

ABSTRACT

This research presents a scenario-based planning tool for construction project planning in utility tunnel construction. The main objective of this research is to provide the construction industry with a systematic procedure for implementing scenario-based planning to take a mature approach to project planning. This research also proposes a new scenario-based planning framework and implementation for tunnel construction.

The presented scenario-based planning tool will enable the project team to define and evaluate a number of scenarios in a real-time setup, and then select the best scenario. Scenario planning is a powerful approach for project planning: it helps stakeholders to define the most effective way to finish a project and achieve the maximum value of the project.

The presented scenario-based planning tool was built based on the concepts of High Level Architecture (HLA), working from FIATECH's vision, presented in the "Capital Projects Technology Roadmap". We used Simphony.NET to implement our approach, which showed the strength and durability of the platform.

The proposed scenario-based planning process will allow users to develop a systematic workshop approach for defining a number of scenarios. Using the scenario-based planning tool presented in this research, the project team can experiment with these options in a timely manner to come up with the best scenario.

We have developed a framework for a multi-user support system for tunnelling operations based on a Construction Synthetic Environment (CoSyE), which in turn is built upon the concepts of the HLA. This framework lays the foundation for introducing multi-user support systems to the construction industry by enabling many users to join a simulation.

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CHAPTER 1. INTRODUCTION

1.01 Introduction

Scenario-based planning is one of the most efficient methods for exploring the future and developing the best strategy to achieve the goals set out for a project. It helps anticipate and leverage change, encourages "out of the box" thinking, reduces risks associated with the project, and provides a consistent approach for project planning (SRI 2008).

Over the years, the scenario-based project planning phase has evolved into a key component for a successful project. In this stage, a number of scenarios are proposed and analyzed; based on criteria set by the project team, the best scenario will be selected. There are a number of tools available to analyze different scenarios. One of these is simulation, which has been proven over the years to be an effective, yet easy-to-use tool.

FIATECH introduced scenario-based project planning as the recommended approach for construction project planning. Using the FIATECH approach, a comprehensive and collaborative project planning system is under development to assist the planning team, as well as to provide the initial data capture for use throughout the life cycle of the project (FIATECH 2008). This system will help the project team evaluate a number of alternatives and enable team members to create optimized project plans and design. The system will be able to incorporate the cost, schedule, and lifecycle performance based on the decisions made.

1.02 Scenario-based planning

The first written documents regarding scenario planning were produced in the 19th century, and this approach to project planning evolved and matured as it gained wider acceptance in the public and private sectors. It was used during World War II as a method for military planning by the British army. In the 1950s, the first formalization of scenario planning was developed by the U.S.

Air Force to propose different alternatives for responding to possible actions by opponents, and the method reached its prime in the 1970s when it was used by Pierre Wack, who used scenario planning to predict the oil price shock for Shell (Daum 2001). Scenario planning was used by businesses to replace forecasting, as forecasting failed to predict the future with desired accuracy. Scenario planning is now used in many industries worldwide for the development of strategic business plans.

Construction project planning can greatly benefit from scenario planning, especially in large-scale and lengthy projects, which need to be studied against a number of futures. In construction, scenario planning can play a large role in selecting among alternatives when planning large projects such as tunnelling. Currently, this method is used in an indirect, non-structured way within the construction industry (e.g. value engineering in the preconstruction stage). With a formal scenario-based planning approach, the project team can best address project risks and improve performance, as well as optimize conflicting objective studies.

1.03 FIATECH scenario-based planning

In its vision for the future of project planning, FIATECH recommends a completely automated project planning and management system for all components of a project's life cycle. In this system, scenario-based planning and simulation modelling tools will help accelerate the evaluation of design alternatives and rapidly generate cost, schedule, and productivity estimates to help select the most effective scenario. In its Capital Project Technology Roadmap, FIATECH presented nine critical components to achieving a fully integrated and automated project planning system that can serve the project throughout its life cycle. These components are (FIATECH 2004):

- Scenario-based project planning
- Integrated automated design
- Automated procurement and supply network

- Intelligent & automated construction job site
- Intelligent self-maintaining and repairing operational facility
- Real-time project and facility management
- Coordination and control, new materials, methods, products, and equipment
- Technology- and knowledge-enabled workforce
- Lifecycle data management and information integration.

The scenario-based planning system will provide a comprehensive, rapid, and effective evaluation for different scenarios to help the project team in selecting the best option for the project's needs. It will allow the user to experiment with cost and schedule for each scenario, and, based on the selected scenario, it will provide the user with the initial input for design, project plans, and specifications. Scenario planning will help the project team fully understand the key issues and potential project risk factors, which will help the team anticipate and adjust for costly errors that may occur in the future (FIATECH 2004). Scenario planning using simulation tools will further improve the quality of construction projects by allowing users to fully explore numerous numbers of scenarios before selecting the best option. It will help the project team deliver better, safer, faster results for more cost-effective projects with more secure outcomes.

This thesis presents a framework for implementing scenario-based planning for tunnel construction projects based on the FIATECH scenario-based planning variables.

1.04 Problem statement

Existing literature shows that scenario-based planning is mainly used in the business sector. In construction, planning activities tend to be informal in small and mid-sized projects. Here, scenario-based planning is limited and occurs indirectly during value engineering workshops and constructability reviews. A new process is needed to facilitate scenario-based planning implementation in construction projects.

The construction industry lacks comprehensive and integrated tools developed specifically for scenario-based planning. The current tools can be divided into two categories: static model-based tools and dynamic model-based tools. Static model-based tools such as CPM, resource constraint scheduling, and Gantt Charts are mainly built to tackle non-repetitive work. Dynamic model-based tools, such as computer-based simulation, are better designed to handle repetitive work (Flood et al. 2006).

Construction static planning tools, such as CPM, fail to address repetitive activities and resource-based projects; these also complicate the model and give no details for the interaction among construction tasks (Harris 1998). In contrast, dynamic planning tools have the capacity to address these issues.

Tools built using simulation environments, such as *Simphony*, use range estimating for cost estimation, PERT for duration estimation, and others for productivity calculations. These planning tools are not integrated, and projects are often described and broken down into disparate components for cost, schedule, productivity, or quality analysis. These tools cannot work together; for example, using range estimating will allow the user to create an estimate for a project, but it can't produce a schedule. Likewise, a PERT will allow the user to develop a better understanding of a project's duration, but it can't be used to develop a cost estimate. This creates an inefficient environment for planning, resulting in poor project execution. Consequently, planners are left with two choices: 1) to use number of planning tools; or 2) to use a single tool, wedging in different components and producing results of limited accuracy. It is very hard to adopt the first choice, as it requires the planner to be proficient in the use of a number of tools. An integrated tool to combine all these tools without losing usability and output quality is required. This integrated tool will provide the planner with a single, comprehensive, and easy-to-use planning tool for cost estimation, project schedule, productivity, and quality analysis. As a result, it will streamline overall project planning.

Tunnelling projects present the same difficulties as other construction projects. Currently, the City of Edmonton uses simulation-based tools for tunnel project planning, as in the Glencoe Tunnel in Calgary (Fernando et al. 2006), and the SW2&3 Tunnel in Edmonton. Using these tools requires a great deal of time and effort; a new toolkit is required to facilitate scenario-based planning for tunnel construction. These tools should allow the user to evaluate each scenario based on number of variables such as cost, schedule, productivity, resources, and materials. They should also allow the user to evaluate the scenarios with ease in an expeditious, timely manner.

1.05 Research objectives

In this thesis, modelling strategies for improving project planning will be discussed. This strategy will focus on investigating comprehensive, collaborative, simulation-based approaches utilizing scenario based planning. Utility tunnelling projects will be used to demonstrate this strategy. The specific objectives are as follows:

- Research and develop a framework for a scenario-based planning tool for tunnelling construction.
- Develop a simulation-based tool for scenario-based planning in tunnel construction based on the proposed framework.
- Propose a scenario-based planning process for tunnelling that will facilitate the application of the developed simulation tool.

The aforementioned objectives will directly contribute to the state of the art in construction engineering and management, as demonstrated by the parallels between the proposed research activity and FIATECH's "Capital Project Technology Roadmap: Vision of the Future" (2004).

1.06 Framework development and implementation

We will use the concept of High Level Architecture (HLA) to develop our scenario-based planning framework for tunnel construction, as demonstrated in Figure 1-1, and Simphony.NET for implementation.

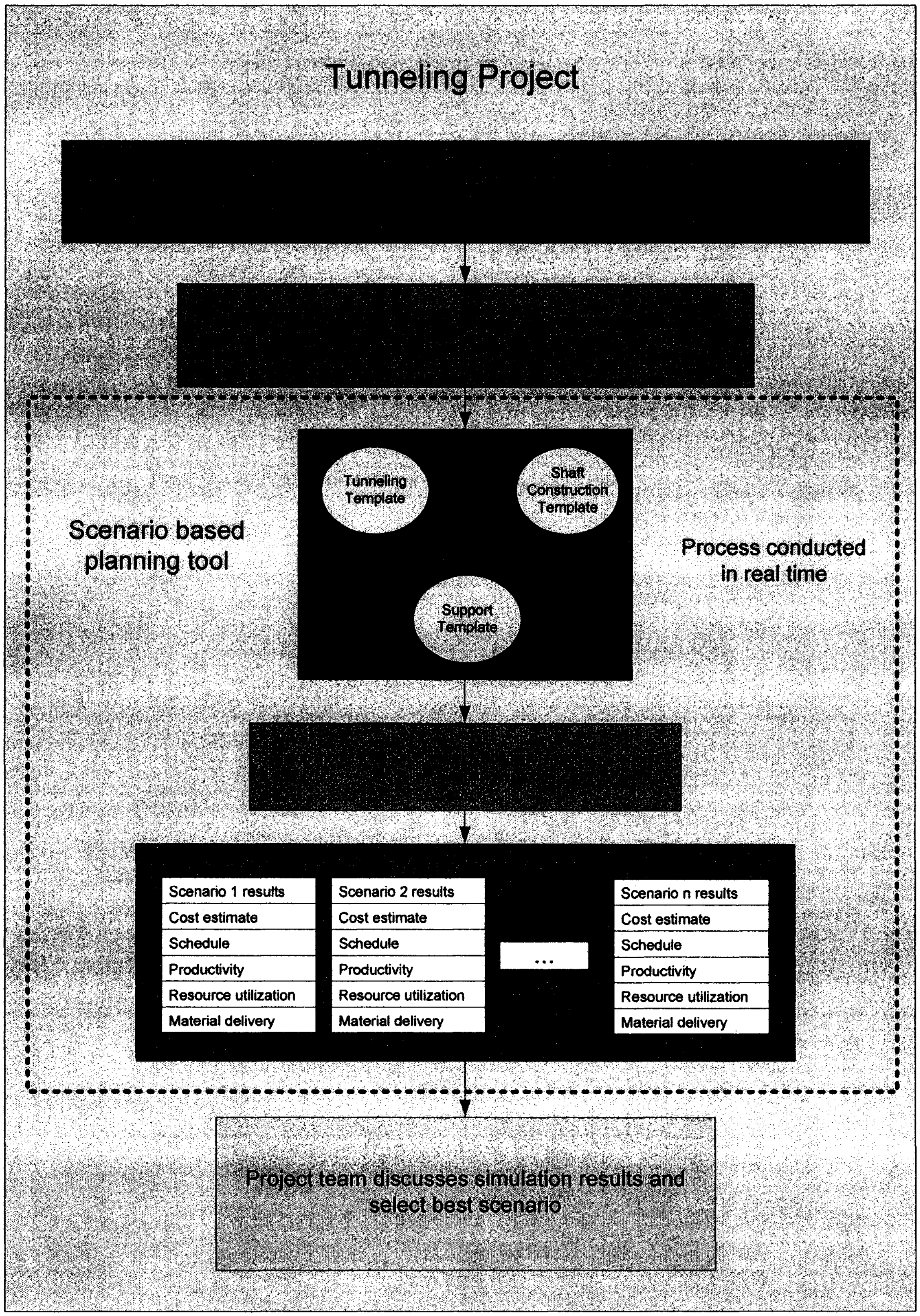


FIGURE 1-1 SCENARIO-BASED PLANNING PROCESS FOR TUNNELLING PROJECTS

1.07 Research methodology

To demonstrate the applications of the framework we are planning to develop, we will implement scenario-based planning for utility tunnel construction projects.

Construction planning has largely remained an intuitive process with little technological automation. Such planning is generally carried out by engineers during the design phase and on some projects with input from constructors (FIATECH 2004). The decisions they make significantly impact the eventual performance of the project in terms of cost, schedule, and overall achievement of project objectives. Scenario-based planning offers a futuristic vision of construction planning processes. Within this vision, a comprehensive model of the project is developed dynamically and interactively as the design matures. Throughout the design phases, project managers can assess and compare alternatives, test the impacts of various design decisions on achieving project objectives, and derive optimized plans for design and construction. This represents dynamic iterative cycles of planning, designing, and experimenting with the facility in a virtual world.

To demonstrate scenario-based planning for utility tunnel construction, we followed the following process:

1. Document the planning process for a select number of projects. Follow projects from conceptual design to construction and identify the process each participant follows, how project planning is achieved, and how it translates into the production of a facility.

2. Apply current simulation technologies (e.g. using Simphony.NET) to contribute to the planning process discussed in step (1). This process shadows the actual planning exercise. We applied this approach with the City of Edmonton on the Glencoe Tunnel in Calgary and the SW2&3 Tunnel in Edmonton with success.

3. Identify gaps and shortfalls in both the planning process and the existing technologies.
4. Design and implement an approach for scenario-based planning using Simphony.NET.
5. Develop a case study to demonstrate the framework.

1.08 Thesis organization

Chapter 2 includes a review of the current literature on simulation environments and the bases for the new simulation framework, which includes the HLA. We also discuss the Simphony.NET framework and explore the concept of scenario planning. Lastly, this chapter presents the FIATECH vision.

Chapter 3 explores current project planning using simulation by presenting the application of simulation in three tunnelling projects constructed by the City of Edmonton: North of Edmonton Sanitary Trunk (NEST), Glencoe Tunnel in Calgary, and South West of Edmonton Sanitary Trunk (SW2&3). We will detail the process for SW2&3 tunnel. Additionally, using the concept of the HLA, we present a scenario-based planning framework.

Chapter 4 presents an implementation of the framework proposed in Chapter 3 for construction utility tunnels based on FIATECH's vision for scenario-based planning. The tool we are presenting includes a number of FIATECH scenario-based planning variables such as schedule, cost, productivity, resource utilization, and material delivery using Simphony.NET.

Chapter 5 applies the simulation tool to the Mill Woods Double Barrel (MWDB) project.

Chapter 6 introduces a conceptual presentation for a multi-user support system for collaborative environments using the CoSyE framework based on HLA rules.

Chapter 7 presents research conclusions, contributions, and recommendations.

CHAPTER 2. BACKGROUND

This chapter explores different components that will be used in this research, starting from project planning techniques, simulation, construction simulation, *Simphony*, scenario planning, and finally FIATECH and its vision. The purpose of this chapter is to build a better understanding regarding the needs of the construction industry and the proposed tool.

2.01 Introduction

Project planning, one of the most crucial steps in construction operations, defines the objective of the project, sets the goals, and determines how they will be achieved. During the planning phase, specific activities should be defined, the schedule created, and the cost calculated. According to the Project Management Institute (Wideman 1986), the discipline of project management can be defined as "the art of directing and coordinating human and material resources throughout the life of a project by using modern management techniques to achieve predetermined objectives of scope, cost, time, quality, and participation satisfaction."

Currently, most project planning initiatives involve a number of teams, each consisting of engineers, superintendents, estimators, coordinators, and managers working collaboratively to devise the project plan. For example, work packages must be completed, resources located, and construction methods and project costs determined.

2.02 Project planning techniques

There are many project planning techniques. Most are related to general planning and not specific to the construction industry. Others were developed to deal with repetitive construction activities. In general, three steps are required to plan for a construction project. The first step is to define the activities required to finish the job and their durations; the second step is to arrange activities sequentially; the last step is to create a schedule for the project.

Bar charts are often used to represent the project schedule. The user defines the basic activities as horizontal strips tracked against the variable of time. Other information, such as resources or relationships with other activities, is also shown.

The task of developing these bar charts was simplified by using computer systems such as Primavera and Microsoft Project. These systems allow the user to create schedules for a large project by introducing hierarchical structures to the system. These also help with resource levelling.

These computer systems use critical path method (CPM) as the methodology for calculating the project duration. CPM has many limitations, the main one being that activity duration is constant. In reality, construction is unpredictable due to the high number of uncertainties involved. Program Evaluation and Review (PERT) takes care of uncertainty in construction activity durations. PERT uses the same methodology as CPM to calculate the project duration; the only difference is that PERT uses a distribution to represent activity duration. Based on the central limit theorem, the outcome of the combined activity durations is a normal distribution.

Monte Carlo simulation takes a more general probabilistic approach to scheduling. The overall project duration is calculated by running a simulation a number of times. During each run, activity duration is calculated randomly based on the distribution representing the activity duration. The total project duration is the normal distribution of the predicted project durations.

The Liner Schedule Method (Johnston 1981) was developed to deal with the repetitive or cyclic activities within a project such as building a high-rise or highway construction.

These methods assume that the resources needed to complete the activities are available all the time when needed. Russel and Dubey (1995) developed a process for resource allocation that allows the user to level a given resource in order to obtain a schedule. However, it was shown that these methods failed to represent some realities of construction projects, specifically the way in which construction projects are characterized by complex, dynamic interaction between resources and processes (Paulson et al. 1987) and the ways in which construction methods vary based on project conditions.

All of the above methods led to the development of simulation-based planning for construction projects.

In the city of Edmonton, with the help of the construction engineering group at the University of Alberta, simulation has been used for years to plan a number of projects, specifically in relation to tunnelling. The *Simphony* framework is used to simulate most of the tunnelling projects undertaken by the City of Edmonton. With any simulation model, the process must be studied closely to devise the best possible representation. In tunnelling construction simulation, a number of visits to the project site must be conducted to record the activities involved, and to note the durations and required resources. These resources include workers and materials or equipment. Equipment, for example, is susceptible to breakdowns, so possible breakdowns should be modelled. As well, material delivery delays could become crucial in determining a project's duration, so the simulation model should include a supply-chain component.

The City of Edmonton uses simulation as a planning tool during the pre-construction planning phase. In this phase, a number of alternatives are proposed for a specific project. Then, a simulation model is created for each alternative, and a comparison helps to determine the best choice. During construction, simulation can also help to predict the completion date as well as the expected cost of the project.

2.03 Simulation

Pristker (1986) defined computer simulation as "the process of designing a mathematical logical model of a real world system and experimenting with the model on a computer." Paul Fishwick (2008) further defined computer simulation as "the discipline of designing a model of an actual or theoretical physical system, executing the model on a digital computer, and analyzing the execution output."

Early simulation users used FORTRAN and other languages to develop simulation models by writing a programming code and changing the code to experiment with the model. After that, simulation-specific programming environments, in which the user develops simulation by writing specific code, were invented. Modelling terms were subsequently introduced to represent a given simulation model. The introduction of a host of systems that allowed for alternative model development was the next major development in simulation, so that the modeller was no longer required to write code. Later, graphical modelling was developed, allowing the user to define the simulation model by using basic building blocks. To create a model, the user need not be proficient in programming (Kreutzer 1986).

To model a problem, the user can employ either discrete event simulation or continuous simulation. In discrete event simulation, the point of time when the system changes is represented and the system is modelled as a series of events, or instances in time when the state-change occurs; an example would be a queue servant system. In continuous simulation, the state of the system changes with time, not in a discrete fashion; an example would be a chemical reaction.

Object-oriented simulations are used to help users develop reusable and modular simulation models. Simula (Ahi and Nyguaard 1966) was the first object-oriented simulation system (OOSS) to support full data encapsulation, inheritance, and polymorphism. It was built using the ALGOL language. In 1986, SmallTalk was developed (Ulgen and Thomasma). OOSS allowed the users to develop a graphical representation for real life objects, building simulation models in a graphical user interface (Bischak and Roberts 1991).

In 1989 Ulgen et al. developed SmartSim, which used object-oriented concepts to present users with a set of elements that could be expanded by building new elements based on the basic ones.

Modular modelling is the process of linking a number of simulation models together to produce a new model. Modules communicate with each other through input and output ports. As well, two modules can be combined to create a new module with its own input and output ports. This development furthered the concept of hierarchical modelling. In 1984, DEVS was presented by Ziegler as a theory for discussing how these concepts can be implemented for discrete event simulation systems.

2.04 Construction simulation

Halpin (1977) introduced the cyclic operation network (CYCLONE) to the construction research community, popularizing the use of simulation in construction research. CYCLONE allows the user to develop simulation models using a set of abstract but simple constructs. The system becomes the basis for a wide range of construction simulation research efforts with the objective of enhancing the basic system's functionality. These measures have included INSIGHT (Paulson 1978), UM-CYCLONE (Ioannou 1989), and REQUES (Chang and Carr 1987). STROBOSCOPE (Martinez and Ioannou 1994) is another CYCLONE-based development, through which the user is able to define entity and resource attributes. A graphical representation for CYCLONE elements was introduced by Huang et al. (1994) through DISCO.

Even though the presentation of CYCLONE and its derivatives introduced computer simulation to the construction research community, its use in the industry was limited as CYCLONE proved practical only for use in small-sized applications. Furthermore, users of CYCLONE were required to be experts in simulation, which demanded training that the industry was not usually ready to invest in for such limited return. Accordingly, researchers started to investigate new concepts to simplify the simulation process.

In 1991, object-oriented concepts were introduced to construction simulation by Chang. This improved readability and allowed users to create simulation models that resembled real life. As a result, the gap between the physical system and its computer representation was bridged (Oloufa 1993).

Model reusability was achieved by applying general simulation concepts in the development of modelling tools. Tommelein (1994) and Shi (1997) utilized a library-based modelling approach that allows project simulation models to be assembled for a set of pre-defined components. The concept of modular modelling was also used to a certain extent. Modular concepts based on those defined by Ziegler (1984) were utilized by Sawhenyc (1996) to develop large-scale simulation systems.

2.05 Simphony.NET

Simphony is a simulation environment developed by the construction engineering research group at the University of Alberta to model construction operations. It supports the development of special purpose simulation (SPS) as well as general purpose simulation (GPS) (AbouRizk 2000).

The concept of SPS provided a crucial step in helping the industry to accept simulation as a viable project planning tool. It helps users who are not knowledgeable in simulation to use simulation in their domain of expertise by developing a visual model to represent the actual construction system. *Simphony* has a number of SPS templates, such as the earth moving template developed to analyze earth moving operations; the PERT template used to run Monte Carlo simulation for scheduling; the tunnelling template used to simulate tunnelling operations from the tunnelling boring machine (TBM) excavation to dumping the dirt using the crane; and the range estimating template used for running Monte Carlo simulation to estimate the project cost.

GPS are used to simulate any system using a process interaction concept. *Simphony* has two GPS templates: the common template, which has all the features required for any standalone general purpose simulation tool, and the

CYCLONE template, which has the standard CYCLONE elements (queue, normal, combi, generate/consolidate). To be able to use the common template, users must have some knowledge of simulation.

The *Simphony* environment provides a number of services such as: Simulation, where *Simphony* supports discrete event simulation including event scheduling as well as contentious simulation; Statistical, which supports the collection of standard statistic averages, standard deviation, minimum and maximum, and also supports graphical representation of the statistics collected via cumulative density function (CDF), histogram, and time graph; Tracing, which allows the user to trace the results and also helps the developer and the user to debug the simulation model; and Animation. Figure 2-1 shows the *Simphony* interface.

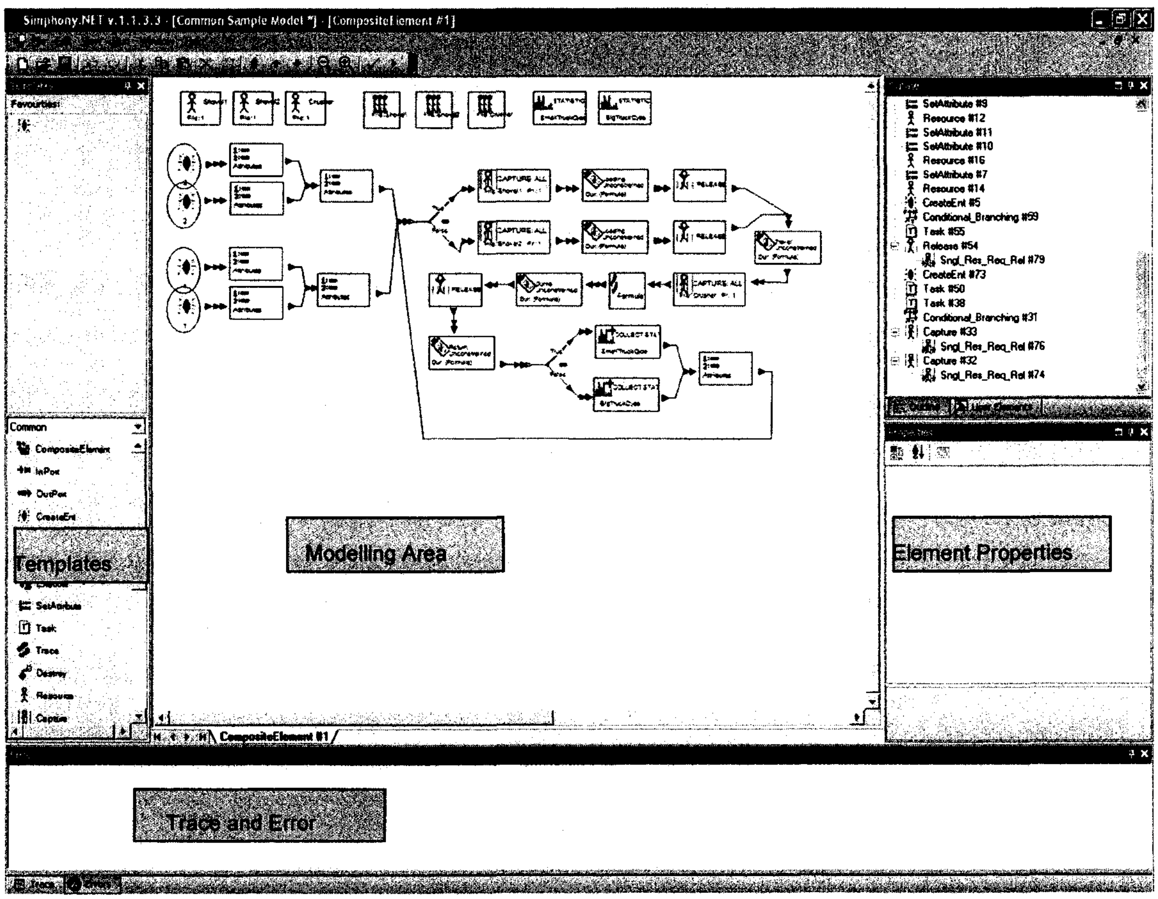


FIGURE 2-1 *SIMPHONY* INTERFACE

Simphony.NET is the second generation of *Simphony*, using the .NET framework to make simulation process runs faster and smoother. It has been built based on the same rules used by *Simphony* and based on the unified modelling methodology presented by Hajjar and AbouRizk (2002).

In this approach, the simulation model is presented as an instance of a modelling element. Each set of elements using the same modelling element will have the same code, but will be distinguished by their own properties (see Figure 2-2).

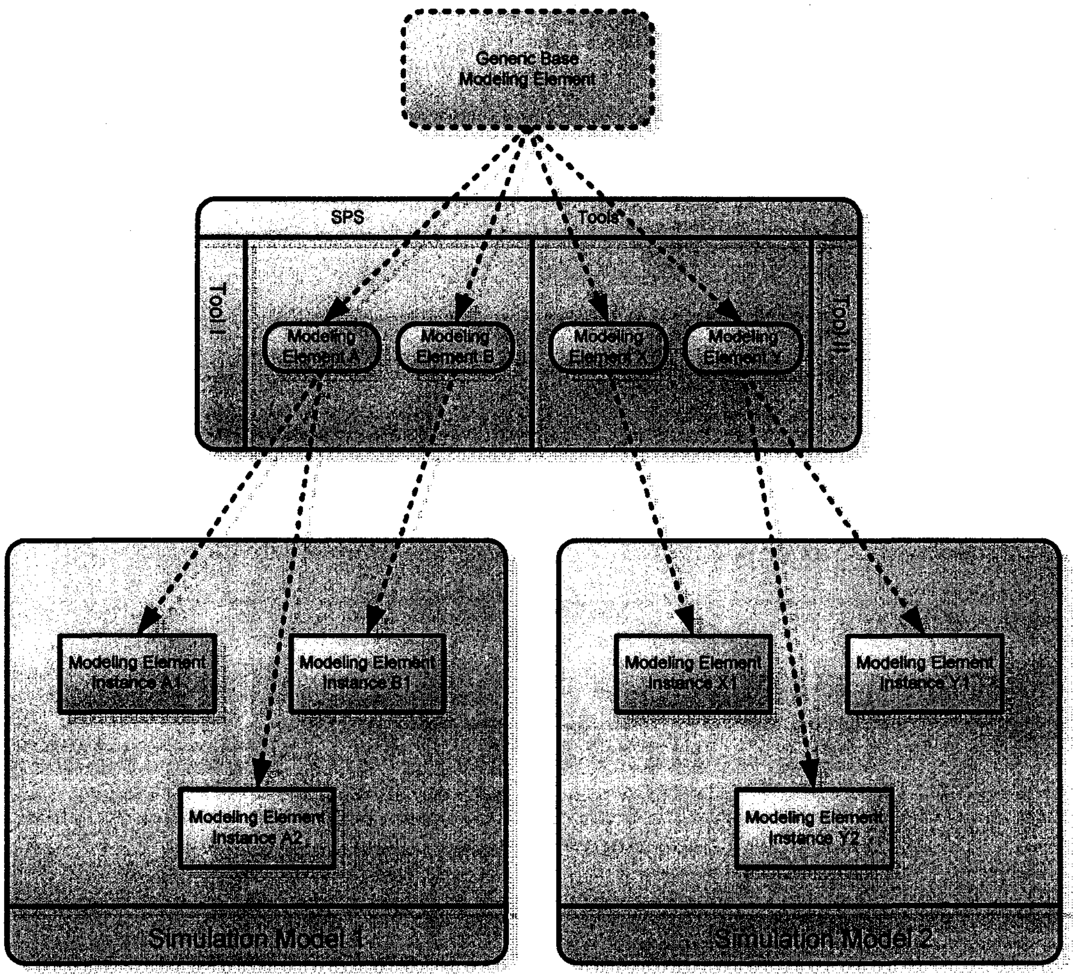


FIGURE 2-2 STRUCTURE OF SIMULATION MODELS BASED ON UNIFIED MODELLING METHODOLOGY (HAJJAR AND ABOURIZK 2002).

Simphony provides a user-friendly and highly flexible simulation environment for developing models. The program supports the following (Hajjar and AbouRizk 2002):

- Modular and hierarchical modelling for use in complex and large construction projects
- Standard modelling templates such as PERT simulation, Range Estimating, GPS, CYCLONE, and many other SPS type templates
- The ability to combine a number of templates to build a simulation model
- Generation of custom outputs in different forms such as tables and graphs
- Automated generation of externally accessible project planning data in a standard format
- Script-based modelling for advanced users
- A user model library which enables the user to easily access commonly used simulation models
- An integrated development environment-style interface for tool development

2.06 Distributed simulation

Distributed simulation has matured over the last few decades since it surfaced in the 1970s. These days, it is used for many applications, such as military training, analysis of communication networks, and in air-control systems. Distributed simulation is concerned with running a simulation model on a number of computers, in which interactions take more time and occur less often. It includes running the simulation model on geographically scattered computers connected by a network connection, such as the internet.

There are two major categories of application for distributed simulation. The first category is concerned with the analysis of a certain system (e.g. to compare a number of alternatives for a complex system, such as air-traffic control). In this case, we are interested in computing the results of the model as fast as possible to use the simulation in an effective manner. For example, by evaluating the available actions as quickly as possible for an air-traffic network, delays that occur because of inclement weather could be reduced. The second category is concerned with the application towards developing virtual environments and 3-D visualizations for training, entertainment, and evaluation of devices. This category is widely used in military training because it is safe and cost-effective.

Distributed simulation provides numerous benefits compared to the classical simulation programs (Fujimoto 2001):

- By dividing the simulation model among a number of computers, the execution time for analytical simulation is reduced. The simulation time can also be reduced by a factor equal to the number of processors used in the simulation. This is clearly an important advantage of distributed simulation in comparison to other types, some of which require several days to run a complex simulation model.
- In online and real-time simulation, quick executions are important since there is ordinarily little time to make decisions. It is important for the virtual environment to execute in real time.
- A distributed virtual environment can be achieved by using distributed simulation.
- Machines from different manufacturers can be integrated using distributed simulation. For example, the flight simulators among different aircrafts.
- Multiple development teams

- Independent but interoperable model development
- Joining and resigning running simulation models
- Different simulation algorithms
- Human/hardware-in-the-loop capability
- Large-scale modelling capability
- Support for intelligent agents

2.07 High Level Architecture (HLA)

HLA is a set of general rules created to manage the development of distributed simulation environments. It was first developed by the U.S. Department of Defence (DoD). The HLA approach supports complex, multi-layer, multi-user applications, such as those in the construction industry. HLA supports complex virtual environments (federations) using distributed simulation technologies. Also, it provides the rules to develop individual components (federates) of such environments by different developers while maintaining interoperability between them. The HLA standards facilitate the reusability of the developed components. These standards consist of three main components: the HLA rules, interface specifications, and the Object Model Template (OMT). HLA rules must be enforced if a federate or federation is to be regarded as HLA. The interface specification defines the functional interface between federate and run-time infrastructure (RTI). The RTI is software that conforms to the HLA specifications and provides software services, such as synchronization, communication, and data exchange between federates to support an HLA-compliant simulation.

These services fall into six main areas:

- Time management
- Object management
- Declaration management

- Federation management
- Ownership management
- Data distribution management

To promote collaborative modelling, reusability, and interoperability, all objects and interactions managed by a federate and visible outside the federate should be specified in detail under a common format. The Object Model Template (OMT) provides standards for documenting HLA object modelling information and consists of three parts: the Federation Object Model (FOM), the Simulation Object Model (SOM), and the Management Object Model (MOM).

2.08 Scenario planning

Success and planning in business go hand-in-hand. For each company to achieve its goals, it should create a plan using the many planning tools available. In this thesis, we will focus on scenario planning. During the planning stage, a number of scenarios will be evaluated. Each scenario represents a future; by examining all possible futures, the company will be able to build a crisis plan for any situation that may occur in the future (Van Der Heijden 1996). The company will also be able to reduce cost and time for the project by eliminating all issues upfront instead of dealing with each problem as it occurs. Through applying scenario planning, many lessons can be learned and a knowledge bank can be created to help the company to avoid the same issues every time.

For any company to build a strategic plan that fits its goals, it should build its strategy based on a number of elements, such as: the company's main future objectives, assessment of the company characteristics, assessment of the current and future environment and the interaction between them, and development of policies. Following from this, the company can determine decisions and act to improve weak areas (Van Der Heijden 1996).

Daum (2001) defines scenario planning as "the process in which managers invent and then consider, in depth, several varied scenarios of equally plausible futures with the objective to bring forward surprises and unexpected leaps of understanding." Simpson (1992) presented scenario planning as "the process of constructing alternate futures of a business' external environment. The goal is to learn to use these alternative futures to test the resiliency of today's action plan."

Scenario planning has been used by the military for many centuries as a strategic planning tool; it is still used today for building war game simulations to help military bodies prepare for war. Although it dates back further, the first written documents regarding scenario planning date to the 19th century, as written by Clausewitz and Moltke, a Russian military strategist who is also credited with developing key strategy planning principles (Boeri 2004).

In the 1940s, General (later Field Marshall) Sir Alan Brooke used scenario planning during World War II. The first formalization of scenario planning came during the 1950s. Following World War II, the U.S. Air Force, with the help of the RAND Corporation, used this method for training soldiers to start imagining what their opponents might do in the future and to start building alternative strategies to prepare for them. Scenario-based planning began to grow after that, and was first used in business in 1960s based on the influence of Herman Kahn (Wack 1985). In the 1970s, scenario planning reached new heights based on the implementation of Pierre Wack, who worked for a newly formed planning group for Royal Dutch/Shell, where he and other planners came up with different scenarios that might affect the price of oil. Some of these potential futures prefigured the oil price shock of 1973, preparing Royal Dutch/Shell for its shake-up to the oil industry (Daum 2001).

During the 1980s and 1990s, the growth of scenario planning escalated with the understanding that complex systems carry a degree of intrinsic unpredictability that cannot be reduced by increased analysis (Boeri 2004). From this, the potential of organizational learning through scenario planning became clear.

Scenario planning was originally created based on the predict-and-control approach, replacing the forecast component with a probabilistic assessment that helped in predicting the most likely future. This advancement didn't provide a fundamental change from other forecast approaches (Van Der Heijden 1996).

To operate in an uncertain world, managers need to be able to question their assumptions about the way the world works in order to see the world more clearly. The purpose of scenario planning, therefore, is to help managers change their view of reality in order to match it up more closely with reality as it is and reality as it is going to be. The end result, however, is not a more accurate picture of tomorrow, but better decisions in the present (Daum 2001).

Scenario planning is an attempt to describe what is possible rather than forecasting the future. The outcome of each scenario is a different future, all of which are plausible. The challenge is in determining how we can prepare for each future.

Scenario planning usually takes place in a workshop setting with different levels of experts; the point of this structure is to have a wide range of ideas from which the group can produce more scenarios than those usually considered. The process should include the personnel that will be involved in applying the strategy based on the scenario analysis. Without their input, the scenario may lack consideration of a number of important issues that should be included in the strategy (NetMBA 2008).

Scenario planning has number of benefits: it helps managers expose the blind spots in project plans and forces them to look outside the box; also, it is easier to define scenarios in the early stages of the project. The method helps managers to identify and realize the reasons for disagreements during the evaluation of different scenarios (NetMBA 2008).

In construction, scenario planning is used to define the best course of action for constructing a project. It helps planners to fully understand the project and prepare for any unforeseen issues that may arise during construction.

2.09 Scenario planning process

Scenario planning is a process through which the project team develops a number of scenarios. Each one of these scenarios represents a story about the future. This story should be possible; it can be extreme, but it shouldn't be a guess or sensitivity simulation (Boeri 2004).

Daum (2001) presented the steps of the scenario planning process as follows (see Figure 2-3):

FIGURE 2-3 SCENARIO PLANNING PROCESS (DAUM 2001)

1. Uncover the decision. During this step, the major issues that will affect the company's future have to be defined.

2. Information hunting and gathering. A scenario is a story that represents the future; to create a realistic story, information from real life should be collected to build our scenario assumptions.

3. Identifying the driving forces of a scenario. This is the first step in building the scenario. The project team should define the driving forces that will affect the major issues defined in the first step.
4. Uncover the predetermined elements. During this step, all certain elements or components should be highlighted.
5. Identify critical uncertainties. Uncertain elements should be defined, then grouped into critical and non-critical based on the major issues identified in step 1.
6. Develop the scenarios by combining the predetermined elements with uncertain elements to create different scenarios.
7. Analyze the implications of the decisions according to the scenarios, and return to step 1 to examine how each issue represented in each scenario.
8. Select leading indicators and signposts. During this final step, a number of monitoring identifiers will be selected to evaluate the project in an ongoing way.

2.10 Current simulation-based planning practice in the City of Edmonton

Simulation has been used for number of years in construction project planning by the City of Edmonton Drainage Services Department for preconstruction analysis. During the preconstruction phase, the project team usually runs a number of workshops to discuss the project and define parameters such as project definition, scope, goals, construction methods, and more.

The project team usually begins with a concept design workshop to define a number of alternatives for constructing the project. Once all alternatives have been defined, the team decides if they will require a value engineering workshop to help them select the best alternative. If yes, another workshop is scheduled, but before meeting, a schedule—typically CPM—and cost estimate should be created for each alternative. During the value engineering workshop, the project team will evaluate each project based on a set of evaluation factors; the project team will select the best alternative based on the highest score at the end of the workshop. The next step is to run a risk analysis workshop in which the project team defines all risk factors related to the alternative they selected and creates a mitigation plan. In some cases, the project team may change the alternative to another one due to the high risk associated with it.

Current practice doesn't include a structured workshop dedicated for scenario planning. Instead, it has been included indirectly in the preconstruction process, as shown in Figure 2-4.

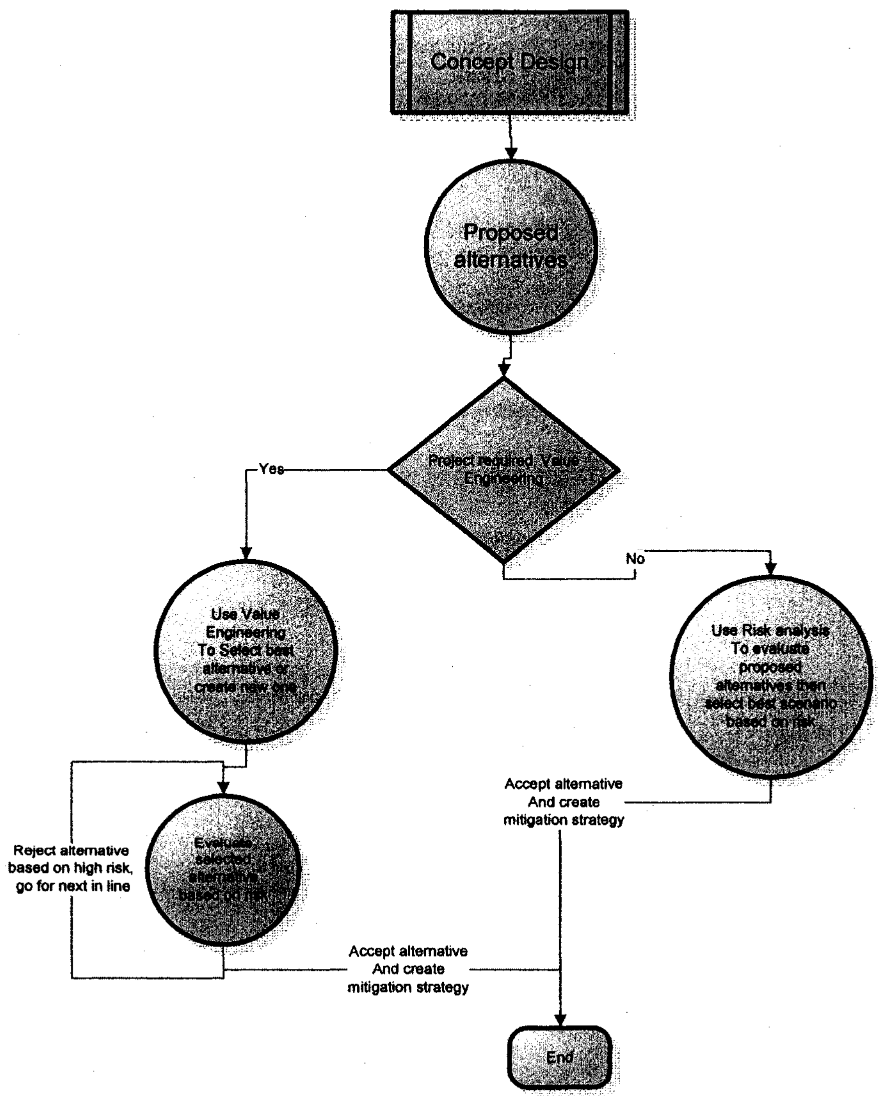


FIGURE 2-4 ALTERNATIVE PLANNING IN CONSTRUCTION BY THE CITY OF EDMONTON.

This thesis presents a scenario-based planning tool based on FIATECH's "Capital Projects Technology Roadmap". The tool will help accelerate the decision-making process by allowing project planners to run the scenarios in real time and examine the results, which include cost, schedule, productivity, resource handling, and material delivery.

2.11 FIATECH

FIATECH is a non-profit association that works with the construction industry to develop fast-track technologies to help improve capital projects in a number of phases, such as design, engineering, build and maintain (FIATECH, "About Us" 2008). They focus on the deployment of existing technologies in the construction industry, as well as any others that may be useful. They also work to enhance and implement industry-wide standards and guidelines for capital projects. FIATECH works on number of projects, including IT applications, chip technologies, web databases, and wearable computing devices.

2.12 FIATECH Capital Projects Technology Roadmap

FIATECH presented a comprehensive vision in their roadmap for planning in the capital projects industry, which is a crucial part of the construction industry that provides infrastructure to the economy (FIATECH 2004). This roadmap proposes a highly automated integrated project planning process using advanced technologies in all phases of the project and its life cycle. The project information will be available on demand for all project stakeholders at any phase. In this integrated environment, all users will be able to interact with each other. This automation of the system and its processes will reduce the time and cost of planning. Scenario-based planning systems will help in selecting the best scenario to complete the job by accurately evaluating all options available. Figure 2-5 shows the roadmap, which consists of nine elements as follows (FIATECH 2004):

- Scenario-based project planning
- Automated design
- Integrated, automated procurement and supply network
- Intelligent and automated construction job site
- Integrated self-maintaining and repairing operational facility

- Real-time project and facility management, coordination and control
- New materials, methods, products, and equipment
- Technology- and knowledge-enabled workforce
- Life cycle data management and information integration

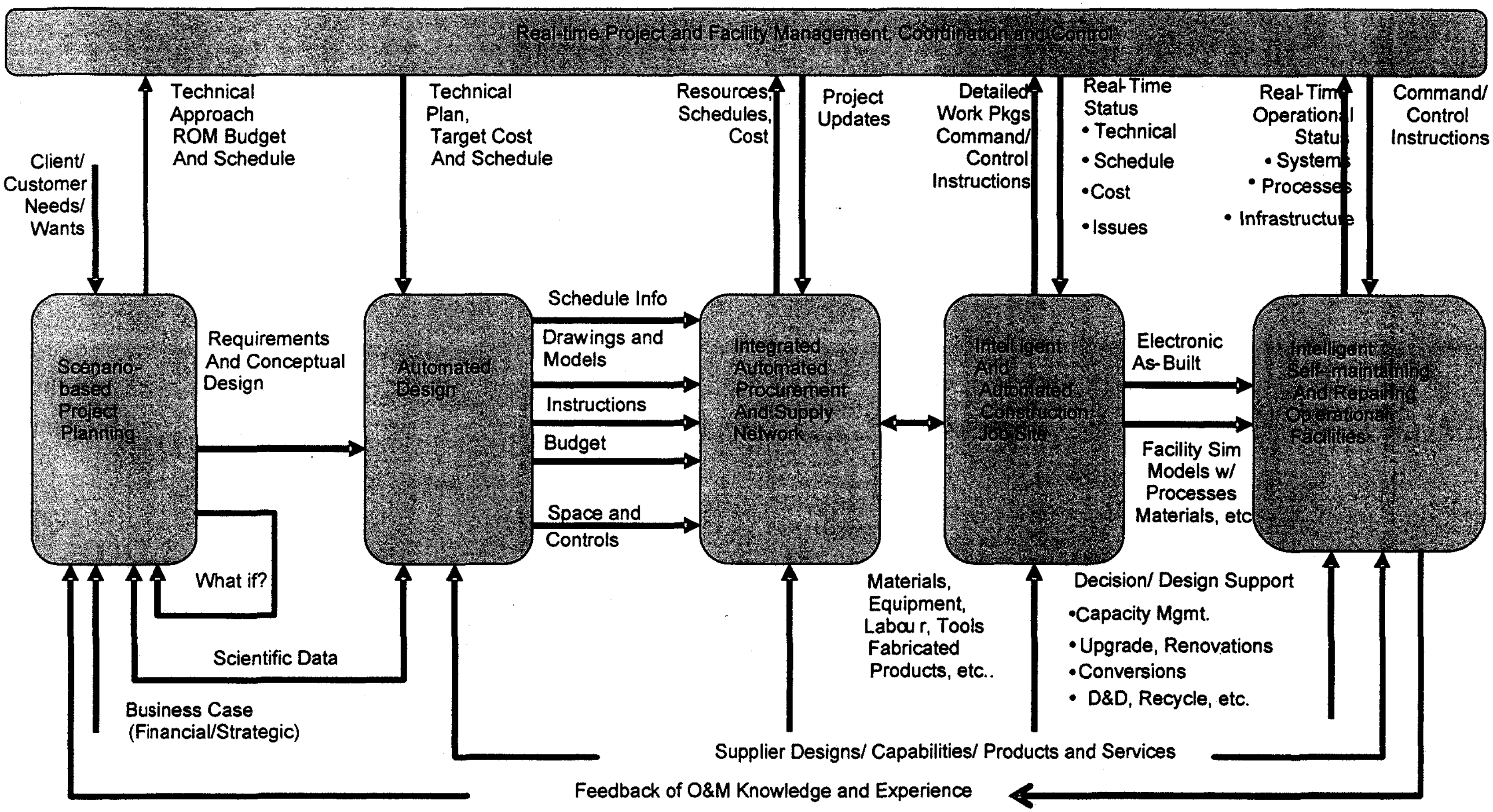


FIGURE 2-5 FIATECH CAPITAL PROJECTS TECHNOLOGY ROADMAP (FIATECH 2004)

2.13 Scenario-based project planning

Scenario-based planning is one of the most efficient methods for exploring the future and developing the best strategy to achieve the goals set for any project. It helps anticipate and leverage change, encourages out-of-the-box thinking, reduces the risk associated with the project, and provides a consistence approach for project planning (SRI, "Scenario Planning" 2008).

FIATECH presents scenario-based project planning as their starting point for project planning. A comprehensive and collaborative project system will be presented in the future to assist the planning team as well as to provide the initial data capture to be used throughout the lifecycle of the project (FIATECH, "Scenario-Based Project Planning" 2008). This system will help the project team to evaluate a number of alternatives and then enable them to create the project plans and design. The system will be able to incorporate the cost, schedule, and life cycle performance based on the decisions made. The comprehensive plans and specifications will be initially provided by the future project planning system under development.

2.13.1 Work processes

A set of requirements and plans will be developed and refined by the project team, interacting with customers and stockholders to review different options. These options will be studied and evaluated using integrated modelling and simulation tools, which allow fast real-time evaluation of scenarios to find the best solution for the project within the context of its life cycle. Based on the project decisions, the detailed model will be created using the conceptual design. Then, the selected scenario can be revisited and evaluated on the milestones level or at critical decision stages to modify or evaluate the subsequent project planning phases. Conceptual design can be iterated by the project team by interacting with the design team, using simulation tools that allow planners and designers to view and concur on such project areas as functionality, layouts, flow sheets, and construction strategies (FIATECH, "Scenario-Based Project Planning" 2008).

2.13.2 Technology enablers

The use of modelling and simulation tools will enable the project team to evaluate and quickly capture, iterate, and find the best solution based on accurate and complete data by linking the simulation to the project's life cycle and other external information sources (FIATECH, "Scenario-Based Project Planning" 2008).

The modelling and simulation tools will help the project team define what to build, where to build, and how to build the capital project, as well as enable risk assessment. The impact of risk and business factors can be used to evaluate scenarios such as site selection, technology selection, current and future needs, and facilities and maintenance operations.

2.13.3 Project planning problems

Even with all the technology advancements in design, construction, and facility operation, project planning still lacks automated technology. It is carried out by a project engineer who may or may not have experience and full understanding of all of the project's internal and external factors and their complex interactions. There are no available automated scenario planning modelling and simulation tools to help decision makers, which will allow for only minimal optimization in the project plans (FIATECH, "Scenario-Based Project Planning" 2008).

2.13.4 Opportunities and challenges

The major benefit of scenario-based planning is the ability to represent a comprehensive understanding of all the issues and risks for the project and develop an alignment among the project team and stakeholders based on the work during this phase. This leads to better communications and helps to eliminate the cost of the errors upfront, improve agreement between stakeholders, and define a number of options faster and more easily (FIATECH, "Scenario-Based Project Planning" 2008).

As stated by the International Institute for Sustainable Development, relative to business strategy, "the aim is to seek win-win situations which can achieve environmental quality, increase wealth, and enhance competitive advantage...In the pursuit of economic, environmental and community benefits, management considers the long-term interests and needs of the stakeholders" (BSDglobal, "The sustainable development journey," 2008). The goal of scenario-based planning is to provide the stakeholders with win-win situations.

However, modelling these relationships will be very difficult because they differ for each project due to its unique factors. The big challenge for scenario-based planning is to be able to understand and incorporate complex interrelationships of variables to achieve the best decision. Some examples of these variables include: site selection, schedule, budget, project strategy, production design, and risk assessments (FIATECH "Scenario-Based Project Planning," 2008).

2.13.5 FIATECH scenario-based planning variables

Each construction project is complex and unique; although the same concept can be applied to any tunnelling project, there are many unique variables for each tunnel, including ground conditions, TBM condition, site location, associated risk factors, tunnel size, tunnel depth, etc. A scenario-based model for a tunnelling project is difficult to construct due to the complexity and variation for each project, and the interrelationship between all these variables mentioned above. A key component in using scenario-based planning in an effective way is to fully understand the variables and their interrelationship to formulate the best decision. Following are a number of variables to be considered in scenario-based project planning (FIATECH "Scenario-Based Project Planning," 2008):

- Site selection
- Facility technology
- Project strategy
- Sourcing and procurement
- Schedule
- Project budget

- Risk assessment and contingency planning and exit strategy
- Information asset
- Business requirement flexibility

2.14 Summary

This chapter presents the advancement in project planning techniques over the years and the superior advantage simulation has over other tools. Also it show cases the strength of scenario planning as a project planning method. FIATECH in their vision showed scenario planning as a major component in any comprehensive planning system. A scenario-based planning framework for construction tunnelling project will be developed in Chapter 3 using HLA concepts.

CHAPTER 3. SIMULATION-BASED PROJECT PLANNING FOR TUNNEL CONSTRUCTION

In this chapter, we will present the current state of the art for construction project planning in tunnelling projects used by the City of Edmonton, a major public sector constructor in western Canada. A number of projects will be presented in detail.

We will conclude by introducing a conceptual scenario-based planning tool using HLA concepts. Using HLA will enable us to develop a tool with support for reusability and integration.

Simulation plays a key role in improving construction operation through planning. The City of Edmonton used simulation for many years to help plan for a number of tunnelling projects, such as the North of Edmonton Sanitary Trunk (NEST), the Glencoe Tunnel in Calgary, and the South West Sanitary Trunk (SW2&3). Simulation can be used for pre-construction planning as well as during construction to help overcome problems encountered during construction.

3.01 Scenario-based planning development for tunnelling projects

To develop our scenario-based planning framework, we took the following steps. The first step was to study the tunnelling process; we accomplished this through site visits to tunnelling projects in Edmonton, where we completed in-depth analysis of the operations. We also attended a number of planning workshops for a number of projects. This was supplemented by a study of the state of the art in simulation tools used for planning. The next step was to define system components based on features extracted from site visits, current simulation tools, and case studies evaluation. The third step was to represent these features using HLA concepts. The fourth and final step was to demonstrate the system using *Simphony* templates.

3.02 Tunnelling project

Preconstruction evaluation is a crucial step in the life of a project. During this step, the project team discusses all issues related to project construction and proposes a number of scenarios to execute the project. These scenarios are then evaluated based on number of criteria, such as production, cost, schedule, risk, etc.

To help evaluate these criteria, the project team can use a number of tools. One of these tools is simulation modelling, in which a simulation model is created for each scenario, and based on the simulation results the project team decides on a project plan. However, before starting to build simulation models for a tunnelling project, the simulator should closely examine tunnelling project components.

Selecting site location is the first step in any tunnelling project. In this stage, the project team should look closely into a number of factors, including availability of water supplies, electricity, easy access points, space to store material on site. After selecting the site, the project team should specify the location for each component that will be used during the construction, including crane, dirt stockpile, material stockpile, crew parking, crew trailer, working shaft, the size of the working shaft, access gates, etc.

The next step is to excavate the working shaft. The shaft could have a circular or rectangular shape. If the shaft is rectangular or circular with a diameter larger than 14.7 ft, workers will use piles to excavate the shaft; they will install the piles up to 25 m deep and then use a backhoe to excavate the shaft. If the shaft is deeper than that, hand excavation using rib and lagging will be used. If the shaft is circular with a diameter less than or equal to 14.7 ft, workers use a machine to drill the shaft in sections: the first section is 14.7 ft in diameter with a depth up to 10 m; the next section will have a 12 ft diameter with a depth up to10 m; the last section is up to 10 m in depth with a diameter of 10 ft. After that, the crew uses hand excavation to expand the 12 ft and 10 ft sections to the required diameter using rib and lagging. In both cases, a safety wall should be installed.

After finishing the shaft to the depth required, the crew starts excavating the tail tunnel, which will be used for material handling during excavation, and the undercut, which will be used to assemble the TBM.

After installing the TBM, the workers can start digging the tunnel. In the beginning, TBM tunnelling will be slow due to using a single dirt car, and due to frequent stoppages. The crew must install the gantry and conveyor belt sections after the TBM finishes excavating a section length. They must also install a liner, and every time the crew completes a specified number of sections, they msut to stop to install tracks for the train. As well, there is surveying required.

Once the gantries and conveyer belt have been completely installed, usually enough for the length of a train, the crew can use a full train designed to carry the length of a TBM section. Tunnelling will then stop to install switches, which allow workers to use two trains to accelerate the tunnelling operation. After that, full-capacity tunnelling can begin. The train travels to the TBM and unloads the material car, which may contain concrete liners or rib and lagging. Then, the TBM starts to excavate the section: if the material is concrete liners, the section is usually 1 m; if rib and lagging, the section is usually 4 ft, as specified by the City of Edmonton. When the train is full, it starts travelling toward the working shaft at the same time as the TBM starts installing the material to support the tunnel. Once the full train reaches the working shaft, the other train (if empty) starts travelling toward the TBM. When that train reaches the TBM, it starts excavating the next section, if TBM is done with installing the material. If not, the train waits. When the train reaches the working shaft, the crew checks whether the previous train has finished unloading. If yes, the train can start unloading the dirt and loading the material; if no, the second train should wait for the previous train to finish loading or unloading.

This operation will continue until the TBM reaches the end of the tunnel. By that time, the removal shaft will be excavated in the same way as the working shaft, and then the TBM will be removed from the tunnel (see Figure 3-1).

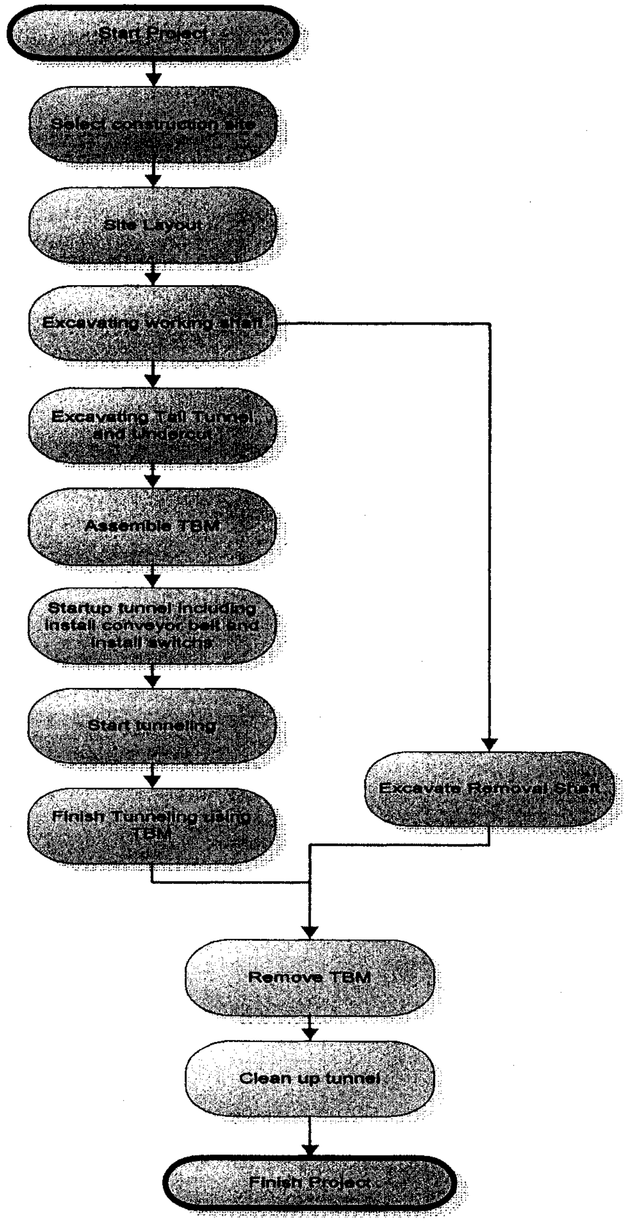


FIGURE 3-1 TUNNELLING PROJECT ACTIVITIES

3.03 Tunnelling simulation

To build a representative simulation model for any construction operation, a number of components should be addressed. These components include: physical components, construction operations, material, and resources.

3.03.1 Physical components

A utility tunnel usually has a number of physical components: a working shaft where the construction usually starts; a tail tunnel and undercut used to install the TBM and later used to accommodate the trains used in dirt removal; tunnel excavation, which involves soil sections, each with its own properties; and, finally, a removal shaft to finalize the tunnel. To develop a simulation model for a utility tunnel, these components should be represented in the model (see Figure 3-2).

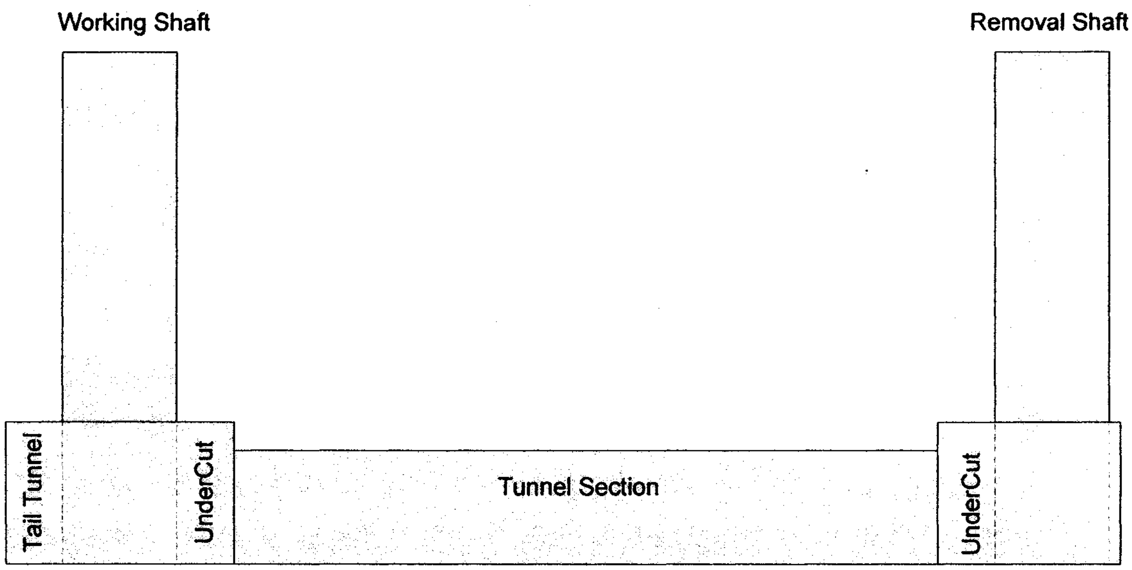


FIGURE 3-2 TYPICAL UTILITY TUNNEL PHYSICAL COMPONENTS

3.03.2 Construction operations

For each component we presented in the previous section, a construction procedure should be modeled. For shaft, both working and removal shaft can have many shapes—in most cases circular or rectangular. For large-sized shafts, piles can be used to help accelerate excavation. To excavate the shaft, we can use drilling machines up to a certain size, hand excavation, or excavation machines such as backhoes. Usually rib and lagging are used to line the shaft.

The tail tunnel and undercut are constructed by using hand excavation and rib and lagging to support them. After excavation of the tail tunnel and the undercut has finished, the TBM can be installed and the crew can start excavating the tunnel. The process of excavating the tunnel is the main part of any utility tunnel simulation; the tunnelling duration and cost will be highly affected by the progress of this activity. The project team usually uses production values calculated from the excavation activity as a project control value for the overall project performance. The process begins with the train travelling to the tunnel face where the TBM is waiting. The TBM starts excavating and fills the train cars. Once the train is full, it travels back to the shaft area and the TBM starts installing liners. When the train arrives at the shaft area, the train starts unloading the excavated material using a crane or a hoist. After it finishes dumping, the crane will load the train with liner material. In most cases, tunnel excavation uses two trains to maximize TBM utilization time. This cycle continues until the end of the tunnel.

3.03.3 Material

In any construction project, material delivery can affect the schedule and consequently the cost. In tunnelling projects, three main material types must be dealt with. The first one is the tunnel support liners, which could be concrete liners or rib and lagging. Without these, the tunnel excavation cannot continue. The second type is the excavated dirt stockpile. In some cases, the tunnelling site has limited space and cannot store a large volume of dirt; if the volume reaches the maximum, the tunnel will shut down. The last type is the TBM parts. Most of the time, the TBM owner does not carry all TBM parts; in this case, when the TBM breaks down, the owner must request the part, which will affect the project progress.

All of these types of material handling should be modelled in any tunnelling simulation.

3.03.4 Resources

No construction project can be executed without resources. Any simulation model without resources cannot give a comprehensive view to all project components. Tunnelling projects have a number of these resources, and all others should be included in the simulation model. The resources can be manpower or machine: machines used by the tunnelling crew are cranes, TBM, loaders, and others. Some of them are critical, such as TBM and crane, while others are not that critical. Having these resources modelled will help identify the utilization of each resource.

3.04 State of the art in practice

After exploring the tunnelling process in depth, we explored the current state-of-the-art simulation tools used for planning by studying a number of case studies. These case studies include the NEST, Glencoe, and SW2&3 tunnels. In the following sections, we will discuss each one of them in detail. The detailed analysis shown in the next sections is based on a risk analysis and constructability reports prepared by S.M.A. Consulting Ltd. and used with permission.

3.05 NEST tunnel

The project's main driver is the need for wet weather capacity as monitoring indicated that we will be out of storm sewer capacity within five years, and also the requirement for servicing the 66 Street catchments area of Lake District North. City Council approved the funding for NEST NL2, NL3 and N1 at $22 million on December 15, 2005.

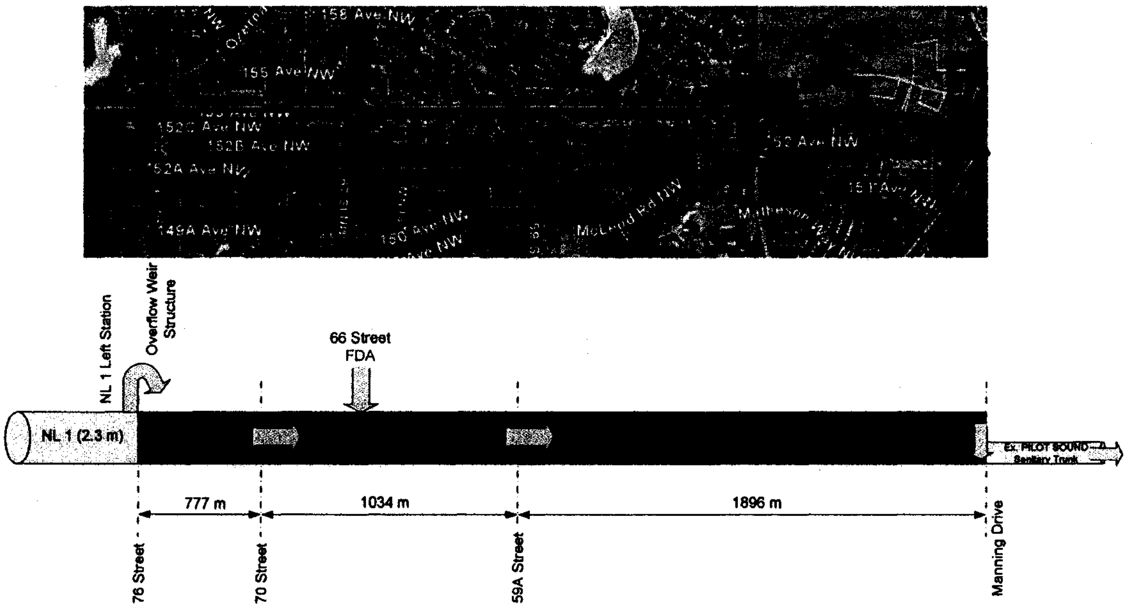


FIGURE 3-3 NEST NL2-NL3 & N1

As shown in Figure 3-3, the project involves constructing a new 2.3 m diameter tunnel with a total length of 3707 m from 76 Street to Manning Drive. Underneath the alignment of 153 Avenue, there will be an overflow weir structure between the existing NL1 pump station and NL2.

3.05.1 NEST NL2-3 & N1 simulation

The City of Edmonton Design and Construction advocates the use of the most cost-effective and efficient approaches to tunnelling projects. To arrive at such approaches, they utilize the appropriate value analysis, risk analysis and constructability review processes during planning sessions.

With regard to NL2-3/N1, the basic approach to the construction method is two-way tunnelling from a shaft at 59A Street, as two-way tunnelling has proven to be superior in most cases, especially when tunnel length exceeds a threshold of 1 km. Please see Figure 3-4.

During the value analysis/risk analysis session this approach was revisited. The main reason for revisiting the two-way tunnelling is the "less-than desirable" and generally unsuitable location of the working shaft. The potential site:

1. Is located in a residential area on 59A Street with very close proximity to residences, bus-stops, and schools, and it is frequented by pedestrians.
2. Does not provide a suitable laydown area for the project, which may necessitate acquiring a site across 59A Street to store pre-cast panels and other required material. Handling such material may present a hazard to public on the street and necessitate closure of the street, or at the very least will require having a full-time flag person on the affected site, which is in proximity to a bus stop and a school.
3. Presents challenges related to tying-in sewers to pump water from the tunnel during construction.
4. Will limit the production schedule to one shift per direction of tunnelling due to proximity to residences.
5. Presents traffic challenges associated with access to the site, resulting in reduced productivity.

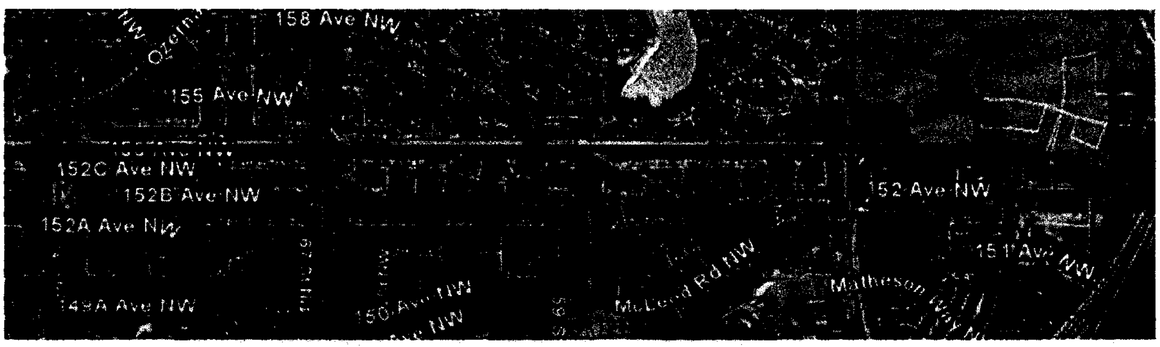


FIGURE 3-4 TWO-WAY TUNNELLING SCHEMA

An alternative that was discussed in the workshop centers on one-way tunnelling from Manning Drive West. The site presents the following advantages (see Figure 3-5):

1. Shallower shaft (reduced cost of shaft construction), using two shafts instead of three
2. Only one TBM is tied up with the project
3. Optimum space for laydown of equipment and storage of material
4. Easier access to the site
5. Easier access to required utilities during construction
6. More separation of site from residential areas
7. Work shifts will not be limited and can potentially double or triple shift if required.
8. Easier to access nearby utilities such as sewer

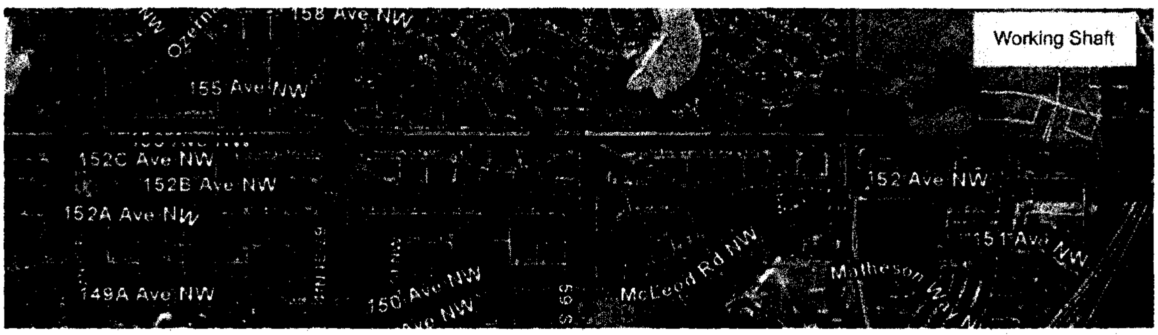


FIGURE 3-5 ONE-WAY TUNNELLING OPTION

The production on this approach is expected to be equal to the two-way tunnelling (if the crew runs two shifts per day) until a point is reached when the productivity will drop and become noticeably lesser than the two-way tunnelling due to the travel distance of muck cars.

A proposed enlargement of the tunnel at a certain location (at an appropriate distance to be determined from simulation analysis) was introduced to facilitate the addition of an extra train, which should effectively eliminate the waiting time of the TBM due to the long travelling distance (see Figure 3-6).

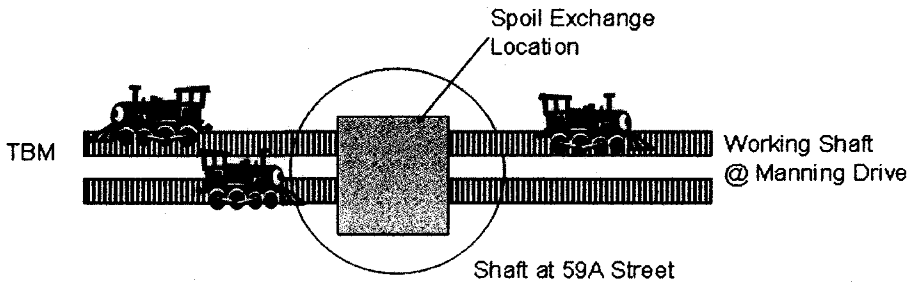


FIGURE 3-6 SPOIL EXCHANGE STATION

A decision on the construction method for NL2-3/N1 was made based on the following input:

1. Cost associated with the two options
2. Production analysis through simulation studies to evaluate the proposed method and quantitatively compare it to the two-way tunnelling
3. An evaluation of possible mitigation measures in the currently proposed working shaft location to see if the site can be enhanced to one more useable
4. Risk analysis and constructability reviews of the two alternatives

3.05.2 Production analysis

This section will discuss the findings of the simulation model built for NL2-3 and N1. The following options were simulated:

Options 1&2*:* Two-way tunnelling. In this option the productivity values for the tunnelling are as shown in Figures 3-7 and 3-8, which account for the geotechnical conditions and the direction of tunnelling (upward, or downward).

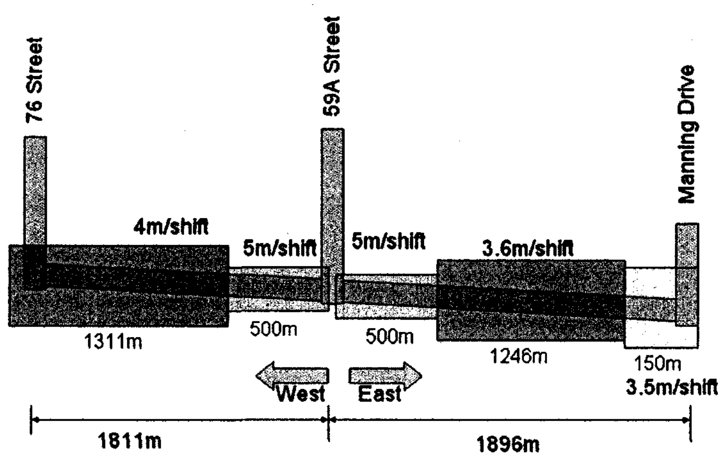


FIGURE 3-7 ASSUMED TUNNELLING PRODUCTIVITY

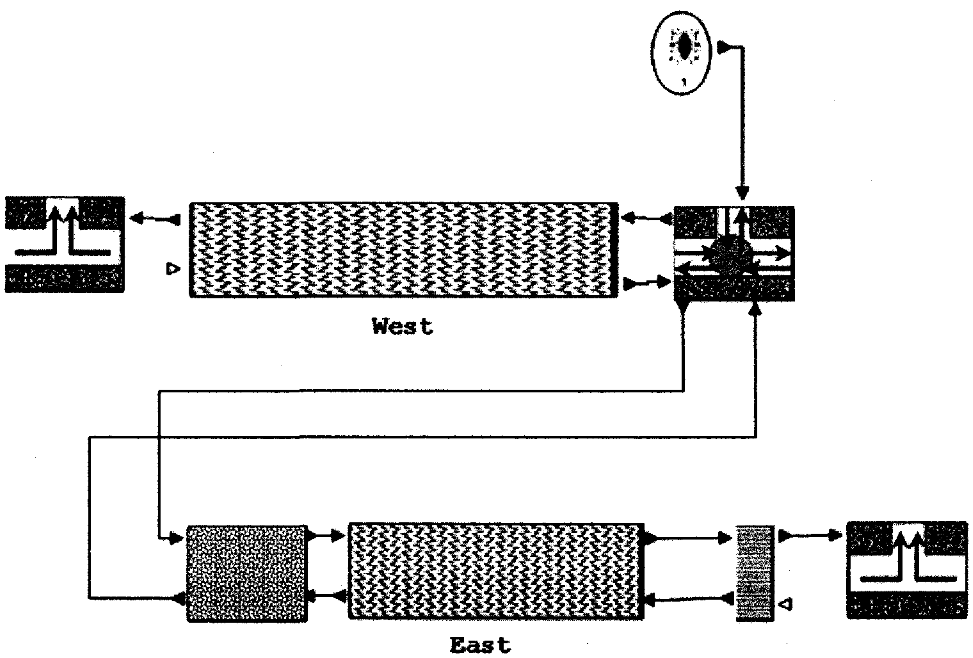


FIGURE 3-8 SIMULATION MODEL FOR OPTIONS 1 AND 2

Options 1 and 2 follow the same configuration except in the shift duration, which was 8 hrs per day for option 1 and 10 hrs per day for option 2.

Options 3&4: One-way tunnelling starting from the east side at Manning Drive, going west along the alignment of 153 Avenue to 76 Street, as shown in Figures 3-9 and 3-10.

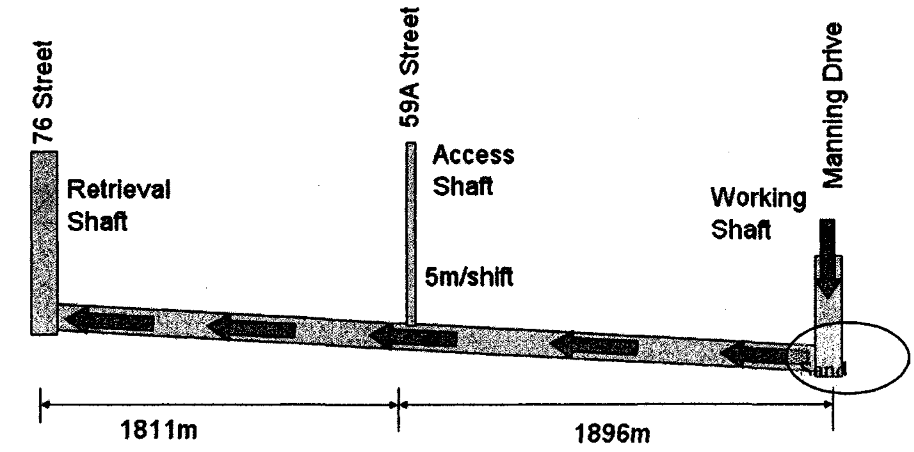


FIGURE 3-9 OPTIONS 3 AND 4

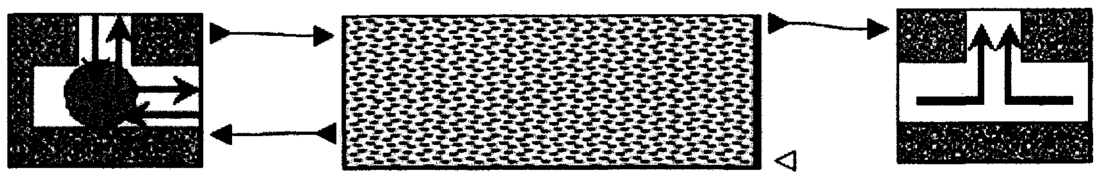


FIGURE 3-10 SIMULATION MODEL FOR OPTIONS 3 AND 4

Options 5, 6, 7, & 8: One-way tunnelling with a switch at a distance from the working shaft. The switch limits the reduction in productivity due to train traveling time by having a stand-by train at this location for exchange with the loaded train. During the analysis, we tried to determine the optimum location for the switch by moving it within the acceptable range and candidate locations; the best location was found to be at the access shafts. The distances are 900 m, 1896 m and 2632 m (see Figure 3-11).

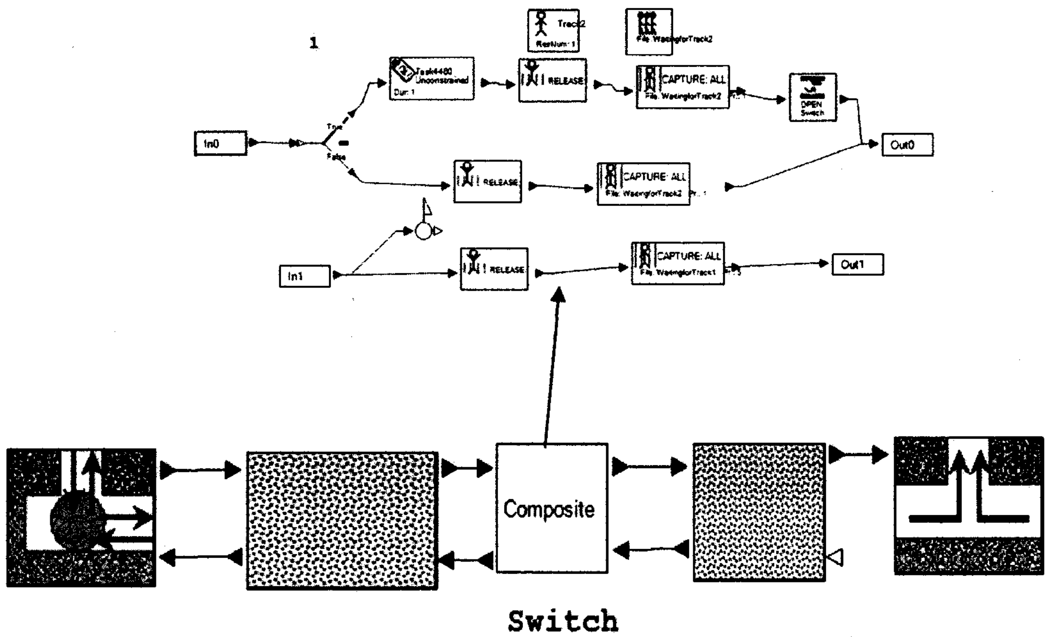


FIGURE 3-11 SIMULATION MODEL FOR OPTIONS 5, 6, 7, AND 8

Table 3-1 shows the options and the resultant duration and productivities.

TABLE 3-1 SIMULATION RESULTS

Alternative	*Shift*	*No. of Shifts*	*Duration (day)*	*Productivity (m/day)*	Switch
Two way	**8 hrs**	**1**	**540**	**6.86**	**NA**
Two way	10 hrs	1	**415**	8.93	NA
One Way	8 hrs	2	**482**	7.69	NA
One Way	10 hrs	2	**370**	10	NA
One Way	8 hrs	2	**424**	8.74	900
One Way	10 hrs	2	**328**	11.3	900
One Way	**8 hrs**	**2**	**401**	**9.24**	**1896**
One Way	10 hrs	2	**311**	11.9	1896

One Way	8 hrs	2	**423**	8.77	2632
One Way	10 hrs	2	**324**	11.44	2632

3.06 Glencoe tunnel

Completion date was critical in planning the Glencoe tunnel. For the City of Calgary to receive a fund from the Infrastructure Canada Alberta Program (ICAP), the project had to be completed by March 31, 2006. Simulation was used to determine if the project could be finished within the specified timeframe. The project team defined a number of scenarios for constructing the project. Each scenario consists of a number of activities. Each activity has a production rate based on historical data and expert opinions. A simulation model based on the activities and input data was created for each scenario using tunnelling and general templates. After running the simulation models for all scenarios and comparing the results, the project team found that the proposed completion date was not feasible. Based on the study, the City of Calgary applied for and was granted an extension.

3.06.1 Project overview

This project aimed to increase storage capacity during storm periods by constructing a storm storage tunnel with a diameter of 2900 mm underneath 27 Avenue, starting from 15th Street SW and going west to 20th Street SW, with a total length of 930 m and a depth ranging from 16 m at the working shaft to 42 m at the retrieval shaft. This project is an ICAP project (Infrastructure Canada-Alberta Program (ICAP), which is a joint partnership between the Federal Government, the Government of Alberta and its municipalities to improve Canadians' quality of life), and it had to be completed by March 31, 2006 to be eligible for a share of ICAP funding.

3.06.2 Construction methods

Project completion date was the major drive for this project, which directed the efforts to discuss and create a constructible construction schedule within the given timeframe. Four construction methods were proposed as follow:

1. Option A: Construct by drilling working shaft and pump station shaft, and then connecting the two shafts by hand tunnelling utilizing two crews (two directions). Once completed, a small undercut, as shown in Figure 3-12, is created, the TBM is set up, and tunnelling commences.
2. Option B: This option utilizes an inverted tail tunnel by constructing a 30 m undercut in the direction of tunnelling using hand tunnelling to avoid working underneath the water main (see Figure 3-15).
3. Option C: Construct a small 6 m undercut in the direction of tunnelling, then start tunnelling using rib and lagging to support the tunnel for the first 30 m. In this case, only one train can be used due to the size of the undercut.
4. Option D: Construct a small 6 m undercut in the direction of tunnelling, and then start tunnelling using concrete liners to support the tunnel. In this case, only one train can be used due to the size of the undercut.

3.06.2.1 Option A: Original design

An implementation of drilling two working shafts at the beginning of the project allowing the construction of the pump station parallel to the tunnelling process (see Figure 4) compared to options B, C, and D reduced project duration by three months.

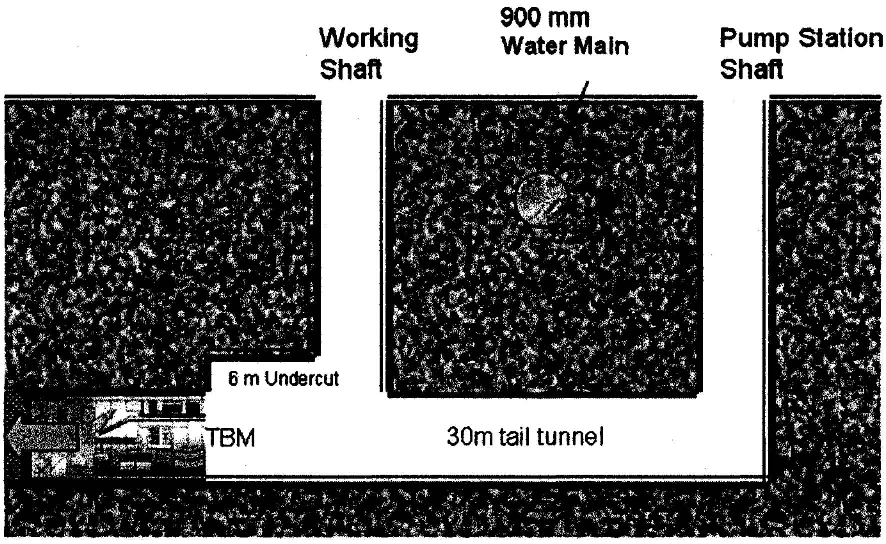


FIGURE 3-12 OPTION A (ORIGINAL DESIGN)

The following are the major activities involved in constructing this project:

1. Drill 14 ft 8 inch working shaft at 15 Street
2. Drill 12 ft working shaft as 15 Street
3. Connect the two working shafts by hand tunnelling
4. Excavate 6 m front undercut (see Figure 3-12)
5. Install mole
6. Excavate 900 m tunnel using TBM
7. Excavate removal shaft at 20 Street
8. Excavate drop manhole at 18 Avenue
9. Remove mole
10. Finish up shafts

A simulation model was produced for the entire project to analyze production. An overview of this model is shown in Figures 3-13 and 3-14.

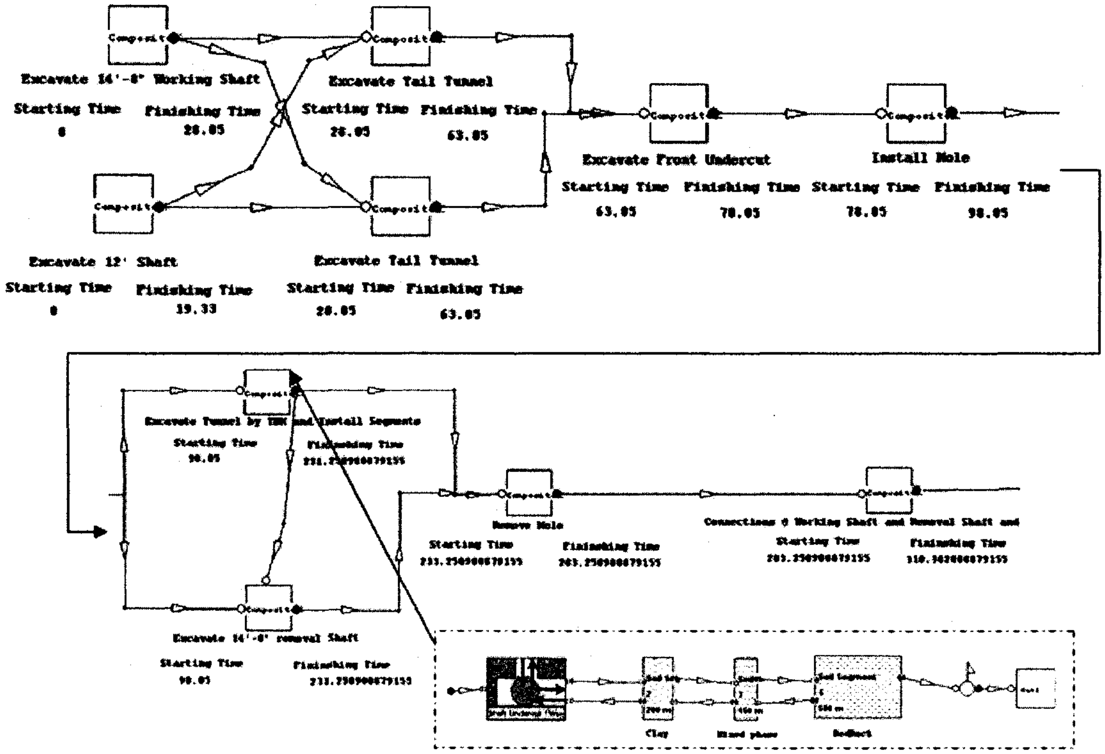


FIGURE 3-13 GLENCOE STORM TUNNEL PROJECT SIMULATION MODEL

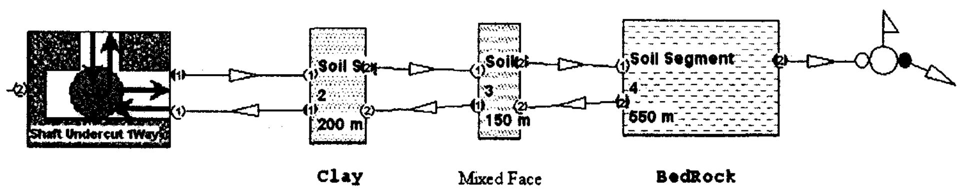


FIGURE 3-14 GLENCOE STORM TUNNEL PROJECT ASSUMED UNDERGROUND CONDITIONS

Eight alternatives were analyzed using the simulation model, as shown in Table 3-2. The variables included: 1) number of hours in each shift; 2) working days per week, and 3) expected penetration rate. The penetration rate included two schemes:

1. Scheme #1: (Uniform Scheme) TBM penetration rate for the entire tunnel length is Beta distribution (3.49, 2.9, 1.8, 8.08).

2. Scheme #2: (Variable Scheme) Represented by three sections based on geotechnical conditions (see Figure 3-14).

    a. Section #1: Till clay with a length of 200 m; and since the TBM is a soft face TBM, TBM penetration rate assumed to be Beta distribution (3.49, 2.9, 1.8, 8.08).

    b. Section #2: Mixed face with a length of 150 m composed of till clay and bedrock; TBM penetration rate will drop by 15%, and we used Beta distribution (3.49, 2.9, 1.8, 7.10).

    c. Section #3: Bedrock with a total length of 550 m, we assumed TBM penetration rate will decreases by 25%.We used Beta distribution (3.49, 2.9, 1.8, 5.00).

TABLE3-2 SCHEDULE ALTERNATIVES

Alternative	*Hours per Shift*	*Days per Week*	*Advance Rate Schema*	Production Rate (m/shift)
1	10	5	Scheme #1	10.16 m/shift
2	10	5	Scheme #2	10.18 m/shift (Section 1) 8.68 m/shift (Section 2) 7.43 m/shift (Section 3)
3	10	6	Scheme #1	10.16 m/shift
4	10	6	Scheme #2	10.18 m/shift (Section 1) 8.68 m/shift (Section 2) 7.43 m/shift (Section 3)
5	12	5	Scheme #1	11.78 m/shift
6	12	5	Scheme #2	11.78 m/shift (Section 1) 10.94 m/shift (Section 2) 9.30 m/shift (Section 3)
7	12	6	Scheme #1	11.78 m/shift
8	12	6	Scheme #2	11.78 m/shift (Section 1)

	10.94 m/shift (Section 2)
	9.30 m/shift (Section 3)

For the listed alternatives, the following are assumed to be the same for tunnelling processes: 1) using two trains; 2) using four muck cars with capacity of 4.59 m^3; and 3) using two material cars. The results of the simulation are shown in Table 3-3.

Alternatives 3, 4, 7, and 8 show a completion date before March 31, 2006. In addition, the starting date for drilling the removal shaft is given to facilitate resource planning. The project manger has to decide which of the successful scenarios to follow. All this analysis is based on the assumption that the TBM machine will be retrieved from 23 Avenue and ready to go at the indicated date in each scenario; any delay will have direct impact on completion date by the same magnitude.

TABLE 3-3 SIMULATION RESULTS

Alternative	*Hours per Shift*	*Days per Week*	*Advance Rate Scheme*	*Project Duration (Working Days)*	*Project Completion Date mm/dd/yyyy*	*Removal Shaft Starting Date mm/dd/yyyy*	Date by which the TBM should be in Calgary
1	10	5	Scheme #1	274.27	5/9/2006	10/18/2005	7/20/2005
2	10	5	Scheme #2	284.45	5/24/2006	11/1/2005	7/20/2005
3	10	6	Scheme #1	274.27	3/7/2006	9/13/2005	6/30/2005
4	10	6	Scheme #2	284.45	3/18/2006	9/24/2005	6/30/2005
5	12	5	Scheme #1	255.33	4/12/2006	9/20/2005	7/20/2005
6	12	5	Scheme #2	264.49	4/25/2006	10/3/2005	7/20/2005

7	12	6	Scheme #1	255.33	2/14/2006	8/20/2005	6/30/2005
8	12	6	Scheme #2	264.49	2/23/2006	8/31/2005	6/30/2005

3.06.2.2 Option B: Original design (forward undercut)

This option is the same as option A, but the 30 m tail tunnel is constructed forward toward the tunnelling direction, as shown in Figure 3-15.

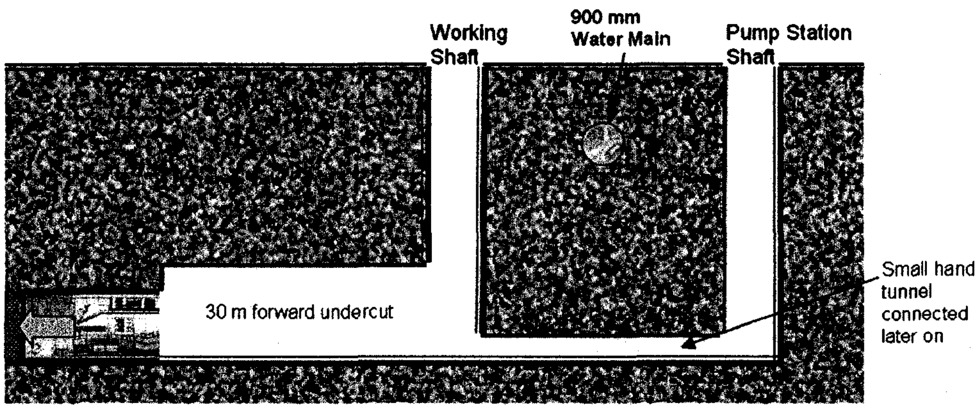


FIGURE 3-15 GLENCOE STORM TUNNEL PROJECT OPTION B (FORWARD UNDERCUT)

3.06.2.3 Option C: Small undercut (6 m) using rib and lagging

Construct (small) 6 m undercut in the direction of tunnelling, then start tunnelling using rib and lagging to support the tunnel for the first 30 m. This will allow us to come back and enlarge this 30 m section if productivity suffers due to limiting the process to one train. This option is shown in Figure 3-16:

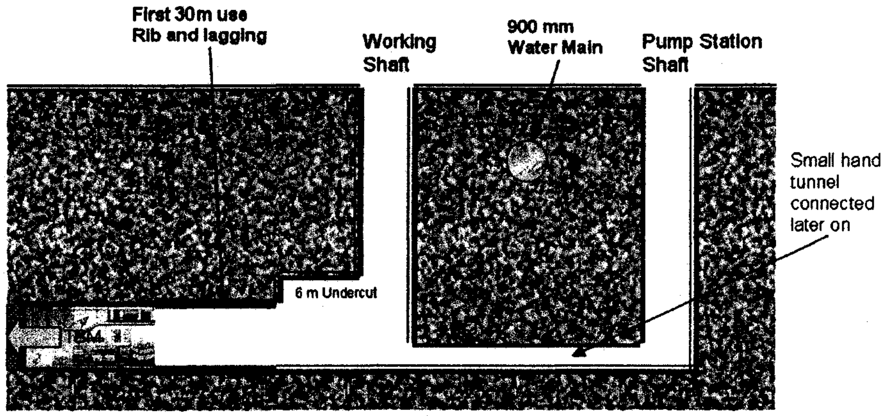


FIGURE 3-16 GLENCOE STORM TUNNEL PROJECT OPTION C (SMALL UNDERCUT, RIB AND LAGGING)

The approach is to observe productivity in the bedrock section: if the productivity is high, then go back and enlarge the first 30 m and use two trains. If the productivity is low (1 m/shift) due to hard rock, then evaluate the best time and location for an intermediate shaft to drop a smaller sized TBM (hard face) and use it for the rest of the tunnel.

3.06.2.4 Option D: Smaller undercut (6 m) using concrete liners

Construct (small) 6 m undercut in the direction of tunnelling, and then start tunnelling using concrete liners to support the tunnel. In this case only one train can be used (see Figure 3-17). Note that in this option there is no flexibility in enlarging the first 30 m section later on as in option C.

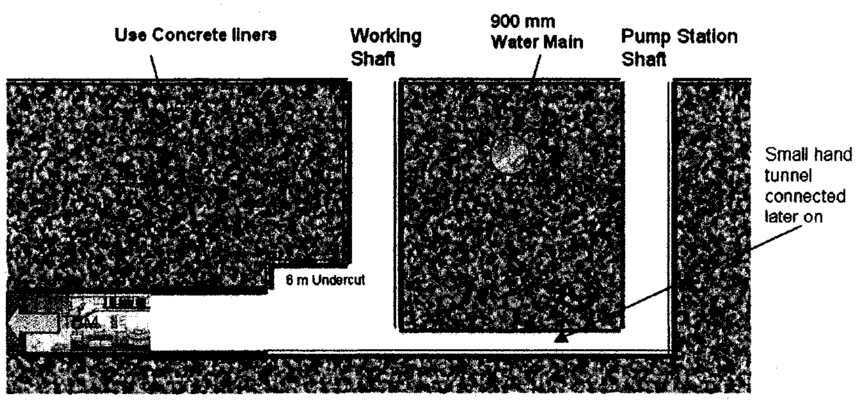


FIGURE 3-17 GLENCOE STORM TUNNEL PROJECT OPTION D (SMALL UNDERCUT, CONCRETE LINERS)

3.06.3 Construction schedule

The most optimistic date to start tunnelling was June 21, 2005. Table 3-4(a) & 3-4(b) show the proposed alternatives for constructing the tunnel:

TABLE 3-4(A) SCHEDULE ALTERNATIVES

Option	*Alternative*	*Soil Condition*	Description
Option B	1	Clay: 300 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08) Bedrock: 600 m @ Penetration rate: Beta (1.865,1.54,1.08,4.84)	This option is constructed as follows: Install the TBM Construct forward undercut (30 m/@ 1m/day) Use 2 trains The expected soil conditions as indicated
Option B	2	Clay: 300 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08) Bedrock: 600 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08)	This option is constructed as follows: Install TBM Construct forward undercut (30 m/@ 1m/day) Use 2 trains Expected soil conditions as indicated
Option C	1	Clay: 300 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08) Hard face (Rock): 100 m @ Penetration rate: Beta (0.255,0.212,0.36,1.62 Bedrock: 530 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08)	This option is constructed as follows: Construct small undercut (6 m, 1m/day) Install TBM Use TBM to go for 30 m using rib and lagging (1m/day) Excavate first 300 m with good productivity In bedrock the productivity will be low Approx. (1m/day) Start constructing working shaft at 18 Avenue (or other location) Bring hard face and drop at the intermediate shaft Proceed tunnelling for the rest of the tunnel with hard face TBM
Option C	2	Clay: 300 m @	This option is constructed as follows:

	Penetration rate: Beta (3.49,2.9,1.8,8.08) Bedrock: 630 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08)	Construct small undercut (6 m, 1m/day) Install TBM Use TBM to go for 30 m using rib and lagging (1m/day) Excavate first 300 m with good productivity In bedrock the productivity is found to be good Enlarge the first 30 m (rib and lagging section) (30 days) Proceed tunnelling with higher productivity

TABLE 3-4(B) SCHEDULE ALTERNATIVES

Option	*Alternative*	*Soil Condition*	Description
Option D	1	Clay: 300 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08) Hard face (Rock): 100 m @ Penetration rate: Beta (0.255,0.212,0.36,1.62) Bedrock: 530 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08)	This option is constructed as follows: Construct small undercut (6 m, 1m/day) Install TBM Use concrete liner Excavate first 300 m with good productivity When reaching bedrock the productivity found to be low Start constructing working shaft at 18 Avenue Bring hard face and drop at 18 Avenue Proceed tunnelling for the rest of the tunnel
Option D	2	Clay: 300 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08) Bedrock: 630 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08)	This option is constructed as follows: Construct small undercut (6 m, 1m/day) Install TBM Use Concrete liner Excavate first 300 m with good productivity When reaching bedrock the productivity is good also Proceed tunnelling

These alternatives have been modelled in *Simphony,* and the results are shown in Table 3-5. The alternatives were scheduled based on 10 hr shifts, and 6 working days per week. The following parameters were evaluated: 1) production rate (m/shift); 2) project duration; 3) completion date; 4) date on which the second TBM is required to be in Calgary; and 5) removal shaft construction starting date. Those parameters are shown in Table 3-6.

TABLE 3-5 SIMULATION RESULTS FOR SCHEDULE ALTERNATIVES

Option	*Alternative*	*Number Of Trains*	*Number Of TBM machines*	*Production Rate (m/10hr shift)*	*Tunnelling Duration (Working Days)*	*Preparation work (days)*	Total Duration
Option B	1	2	1	300 m @ 10.53 m/shift 600 m @ 7.82 m/shift	110 days	Undercut (30 days)	150
Option B	2	2	1	300 m @ 10.20 m/shift 600 m @ 9.60 m/shift	97 days	Undercut (30 days)	127
Option C	1	1	2	300 @ 8.18 m/shift 100 @ 0.97 m/shift 530 @ 7.71 m/shift	211 days	Undercut (6 days) Rib & lagging (30 days)	247
Option C	2	1 train 300 m 2 trains 630 m	1	300 m @ 8.65 m/shift (38) 630 m @ 11.11 m/shift (46)	84 days	Undercut (6 days) Rib & lagging (30 days)	120
Option D	1	1	2	300 m @ 8.89 m/shift 100 m @ 0.98 m/shift 530 m @ 7.75 m/shift	207 days	Undercut (6 days)	213
Option D	2	1	1	300 m @ 8.62 m/shift 630 m @ 8.23 m/shift	115 days	Undercut (6 days)	121

TABLE 3-6 SIMULATION RESULTS FOR SCHEDULE ALTERNATIVES

Option	*Alternative*	*Number Of Trains*	*Number Of TBM machines*	*Total Duration (Day)*	*Completion Date*	*2nd TBM is needed in Calgary*	Removal shaft Start Date
Option B	1	2	1	217	3/20/06	N/A	9/26/05
Option B	2	2	1	204	3/04/06	N/A	9/10/05
Option C	1	1	2	323	7/28/06	12/15/05	1/23/06
Option C	2	1 train 300 m 2 trains 630 m	1	197	2/24/06	N/A	9/1/05
Option D	1	1	2	290	6/15/06	11/16/05	12/12/05
Option D	2	1	1	198	2/25/06	N/A	9/2/05

3.06.4 Construction schedule "balanced case"

Based on the previous schedule analysis, option D was found to be more attractive than option C in both best and worst case alternatives. If the soil conditions were favourable, then the project completion date would be within the required timeframe (end of February 2006). On the other hand, if the soil conditions were unfavourable, requiring the crew to use hand tunnelling to get through the mixed face, then the project would be delayed (June 15, 2006). This section provides further analysis to minimize the project duration based on scenario D1 (if bad ground conditions limit us to hand excavation in the 100 m section). The following alternatives are undertaken:

1. Alternative 1: Working shaft @18 Avenue to be moved east.
    a. Tunnelling through clay section (300 m @ 8.5 m/shift)
    b. Tunnelling through the mixed face (5 m @ 1 m/shift)
    c. Start constructing second working shaft at distance X (X=51 m) from current location (distance 305 m from start).
    d. Proceed with hand tunnelling so that the finishing date of installing the new TBM and breaking through is the same (see Figure 3-18).

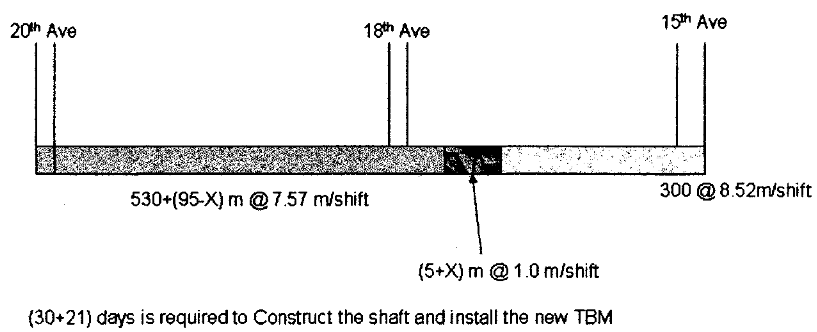


FIGURE 3-18 OPTION D: ALTERNATIVE #1

2. Alternative 2: Construct working shaft @ Distance (51 m) at the start of tunnelling
    a. Tunnelling through clay section (300 m @ 8.5 m/shift)
    b. Tunnelling through the mixed face (51 m @ 1m/shift)
    c. Proceed with hand tunnelling so that the finishing date of installing the new TBM and breaking through is the same.
3. Alternative 3: Construct working shaft @ 18 Avenue at the start of tunnelling
    a. Tunnelling through clay section (300 m @ 8.5 m/shift)
    b. Tunnelling in the through the mixed face (100 m @ 1m/shift)
    c. Proceed with hand tunnelling to 18 Avenue

The results of alternatives 1, 2, and 3 are given in Table 3-7

TABLE 3-7 RESULT OF BALANCING EXERCISE

Alternative	*Description*	*Project Duration*	*Completion Date*	*Tunnelling Completion Date*	*2nd Working shaft location from start point*	*2nd working shaft Start date*	*2nd TBM required in Calgary*	Note
D1.1	Start constructing 2nd working shaft at distance 51 m, after hitting 1m/shift for 5 days.	250	4/28/06	1/25/06	356	8/16/05	9/21/05	Throwaway cost is possible
D1.2	Start constructing 2nd working shaft at distance 351m, at the start of tunnelling	206	3/6/06	11/22/05	351	6/20/05	7/26/05	Throwaway cost is possible
D1.3	Construct 2nd working shaft @ 18 Ave, at the start of tunnelling	289	6/13/06	3/11/06	400	6/20/05	7/26/05 Or later	Less throwaway cost is possible

3.06.5 Construction schedule simulation

Based on the schedule analysis given in previous section, we decided to acquire information as soon as possible while minimizing throwaway costs. In summary, the following should take place:

1. Proceed with installing the TBM at 15 Street and start tunnelling toward 22 Street.
2. Construct the shaft at 22 Street as soon as is practical. Once the shaft is built, we will be able to properly acquire information related to tunnelling productivity (knowing the hardness of the rock layer we are better able to estimate productivity).
3. Based on the findings in step (2) above, a decision can be made regarding whether two-way tunnelling is necessary or not. If the 2990 mm TBM cannot be used in the bedrock or the projected productivity is very low (less than 2m/day), then a hard face TBM must be procured and we would have to commence tunnelling from 22 Street toward 18 Street where an extraction shaft would be built. On the other hand, if it is found that the current 2990 mm TBM can go through the bedrock and mixed face with good productivity, then there would be no need to get a new TBM and no need to construct an extraction shaft at 18 Street.

Two different alternatives have been identified based on the execution plan and the projected alternatives. Although the schedule is known in general, more analysis was required in order to better understand the uncertainties associated with the main delivery dates. In order to accomplish this, a simulation model was developed for the two alternatives, presented in Table 3-8.

TABLE 3-8 CONSTRUCTION SCHEDULE ALTERNATIVES

Alternative	*Soil Condition*	Description
1	Clay: 300 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08) Mixed face (Rock): 100 m @ Penetration rate: Uniform (0.1,0.18) Bedrock: 530 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08)	This option is constructed as follows: Construct undercut (12, 1m/day) Install TBM Excavate first 300 m with good productivity When reaching bedrock the productivity found to be low Excavate last 530 m with good productivity
2	Clay: 300 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08) Hard face (Rock): 100 m @ Penetration rate: Uniform (0.1,0.18) Bedrock: 530 m @ Penetration rate: Beta (3.49,2.9,1.8,8.08)	This option is constructed as follows: Construct undercut (12 m, 1 m/day) Install TBM Excavate first 300 m with good productivity When reaching bedrock the productivity found to be low Construct working shaft at 22 St. Construct under cut drop TBM machine Excavate 530 m with good productivity towered 18 St Construct exit shaft at 18^{S}t.

Using *Simphony*, two models were created using the same general inputs as shown in Table 3-9.

TABLE 3-9 MODEL GENERAL INPUT

Number of Trains	1
Number of muck cars (Dirt)	4
Number of muck cars (Material)	[illegible]
Muck car capacity (m3)	4.59
Number of shifts per day	2
Shift Duration (hrs)	10

3.06.5.1 Alternative 1

In this alternative, one TBM machine will excavate the total length of the tunnel (930 m) starting from 15 Street to 22 Street. Table 3-10 shows all the activities included in the simulation model and its duration.

TABLE 3-10 ALTERNATIVE 1 TASK DURATIONS

Task	Duration (days)
Excavate 12 m undercut	
Install Mole	Uniform (15,22)
Excavate Tunnel Segment for 300m	Penetration Rate: Beta (3.49,2.9,1.8,8.08)
Excavate Tunnel Segment for 100m	Penetration Rate: Uniform (0.1,0.18)
Excavate Tunnel Segment for 530m	Penetration Rate: Beta (3.49,2.9,1.8,8.08)
Patch & Rub Crown 930m	Excavation duration+ 10 days
Mole Dismantling & Removal	Uniform (10,14)
Clean Tunnel and Remove Track	20
Hand Install Segments	Uniform (20,27)
1200mm dia. MH on new line @ Working Shaft	Uniform (7,12)
Build Connections for MH's	Uniform (14,21)

Simphony's tunnelling template was used to come up with excavation duration and the construction schedule: see Figure 3-19.

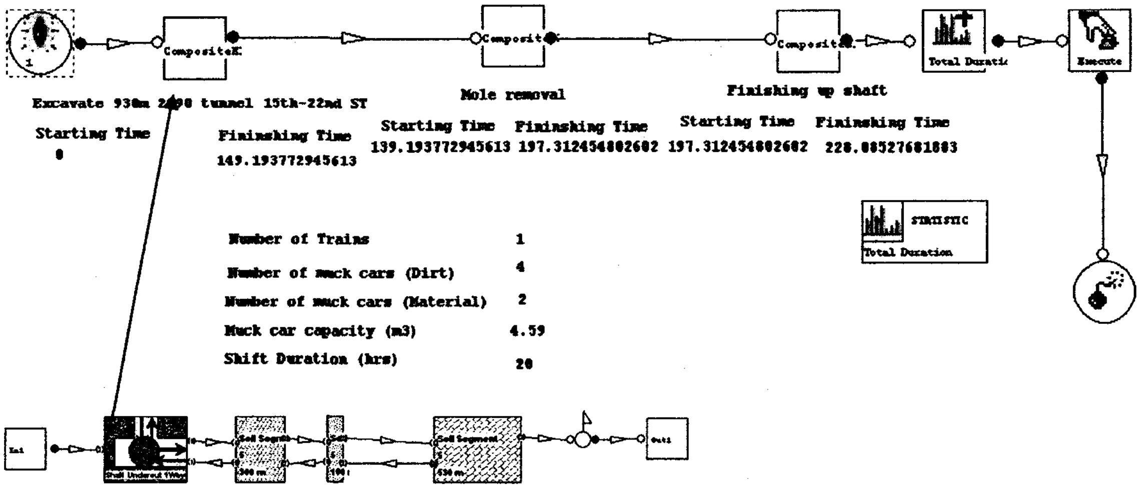


FIGURE 3-19 ALTERNATIVE 1 SIMULATION MODEL

After running the model for 50 iterations, the following results were found:

- The average total project duration was 221 days with a standard deviation of 5.61 and an 80th percentile of 226 days (see Figures 3-20 and 3-21).

Statistic #3631

Parameters | Outputs | **Statistics**

Statistic	Runs	Mean	First StdDev	Global StdDev	Minimum	Maximum	Graphs
Stat	50	221.22	0.00	5.61	211.82	233.59	View

FIGURE 3-20 ALTERNATIVE 1 TOTAL DURATION BASIC STATISTICS

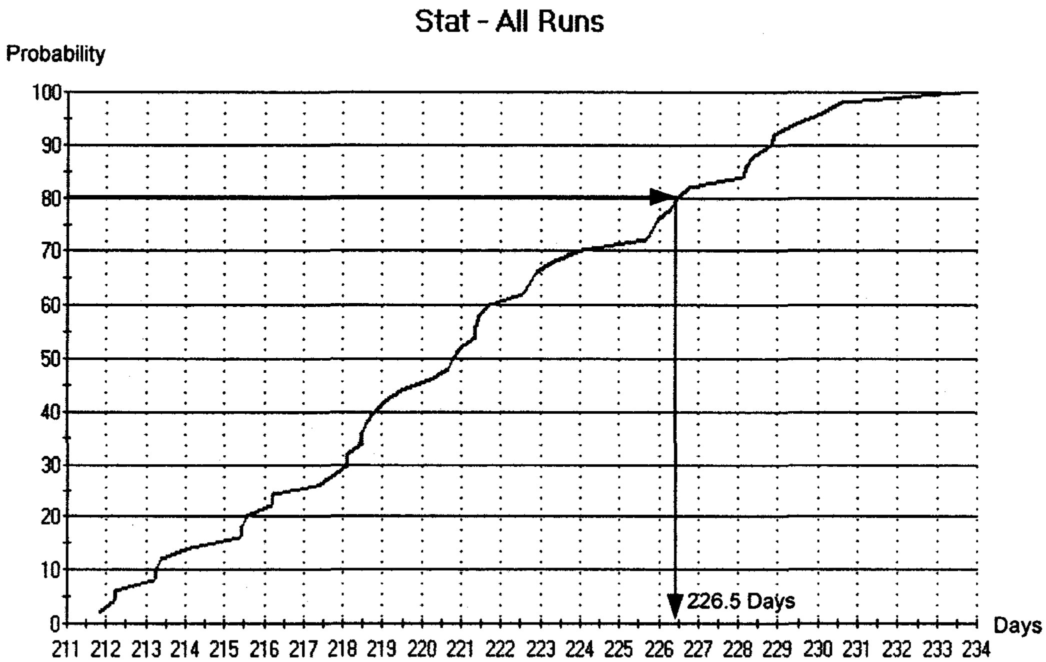


FIGURE 3-21 ALTERNATIVE 1 TOTAL DURATION 80TH PERCENTILE

- The average duration for the excavation task including all three soil segments was 108 days with a standard deviation of 1.17 and a 80th percentile of 109 days (see Figures 3-22 and 3-23).

Statistic #3618

Parameters | Outputs | **Statistics**

	Statistic	Runs	Mean	First StdDev	Global StdDev	Minimum	Maximum	Graphs
▶	Stat	50	108.26	0.00	1.17	104.99	110.77	View

FIGURE 3-22 ALTERNATIVE 1 TOTAL EXCAVATION DURATION

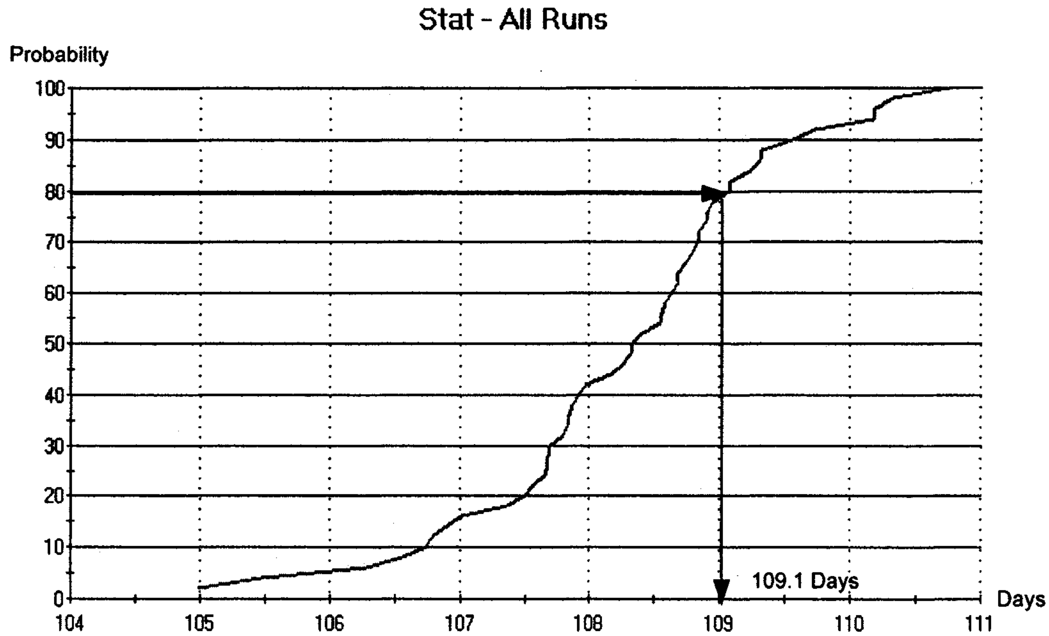


FIGURE 3-23 ALTERNATIVE 1 80TH PERCENTILE FOR TOTAL EXCAVATION DURATION

3.06.5.2 Alternative 2

In this alternative, two TBM machines will be used to excavate the total length of the tunnel (930 m). The first TBM will start from 15 Street to 18 Street, the second one from 22 Street to 18 Street, The following table shows all the activity included in the simulation model and its duration:

TABLE 3-11 ALTERNATIVE 2 TASK DURATIONS

Task Name	Duration
Excavate 12 m undercut	12
Install Mole	Uniform (15,22) day
Excavate Tunnel Segment for 300 m	Beta (3.49,2.9,1.8,8.08) (Penetration Rate)
Excavate Tunnel Segment for 100 m	Uniform (0.1,0.18) (Penetration Rate)
Patch & Rub Crown 400 m	Excavation duration
Excavate Removal Shaft at 18 St.	76 days
Excavate Working Shaft at 22 St.	Uniform (0.5,1.0) day per shift
Excavate 12m undercut	Uniform(6,12) day
Drop new TBM Machine	Uniform(21,19) day
Excavate Tunnel Segment for 530 m	Beta (3.49,2.9,1.8,8.08) (Penetration Rate)
Patch & Rub Crown 430m	Excavation duration
Mole Dismantling & Removal	Uniform (10,14)
Clean Tunnel and Remove Track	20
Hand Install Segments	Uniform (20,27)
1200mm dia. MH on new line @ Working Shaft	Uniform (7,12)
Build Connections for MH's	Uniform (14,21)

The model was simulated (see Figure 2-24) for 50 iterations and the following results obtained:

- The average total project duration was 218 days with a standard deviation of 5.22 and an 80th percentile of 222.5 days (see Figures 3-25 and 3-26).

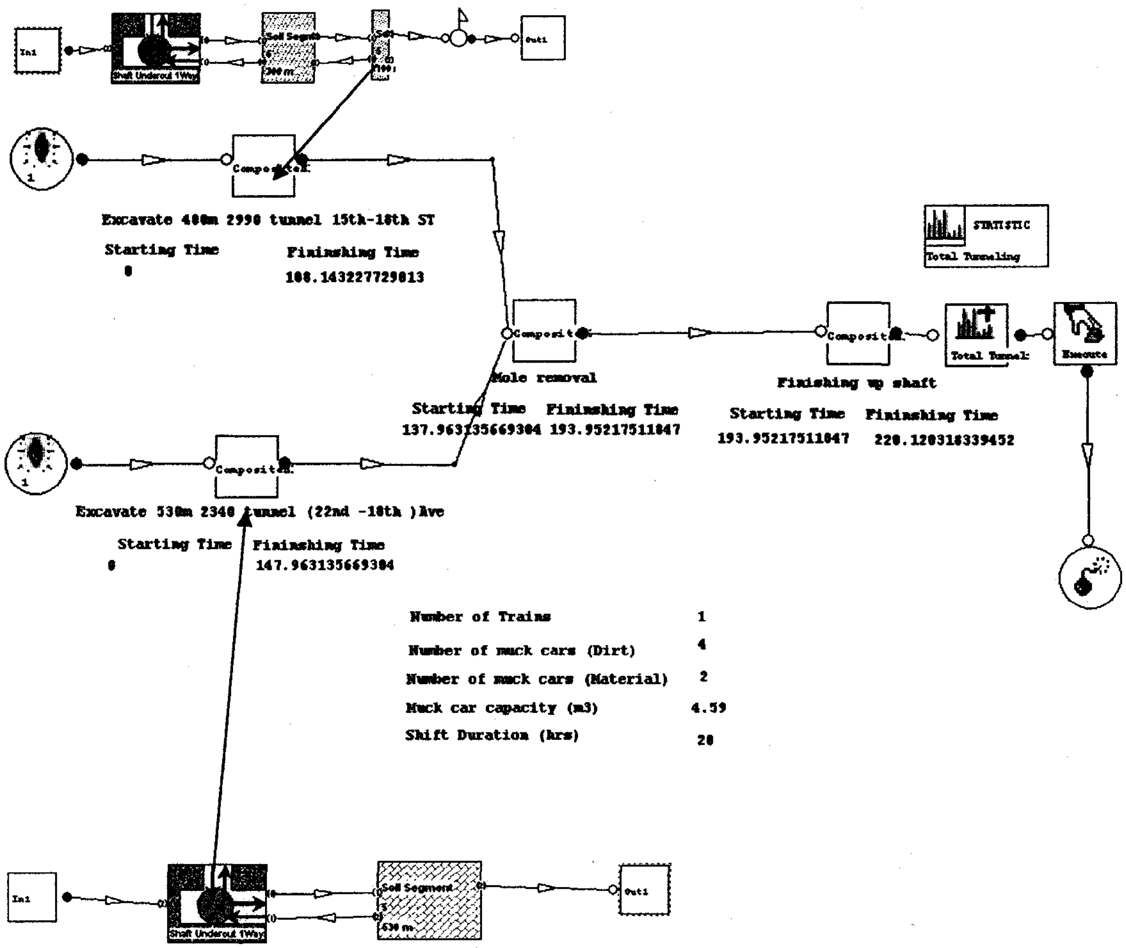
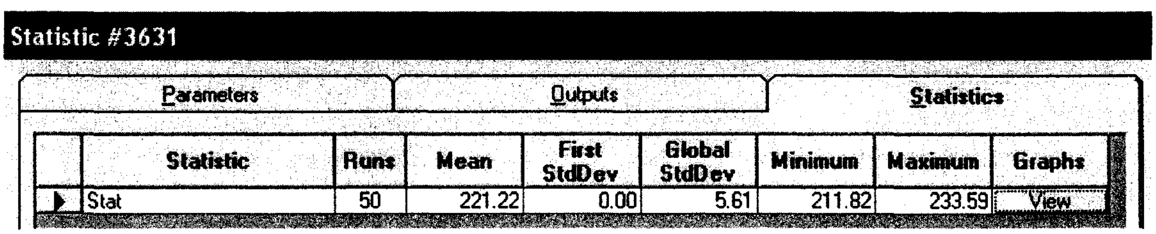


FIGURE 3-24 ALTERNATIVE 2 SIMULATION MODEL



Statistic #3631

Parameters | Outputs | Statistics

Statistic	Runs	Mean	First StdDev	Global StdDev	Minimum	Maximum	Graphs
Stat	50	221.22	0.00	5.61	211.82	233.59	View

FIGURE 3-25 ALTERNATIVE 2 TOTAL DURATION BASIC STATISTICS

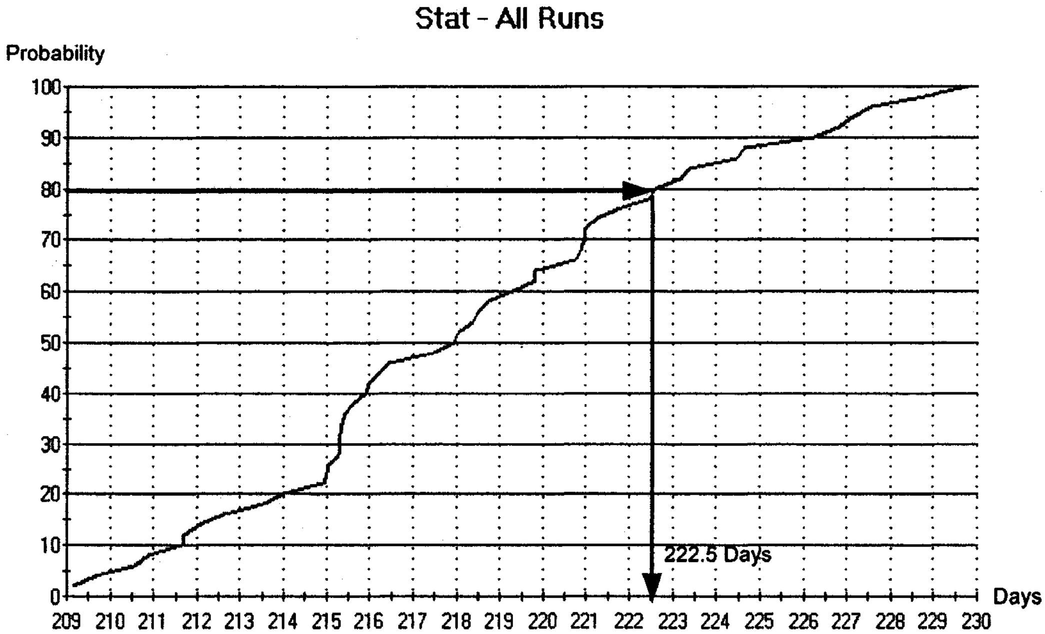


FIGURE 3-26 ALTERNATIVE 2 TOTAL DURATION 80TH PERCENTILE

The average duration for the excavation from 15 Street to 18 Street is about 68.75 days, with a standard deviation of 1.02 and the 80th percentile of 69.7 days: see Figures 3-27 and 3-28.

Statistic #4831

Parameters | Outputs | Statistics

Statistic	Runs	Mean	First StdDev	Global StdDev	Minimum	Maximum	Graphs
Stat	50	68.75	0.00	1.02	66.29	70.58	View

FIGURE 3-27 ALTERNATIVE 2 TOTAL EXCAVATION DURATION FROM 15 ST. TO 18 ST.

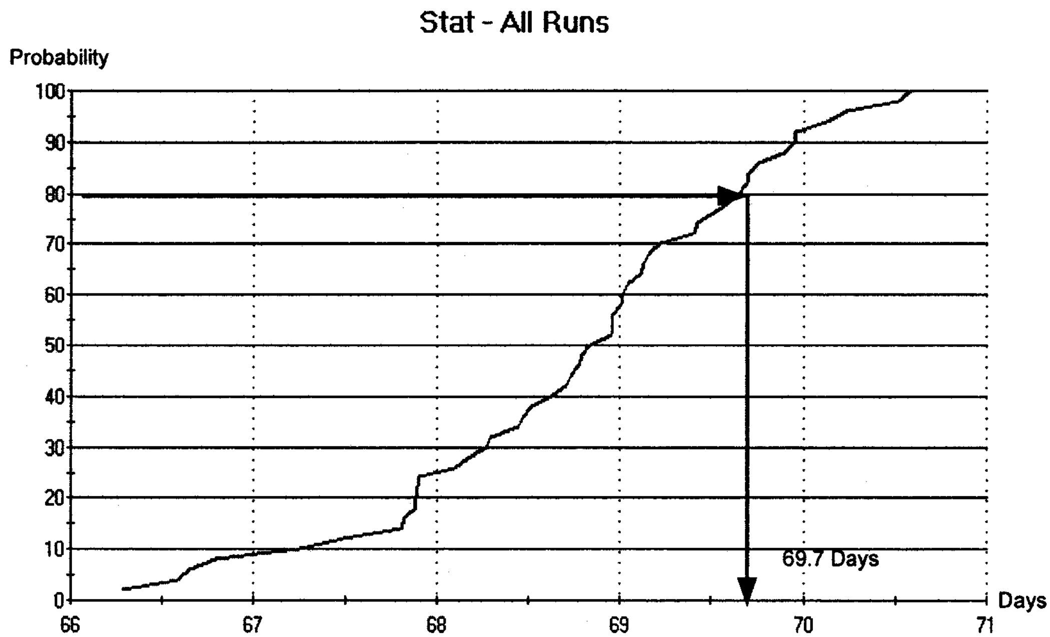


FIGURE 3-28 ALTERNATIVE 2 80TH PERCENTILE FOR TOTAL EXCAVATION DURATION FROM 15 ST. TO 18 ST.

The average duration for the excavation from 22 Street to 18 Street was 37.62 days, with a standard deviation of 0.67 and a 80th percentile of 38.2 days: see Figures 3-29 and 3-30.

Statistic #4817

Parameters | Outputs | Statistics

Statistic	Runs	Mean	First StdDev	Global StdDev	Minimum	Maximum	Graphs
Stat	50	37.62	0.00	0.67	36.07	39.36	View

FIGURE 3-29 ALTERNATIVE 2 TOTAL EXCAVATION DURATION FROM 22 ST. TO 18 ST.

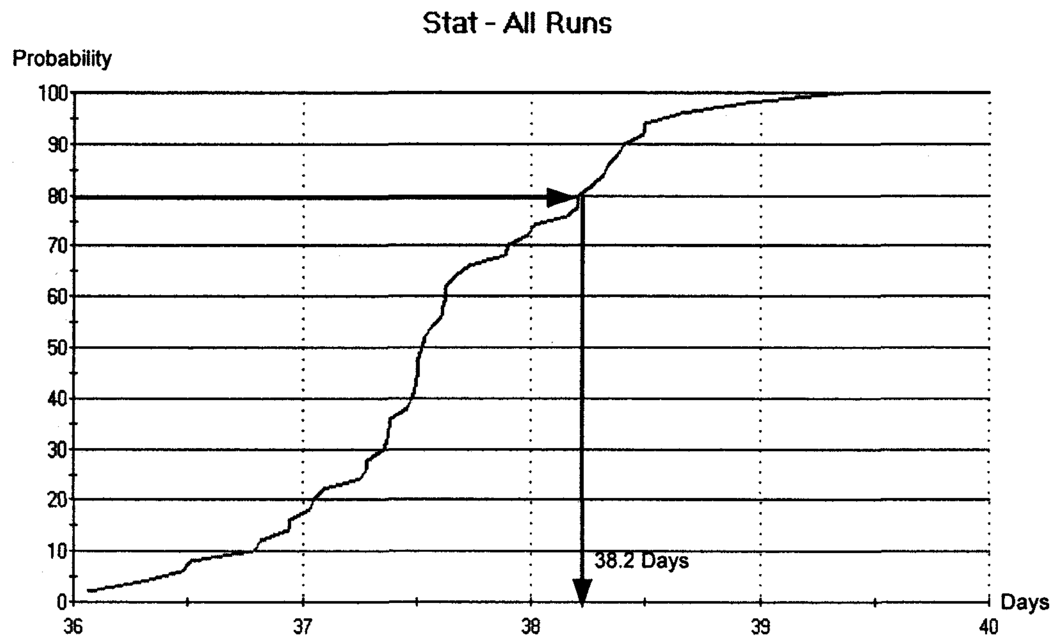


FIGURE 3-30 ALTERNATIVE 2 80TH PERCENTILE FOR TOTAL EXCAVATION DURATION FROM 22 ST. TO 18 ST.

3.06.6 Recommendations

The following summarizes the conclusions and recommendations:

1. The preferred construction strategy is as follows:

   - Knowing that there is a chance that productivity will be low, start discussion with ICAP to extend project completion to mid-May 2006.

   - Option D1.1 will allow us to wait and see thus minimizing throw away costs associated with shaft at 18 Avenue and cost of second machine.

   - If extension is not possible then adjust budget to account for 18 Avenue shaft, start constructing it as soon as practical or as per option D1.2. This approach is safe but more expensive.

2. The working shaft should go deeper than previously planned with about 1 meter to get better cover in the clay layer.
3. Try to go as fast as possible (double shifts) in the clay section.
4. Continue communication with Lafarge to secure liner delivery.

3.07 SW2&3 tunnel

The project deals with the installation of approximately 3.5 km of a sanitary system. The work began in February 2006 with the tunnelling portion of the project expected for completion in December of that same year. However, due to a number of problems, including ground conditions and resources, the project was delayed. As a result of these delays, a new problem was introduced, as there is a creek in the path of the tunnel. The creek needed to be crossed before April 15, 2007, because the project was unable to divert the creek during the period when it flows, from April 15 to July 31. If the crew was unable to cross the creek, the project would be stalled until the end of July, meaning the tunnel would remain incomplete through the end of 2007 (see Figure 3-31). Simulation using the tunnelling template of Simphony.NET was used to determine the best course of action. In order to develop a realistic simulation model, a number of site visits were conducted in which we studied the tunnelling process activities. We also recorded the productivity data and the breakdowns (see Table 3-12), as well as the duration of different activities including excavation, lining, dumping, etc. After the site visits, we were able to understand the problem, and initially we proposed four solution alternatives:

FIGURE 3-31 SW3 PROJECT

TABLE 3-12 SAMPLE DATA

Date	*Productivity (m)*	*Shift Number*	*Shift Duration (hr)*	*Interruption Duration (hr)*
02/10/2006	8	1	10	
03/10/2006	8	1	10	
04/10/2006	7	1	10	3
05/10/2006	0	1	10	10
06/10/2006	5	1	10	5
10/10/2006	5	1	10	
11/10/2006	3	1	10	5
12/10/2006	6	1	10	
13/10/2006	3	1	10	
16/10/2006	4	1	10	
17/10/2006	4	1	10	
18/10/2006	6	1	10	
19/10/2006	0	1	10	10
20/10/2006	0	1	10	10
23/10/2006	0	1	10	10
24/10/2006	5	1	10	
25/10/2006	7	1	10	
26/10/2006	7	1	10	
27/10/2006	6	1	10	0.75
30/10/2006	2	1	10	5
31/10/2006	6	1	10	

3.07.1 Alternative 1

In order to analyze various alternatives, we conceptually staged the construction as shown in Figure 3-32, where point B represents the location of the TBM at the time the analysis was performed (point B is approximately 659 m from the working shaft at point A). The creek is rounded by points C1 and C2 with C1 at 10 m from creek. Point D is the exit shaft.

Having started at A, the crew is now at B: 1205 m left to tunnel, 995 m to the creek. Average production is now 3.47 m/shift; assume we can maintain this production. By running two shifts of 10 hrs each, the average production will be 6.95 m/day. Starting on November 27, 2006, we will reach the creek on June 16, 2007 (143 days). The operation would then need to be stopped until September 3, 2007, after which it could carry on for the remaining 210 m (31days). The expected finish time would be October 15, 2007 (see Figure 3-32).

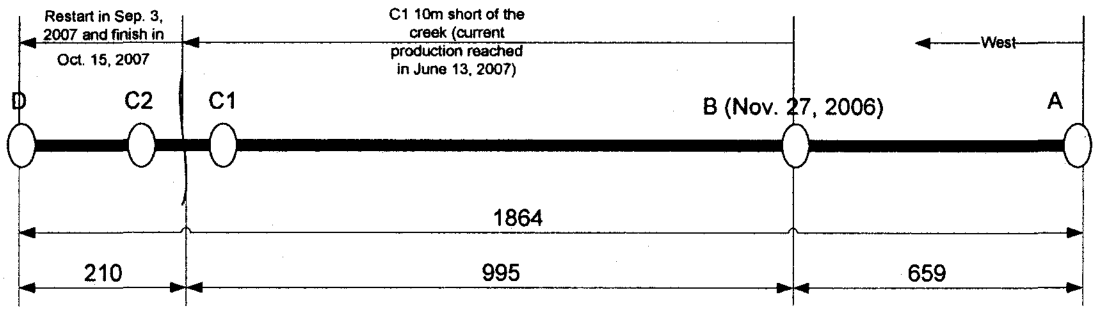


FIGURE 3-32 ALTERNATIVE 1

3.07.2 Alternative 2

Having started at A, the crew is now at B: 1205 m left to tunnel, 995 m to the creek. Average production is now 3.47 m/shift; assume we can maintain this production. By running two shifts of 10 hrs each, the average production will be 6.95 m/day. Starting on November 27, 2006, we will reach C1 50m short of the creek on June 5, 2007 (136 days). Start parallel work if we have crews, going from C1 to D using hand tunnelling or spider mole at 2 m/day (130 days). Starting January 8, 2007 we would finish July 6, 2007 (see Figure 3-33).

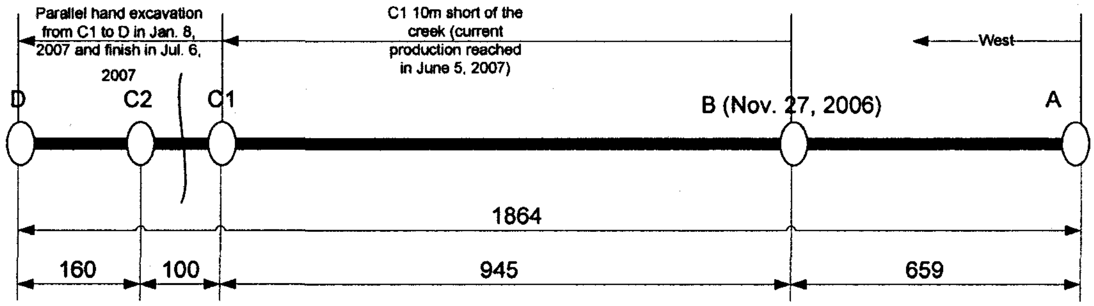


FIGURE 3-33 ALTERNATIVE 2

3.07.3 Alternative 3

Having started at A, the crew is now at B: 1205 m to go, 995 m to the creek. Average production is now 3.47 m/shift; assume we can achieve this production by going back to the old set of teeth, which been changed earlier. By running two shifts of 10 hrs each average production will be 6.95 m/day. Starting November 27, 2006, we will reach C1 (the best location to finish both sides at the same date) 10 m short of the creek on June 13, 2007 (142 days). Start parallel work if we have crews, going from D to C1 using hand tunnelling or spider mole at 2 m/day (110days). Starting January 8, 2007, we would finish on June 8, 2007 (see Figure 3-34).

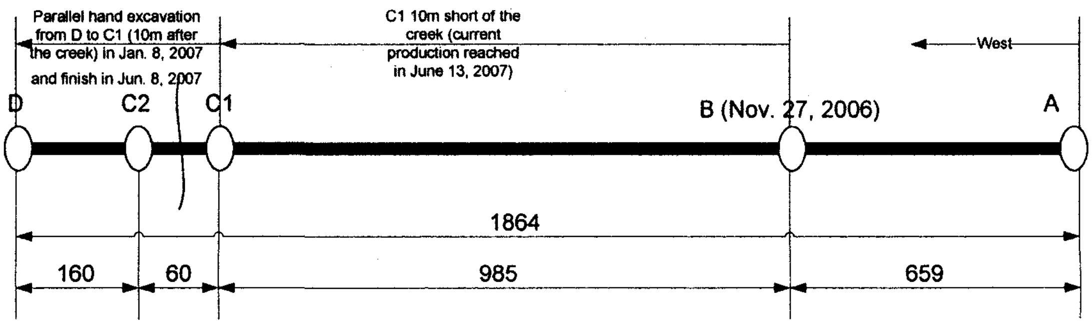


FIGURE 3-34 ALTERNATIVE 3

3.07.4 Alternative 4

Having started at A, the crew is now at B: 1205 m to go, 995 m to the creek. Average production is now 3.47 m/shift; assume we can achieve this production by going back to the old set of teeth, which been changed earlier. By running two shifts of 10 hrs each average production will be 6.95 m/day. Starting November 27, 2006, we will reach C1 50 m short of the creek on June 5, 2007 (136 days). With a double shift on the east side starting November, 27, 2006 average production would be 7.78 m/shift. By running two shifts of 10 hrs each, average production would be 15.5 m/day and we would finish the east side on February 27, 2007 (1050 m). Then we would move the TBM to C1 and start parallel work if the crews are available. Tunnelling would go from C1 to D @ 6.95m/day (37 days) starting March 27, 2007 and would finish on May 15, 2007 (see Figure 3-35).

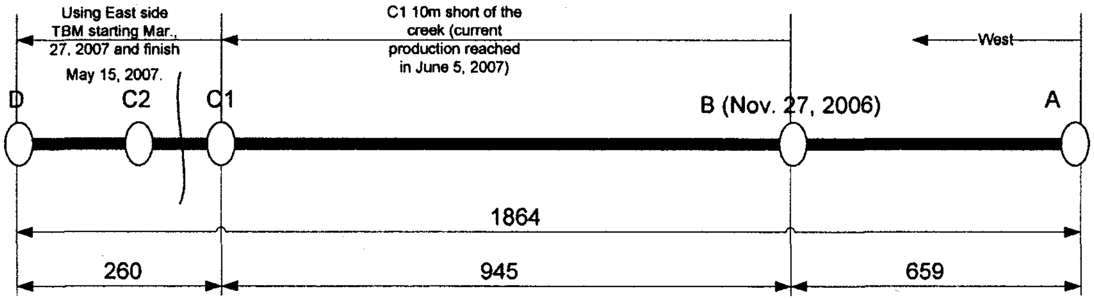


FIGURE 3-35 ALTERNATIVE 4

After developing the models and running them using Simphony.NET, the project team met to discuss the results. Based on the dissection, another set of alternatives were proposed:

- Running two shifts of TBM tunnelling per day, six working days per week, all the way to the endpoint D (refer to Figure 3-36, below) of the project.
- Running two shifts of TBM tunnelling per day, six working days per week to point C1 (refer to Figure 3-36); constructing an access shaft at C2 for sinking spider mole, which is used to complete the tunnel

portion C2-D; and adopting hand tunnelling for the creek portion C2-C1. One shift per day is applied to spider mole tunnelling, while two shifts per day are applied to hand tunnelling; five working days per week are applied to both tunnelling methods.

The total length of the SW3 tunnel is 1864 m, 762 m of which were completed with excavation and liners installation by December 13, 2006. According to the data available, the length for spider mole tunnelling and hand tunnelling is indicated in Figure 3-36; therefore, the remaining TBM tunnelling length can be calculated as 872 m, corresponding to portion B-C1 in Figure 3-36. The above-mentioned scenarios and the simulation models are detailed in the following sections.

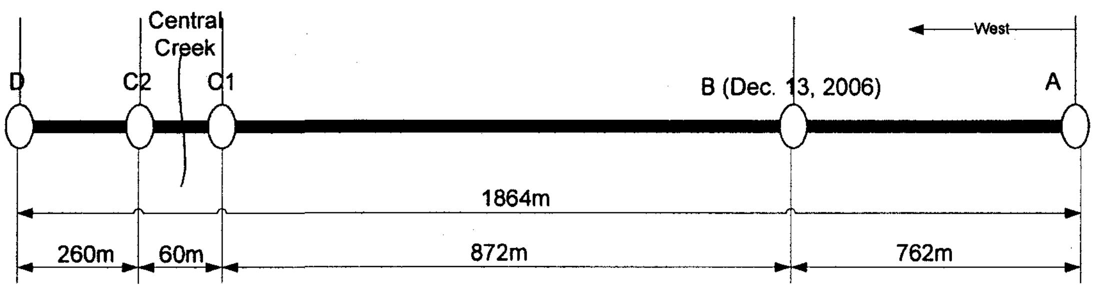


FIGURE 3-36 PROJECT STATUS DURING ALTERNATIVE ANALYSIS

3.07.5 Alternative 5: TBM tunnelling all the way to the end

3.07.5.1 Alternative 5a: Average tunnelling production 3.74 m/shift

Based on the data collected over four months (September 15, 2006 to December 15, 2006), the average tunnelling production (including excavation and liners installation) was 3.74 m/shift, 7.48 m/day (2 shifts/day, 10 hrs/shift). Assuming this productivity remains consistent, the tunnelling job can be completed by

November 5, 2007, along with the dates of other milestones specified in Figure 3-37.

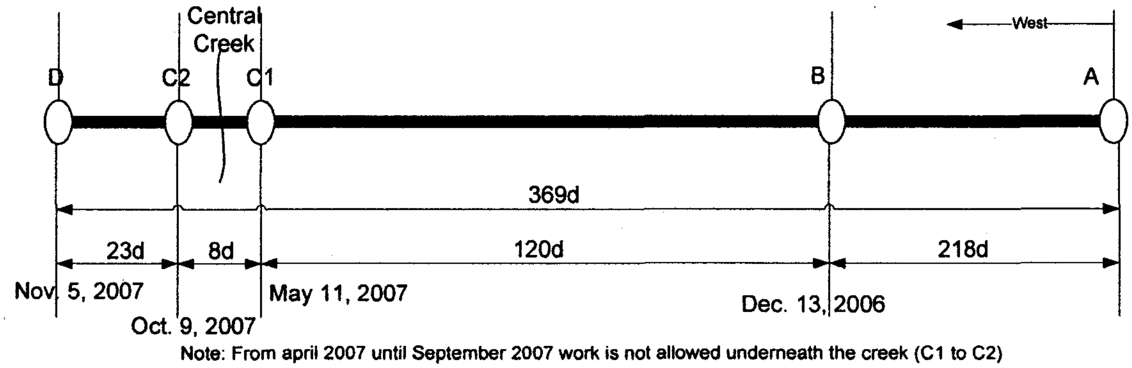


FIGURE 3-37 ALTERNATIVE 5A TBM ALL THE WAY TO THE END OF THE TUNNEL (3.74 M/SHIFT)

The results of the simulation models are shown in Figures 3-38 and 3-39, which are total duration for each activity and daily production.

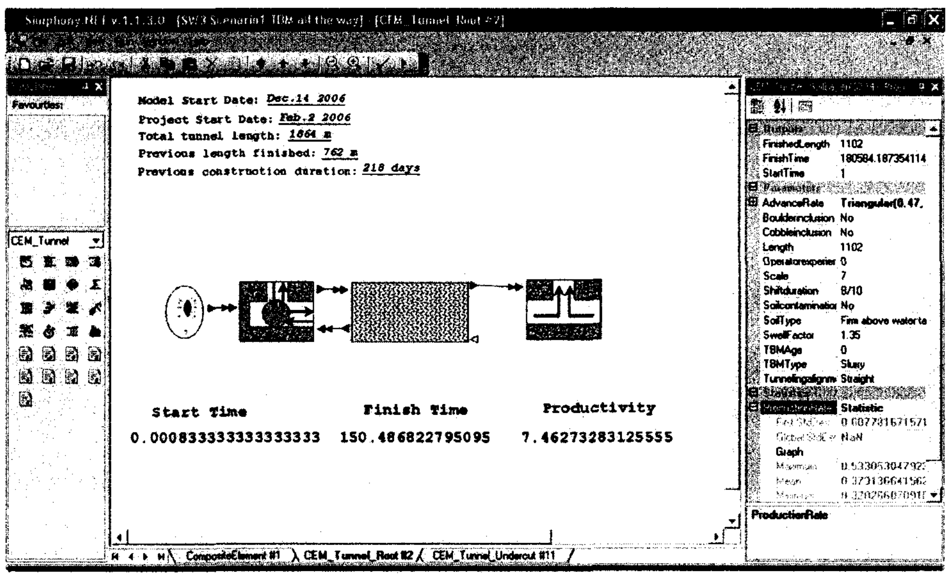


FIGURE 3-38 SIMULATION MODEL FOR ALTERNATIVE 5A (1)

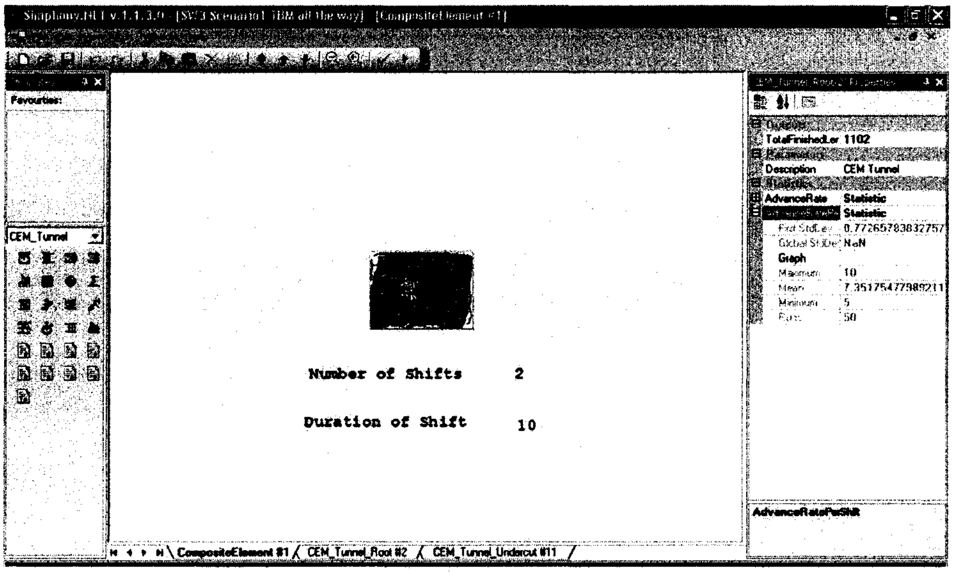


FIGURE 3-39 SIMULATION MODEL FOR ALTERNATIVE 5A (2)

3.07.5.2 Alternative 5b: Average tunnelling production 6.0m/shift

Over two weeks (December 1, 2006 to December 15, 2006), the average tunnelling production (including excavation and liners installation) was 6.0 m/shift, 12.0 m/day (2 shifts/day, 10 hrs/shift). Assuming this productivity remains consistent, the tunnelling job can be completed by April 10, 2007, along with the dates of other milestones specified in Figure 3-40.

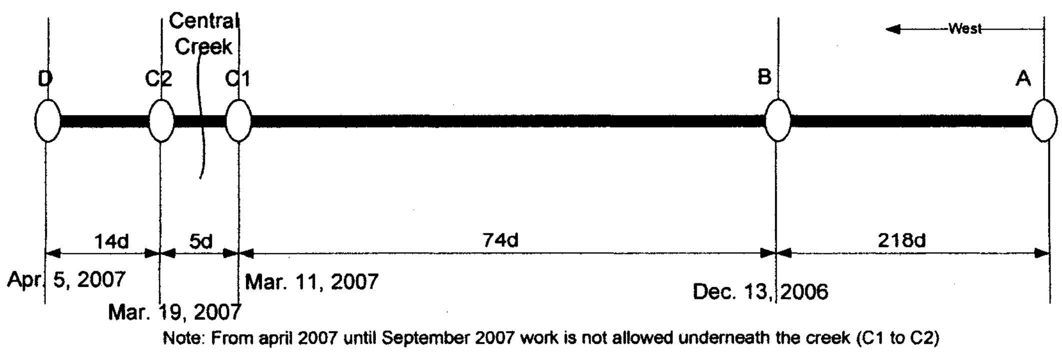


FIGURE 3-40 ALTERNATIVE 5B TBM ALL THE WAY TO THE END OF THE TUNNEL (6.0M/SHIFT)

The results of the simulation models are shown in Figures 3-41 and 3-42, which are total durations for each activity and daily production.

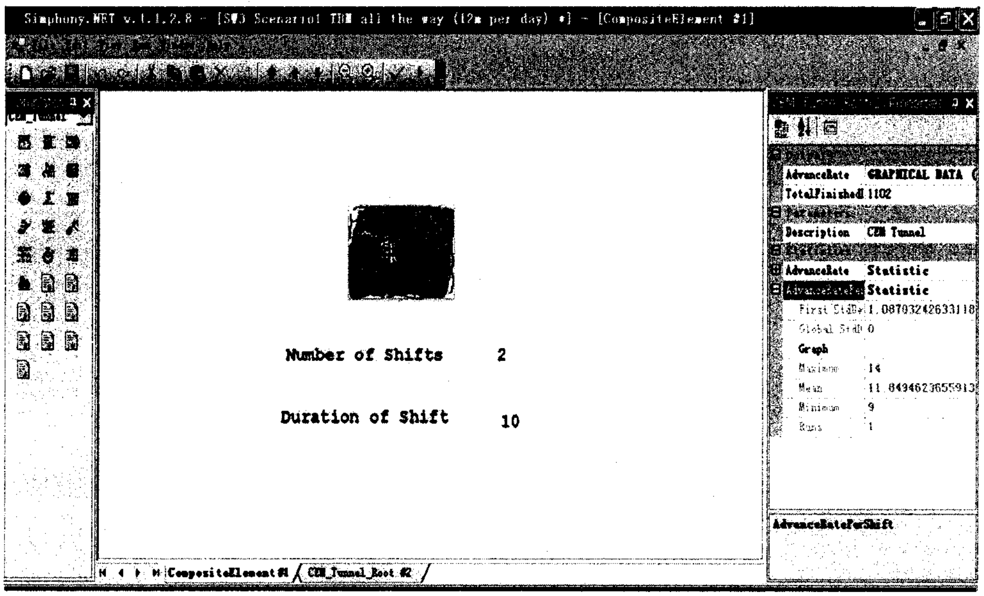


FIGURE 3-41 SIMULATION MODEL FOR ALTERNATIVE 5B (1)

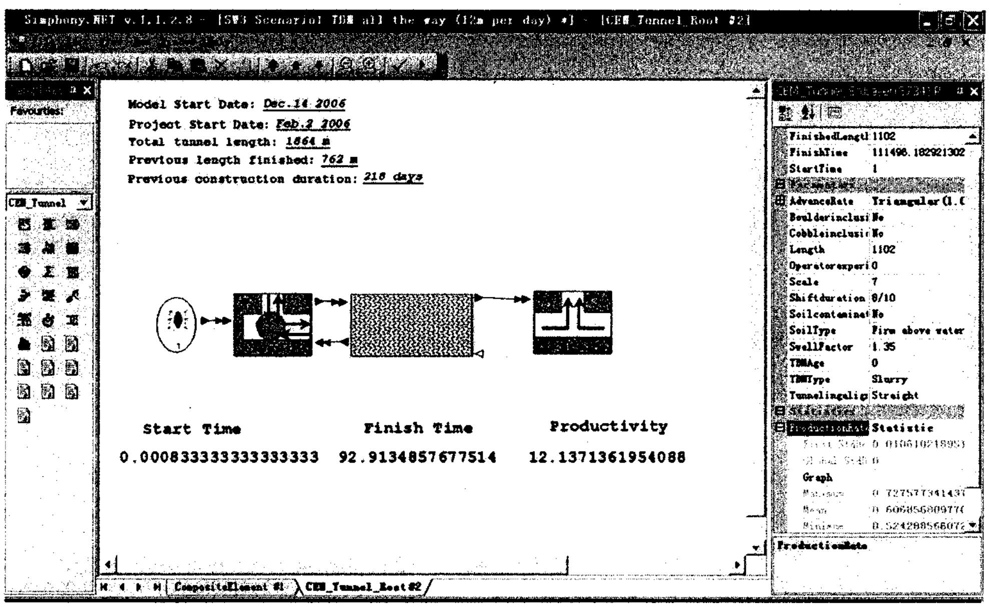


FIGURE 3-42 SIMULATION MODEL FOR ALTERNATIVE 5B (2)

3.07.6 Alternative 6: TBM + Spider Mole + Hand Tunnelling

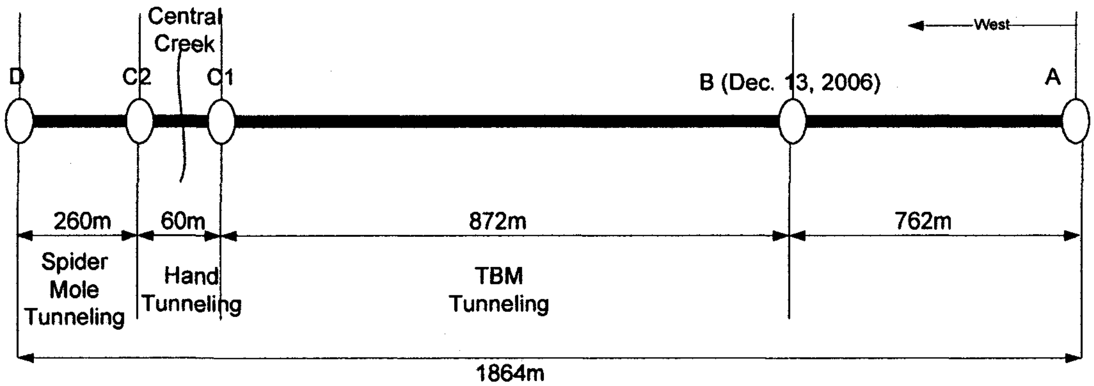


FIGURE 3-43 ALTERNATIVE 6 TBM + SPIDER MOLE+ HAND TUNNELLING

3.07.6.1 Alternative 6a: Average TBM tunnelling production 3.74 m/shift

Similar to Alternative 5a: assuming the TBM tunnelling productivity of 7.48 m/day is consistent, the TBM tunnelling portion (B-C1) can be completed by June 5, 2007. Meanwhile, construction of an access shaft (15 m) at C2 would commence on December 14, 2006. The completion dates for the other main activities are indicated in Figure 3-44 (below). The estimated duration and productivity of all main activities are listed in Table 3-13.

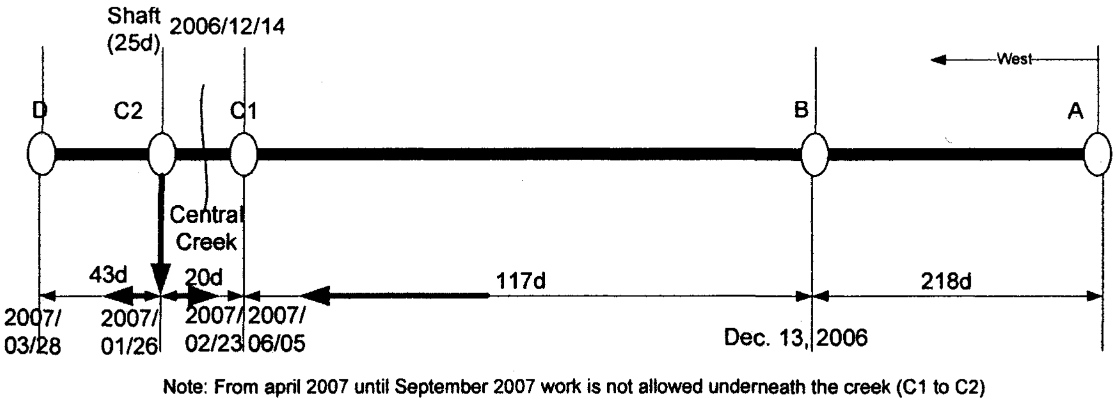


FIGURE 3-44 ALTERNATIVE 6A TBM (3.47 M/SHIFT)+ SPIDER MOLE+ HAND TUNNELLING

TABLE 3-13 ESTIMATED DURATION AND PRODUCTIVITY FOR ALTERNATIVE 6A

Parameters Mentioned	Values
TBM Tunnelling Production	7.48m/day
Spider Mole Production	4m/day
Hand Tunnelling Production	3m/day
Shaft Construction Duration	25days
Working Days/Week	5
Shifts/day (TBM tunnelling)	2
Shifts/day (Spider Mole & Hand Tunnelling)	1

The results of the simulation models are shown in Figures 3-45 and 3-46, which give the total durations for each activity and daily production.

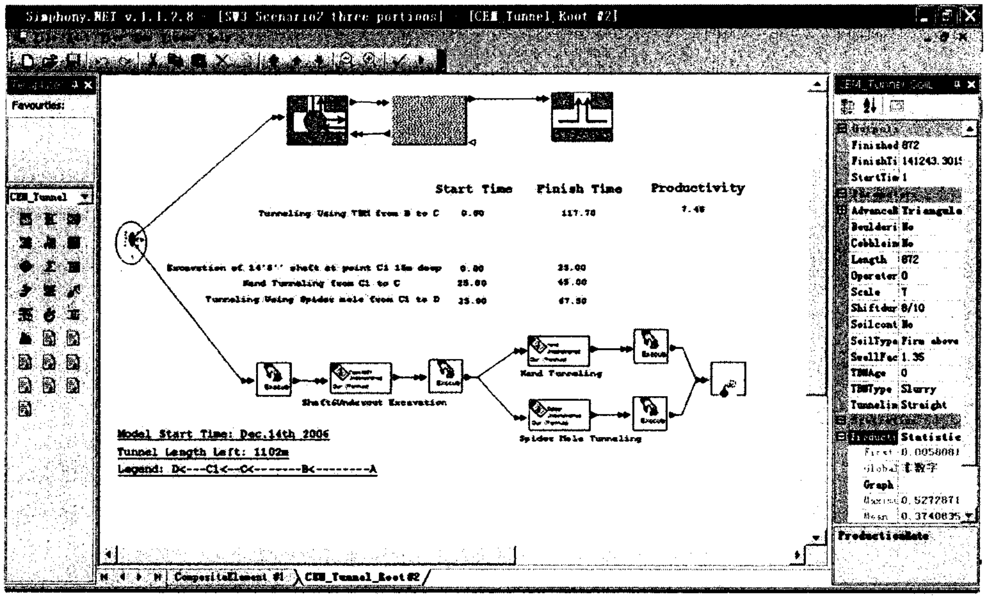


FIGURE 3-45 SIMULATION MODEL FOR ALTERNATIVE 6A (1)

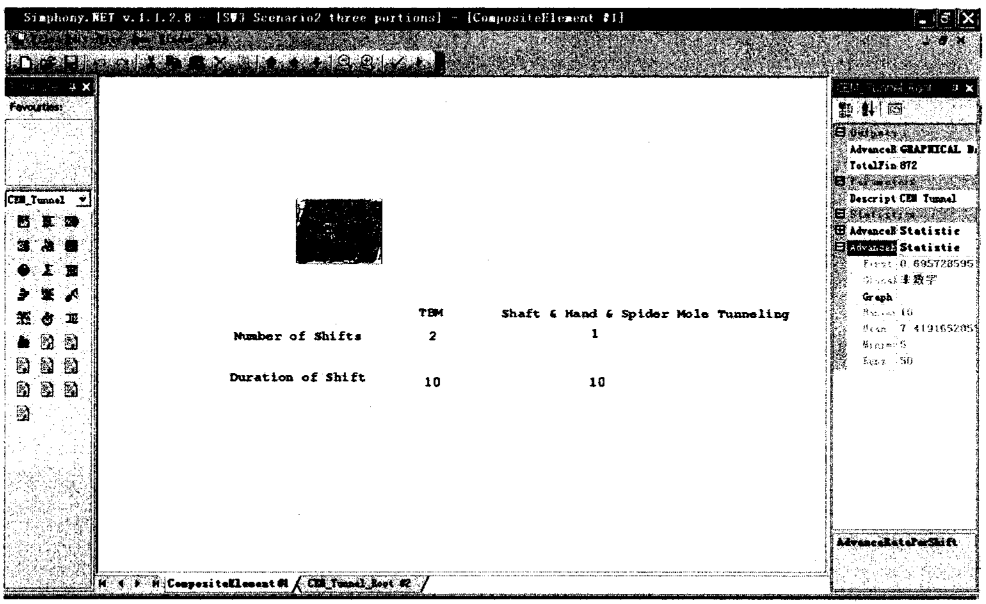
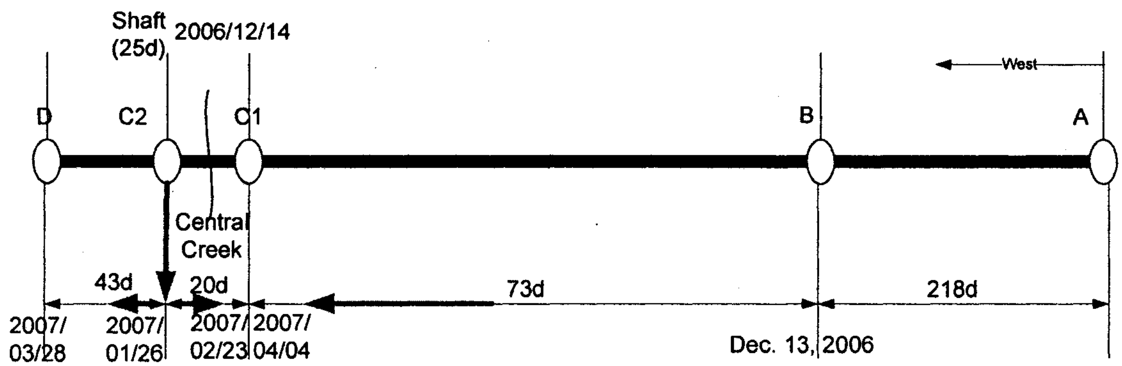


FIGURE 3-46 SIMULATION MODEL FOR ALTERNATIVE 6A (2)

3.07.6.2 Alternative 6b: Average TBM tunnelling production 6.0m/shift

Similar to Alternative 5b: assuming the TBM tunnelling productivity of 12.0 m/day is consistent, and all other parameters are the same estimated values as Scenario 6a (refer to Figure 3-42 and Table 3-2), then the TBM tunnelling portion (B-C1) can be completed on April 4, 2007. The completion dates for the other main activities are indicated in Figure 3-47.



Note: From april 2007 until September 2007 work is not allowed underneath the creek (C1 to C2)

FIGURE 3-47 ALTERNATIVE 6B TBM (6.0 M/SHIFT)+ SPIDER MOLE+ HAND TUNNELLING

Results of simulation models are shown in Figures 3-48 and 3-49, which give the total durations for each activity and daily production.

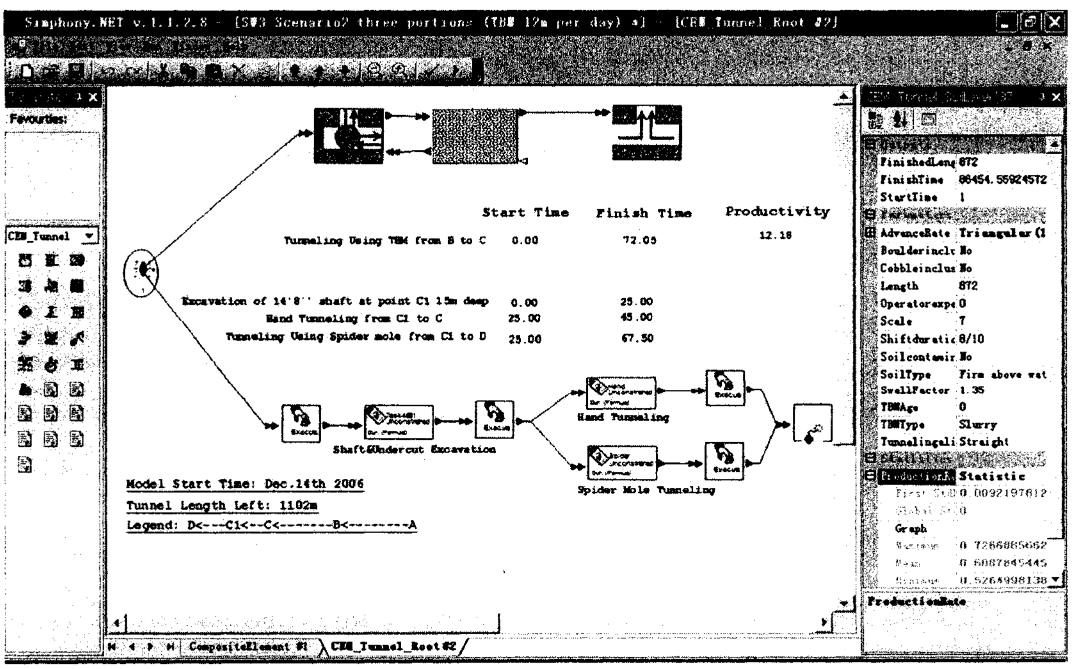


FIGURE 3-48 SIMULATION MODEL FOR ALTERNATIVE 6B (1)

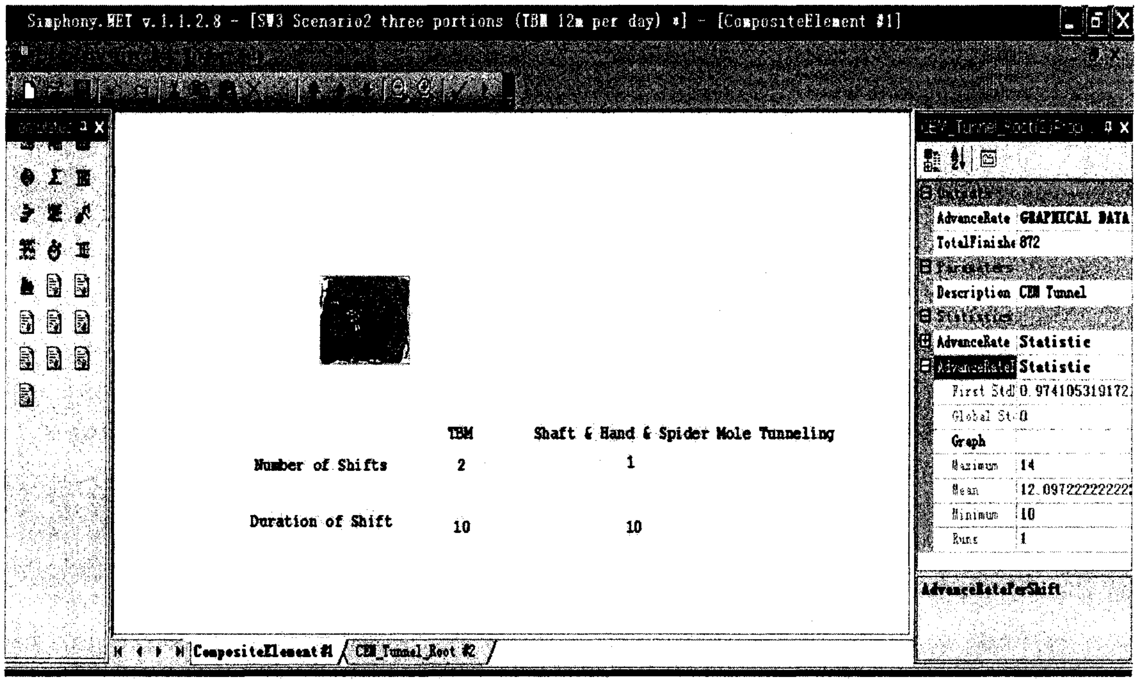


FIGURE 3-49 SIMULATION MODEL FOR ALTERNATIVE 6B (2)

3.08 Discussion of the previous scenarios

The following issues were discussed with reference to the presented alternatives (alternatives 5a, 5b, 6a, and 6b: see Table 3-14 for results summary) by the project team in a meeting:

TABLE 3-14 ALTERNATIVES 5A, 5B, 6A, AND 6B SUMMARY RESULTS

Alternative	*Section*	*Duration (Days)*	*Start Date*	*Finish Date*
5a	B-C1	120	13/12/2006	11/05/2007
	C1-C2	8	01/10/2007	09/10/2007
	C2-D	23	09/10/2007	05/11/2007
5b	B-C1	74	13/12/2006	11/03/2007
	C1-C2	5	11/03/2007	19/03/2007
	C2-D	14	19/03/2007	05/04/2007
5a	B-C1	117	13/12/2006	06/05/2007
	C1-C2	20	26/01/2007	23/02/2007
	C2-D	43	26/01/2007	28/03/2007
5a	B-C1	73	13/12/2006	04/04/2007
	C1-C2	20	01/10/2007	09/10/2007
	C2-D	43	09/10/2007	05/11/2007

- Hand-tunnelling productivity was approximately 1.2 to 1.5 m per shift; therefore, two shifts are required to achieve the adopted production of 3 m/day. As well, the estimated productivity of spider mole tunnelling is about 3 m/shift instead of 4 m/shift.

- Referring to Figure 3-36, the length of hand tunnelling portion (C2-C1) and spider mole tunnelling portion (C2-D): 107 m from C2-C1 and 150 m from C2-D are the final determined dimensions.
- The project team stated that using 12 m/day as a production average for TBM tunnelling production for the remaining tunnel is over-aggressive. To mitigate the risk and to be more realistic, an average production over the last four months of 8 m/day for SW3 and 7.66 m/day for SW2 should be used as a production target for TBM tunnelling.
- The access shaft at C2 is as shallow as 6 m (20 ft long; 12 ft in diameter), and sinking the shaft with liner plates takes about 2 days with ideal ground conditions. (More recent information indicates that 9 ft have been drilled by a machine and 11 ft must be completed by hand. The typical hand excavation rate for bedrock adopted here is 1 ft/8 hrs.)
- The preference is to finish the pure tunnelling work before November 2007, since delaying the project would cause more problems. Hence, the option in which the TBM tunnels all the way to the end is not feasible.

3.09 Simulation model for the final alternative

Based on the previous discussion the project team agreed on the options detailed below:

- Construct an access shaft at C2, 17 m deep and 12 ft in diameter (Refer to Figure 3-46). The activity commenced on January 3, 2007.
- Construct access road to C1, where the retrieval shaft is located. This activity can run parallel with tunnelling.

- Bypass the creek. The activity can also run parallel with hand tunnelling.
- Proceed with TBM tunnelling from B to C1.
- Start spider mole tunnelling from C2 to D on February 15, 2007.
- Start hand tunnelling from C2 to C1.

This final decision is illustrated in Figure 3-50: up to January 15, 2007 the length of the completed tunnel portion had reached 858 m. The remaining TBM tunnelling portion is 747 m.

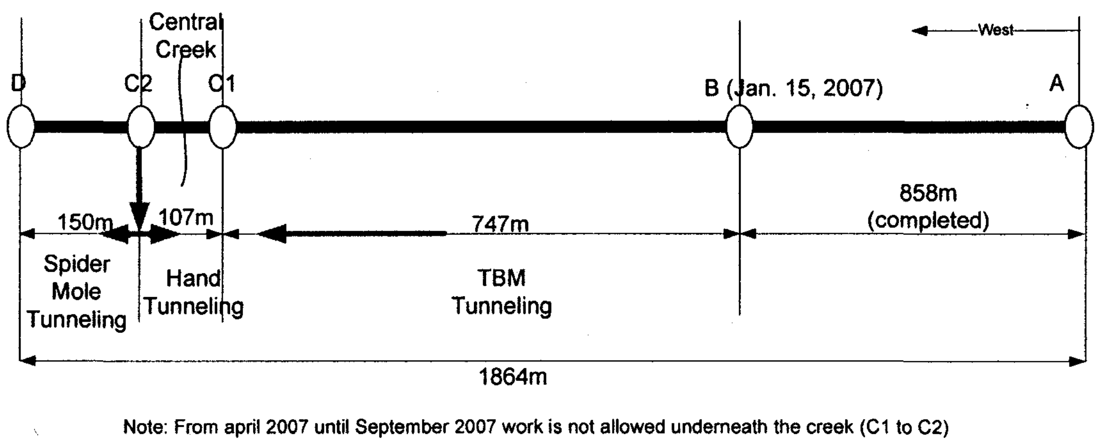


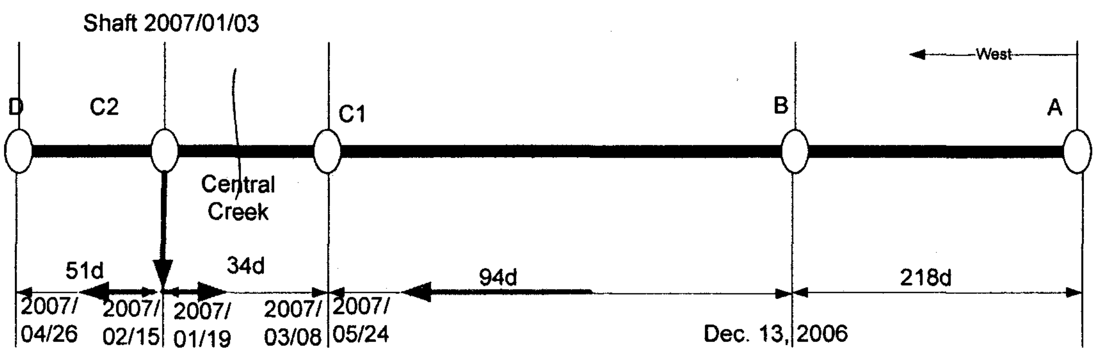
FIGURE 3-50 PROPOSED OPTION: TBM + SPIDER MOLE + HAND TUNNELLING

Based on the dimensions shown in Figure 3-51 and using the corrected productivity information indicated in Table 3-15 as the input of the simulation model, the completion date for each main activity can be obtained, as indicated in Figure 3-51. Spider mole tunnelling cannot begin until February 15, 2007 due to the unavailability of equipment (in use by another project). The pure tunnelling work can be finished by May 24, 2007.

TABLE 3-15 PARAMETERS ADOPTED WITH FINAL ALTERNATIVE

Parameters Mentioned	*Shifts/Day*	*Days/Week*	*Production (m)/Day*
TBM tunnelling (SW3)	1	5	8.0
TBM tunnelling (SW2)	1	5	7.66
Spider Mole Tunnelling	1	5	Triangular (2,3,4)
Hand Tunnelling	2	5	Triangular (2.4,3.2,4.4)
Shaft Construction	2	5	0.61 (2ft)

Note: For triangular (a, b, c): a = low possible value; c = high possible value; b = most probable value.



Note: From april 2007 until September 2007 work is not allowed underneath the creek (C1 to C2)

FIGURE 3-51 PROPOSED OPTION MILESTONES

3.10 Scenario-based planning features

During our study for both actual tunnelling project and the case studies, a number of common features were found for tunnel project simulation models. These features are included in a scenario-based planning framework for tunnelling operation shown in Figure 3-52.

We extracted some of the features from case studies, including schedule, productivity, and cost. Other features were identified from site visits and attending project planning workshops, such as weather processes, dirt removal processes, and material supply processes. By studying the current tools available to simulate tunnel operation, we defined modelling elements as common features used to define different physical and managerial components of tunnelling projects.

To build an effective scenario-based planning tool, these common features should be included in the design. The user should be able to make use of these features to efficiently develop a model for each scenario.

In other words, we should design our tool in distributed way and allow the user to select the parts required for his/her model. Through the literature, we found that using HLA concepts will be very beneficial in designing such a tool. These features will be discussed below:

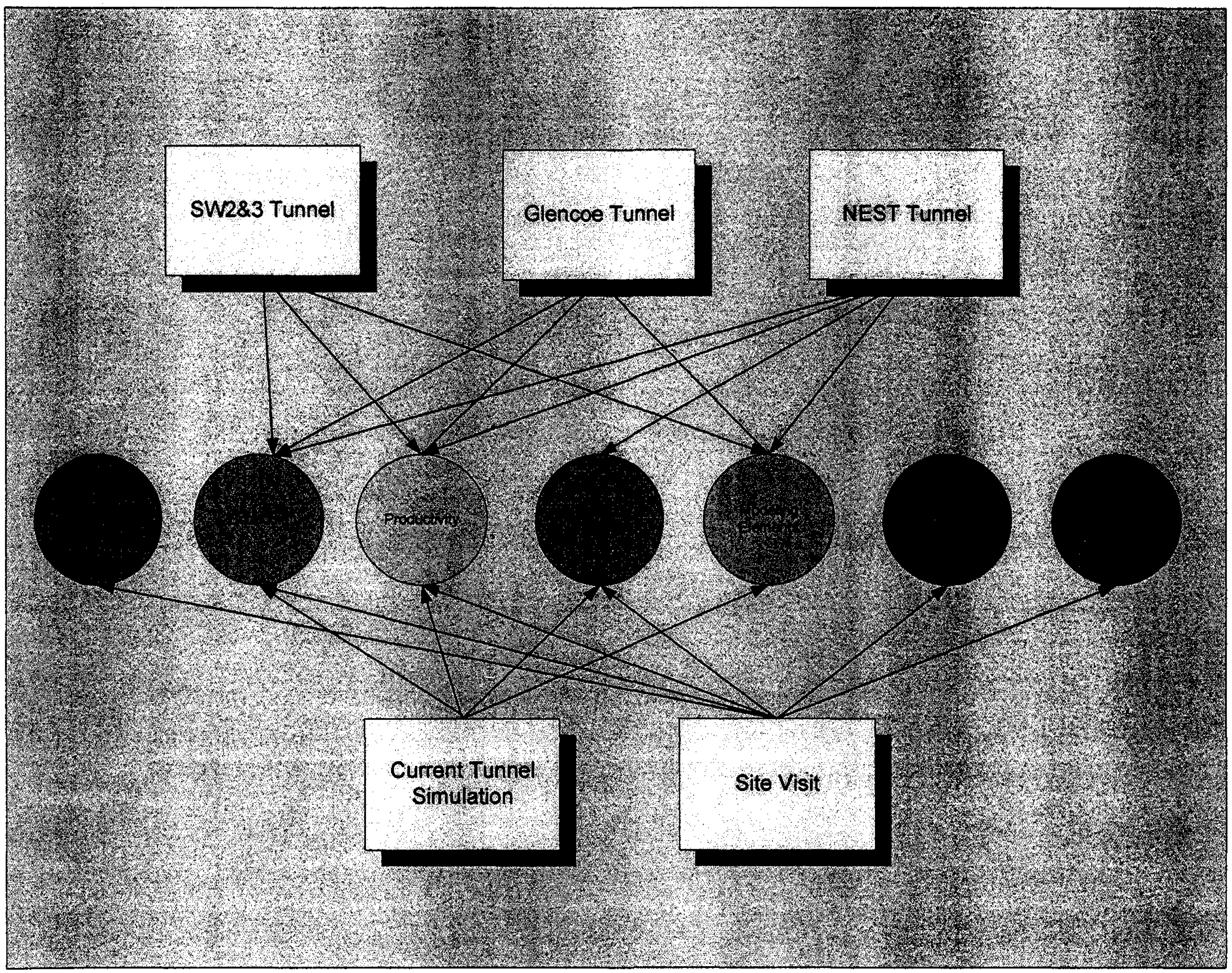


FIGURE 3-52 FEATURES IN UTILITY TUNNEL CONSTRUCTION SIMULATION

3.10.1 Modelling elements

The modelling elements for a specific SPS tool are domain-based simulation building blocks used to map the real physical or logical components of the targeted process. These simplify the process of developing a simulation model. Each modelling element represents a physical component in real life, meaning the user doesn't have to be experienced in simulation, although s/he should be experienced in the field we are trying to model. This feature has been realized through studying the current simulation environments.

3.10.2 Cost estimate

Cost is a major component in any tunnelling project; most of the time cost is the driving criteria in selecting among options. Usually, cost estimates for each scenario will be required to decide the best option. As such, it is very important to have a scenario-based planning tool capable of estimating the cost. This feature was extracted from the case studies and from the workshops.

3.10.3 Schedule

Schedule is another defining feature: in any project, a schedule is required to help assign the project progress and performance. In some cases, project finish date is the major drive in the project, as in the Glencoe tunnel, for example. It is very crucial to have schedule as a major component in our framework. This feature was found in all case studies, and also in all workshops we attended. The project team also uses project schedule as a project control tool to evaluate the project's actual progress compared to the planned one.

3.10.4 Productivity

During construction, productivity is mainly used as a control factor for the project progress and gives an indication of how things are going. The productivity unit used in tunnelling projects is either meters per hour (m/hr) or meters per shift (m/shift). Productivity can be used to select the best scenario since it plays a significant role in determining the project's total duration and its cost. Productivity was calculated in all case studies; it was also one of the main sets of data collected on site and sent to the project manager.

3.10.5 Weather

Weather may play a major role during construction. For example, in tunnel construction if it is raining, the dirt dumping process will be difficult and require more time. Consequentially, it will affect production, which will affect the schedule and cost. As another example, during instances of high wind it is very difficult for the crane operator to control the crane. This will shut down the operation, which means more time and more money are needed to complete the project. So, to address these issues weather should be represented in the framework. This feature was pointed out while collecting the tunnel project breakdown data during site visits.

3.10.6 Material delivery

During the study, we found out that material delivery to the site can be a controlling factor in project progress, especially if it is related to tunnel liners or TBM spare parts. Tunnel liners can be rib and lagging or concrete segments. In some cases the suppliers cannot keep up with the demand, which will force the project to slow down. Usually the TBM owner does not carry all spare parts in-house, so in some cases of TBM breakdown the owner will be forced to order parts from suppliers who may or may not have them on hand. This feature was realized in the same way as weather effects during the site visits.

3.10.7 Dirt removal

Usually a tunnelling site is limited in area; the amount of dirt stockpile that can be stored on site is also limited. A dirt removal operation to remove the dirt stockpile is an ongoing process and should be part of the whole system. During visits to the SW2&3 site, we noticed that when it is raining, the dumping areas shut down because it is too wet to operate, and that forces the project to slow down—and in some cases shut down—if there is no space available for storing the dirt.

3.11 Scenario-based planning using HLA concepts

HLA is a simulation standard developed by the United States Department of Defence (DoD) for distributed simulation, enabling them to reuse the simulation models individually or in combination, which will increase the investment benefit (Kuhl 1999). HLA supports the development of a federation, which consists of a number of federates communicating with each other using messages through the Run Time Interface (RTI).

To design our tool, we used HLA concepts to allow for reusability of the simulation models we are creating. Also, this will allow the user to integrate different components used in our tool through utilizing communication standards defined in the HLA. Using the HLA standards will further allow for developing our tool to support multiple users in multi-dimension project environments in a collaborative setup.

To represent what we have discussed and to include all features we defined, we propose a number of federates to represent our tunnelling federation. These federates can be grouped into two groups: construction federates and supporting federates.

Construction federates include the shaft construction federate and the tunnel excavation federate. These federates will be used to simulate the actual construction process for both the shaft and the tunnel. Also, they will calculate the total cost and productivity of the process. The tunnel federate has to communicate with the shaft excavation template to identify if the shaft being built is a working shaft or not. If it is a working shaft, the tunnel excavation can't proceed and must wait until shaft excavation has finished. Once it is finished, the shaft excavation federate will send a message to the tunnel federate to allow it to proceed.

Supporting federates are used to model supporting activities and managerial issues. These federates include:

- Calendar federate: This federate will be used to transfer simulation time (which is in minutes) into actual calendar dates, using a database accounting for all non-working days in the year. If the current date is a holiday, it will skip to the next date and so on. The shaft excavation and tunnel excavation template will receive messages from the calendar federate to inform them with the current date. By utilizing this date, the schedule for shaft and tunnel excavation can be defined. Similarly, the calendar date is used by the weather federate to determine the weather, which will subsequently impact the productivity for construction activities taking place on that day.

- Project federate: This federate is used to distinguish between different projects in the federation as it collects the project total cost and schedule. At the beginning of the simulation execution, the project federate will send a message containing the project name to the tunnel and shaft excavation federate, if both are required. At the end of the simulation, the tunnel and shaft excavation federate will send the cost and schedule data to the project federate.

- Dirt removal federate: This federate will be used to simulate dirt removal from the work site to the dumping site. At the beginning of the simulation execution, the dirt removal federate will send a message to the shaft and tunnel excavation federates to notify them of its existence, and then during simulation the tunnel excavation template will request trucks from the dirt removal federate to remove dirt from the site. This process is ongoing during simulation, and at the end of simulation the dirt removal federate will send the total cost to the project federate to add to the other costs.

- Supply federate: This federate is responsible for simulating delivering materials to the tunnel project. It supplies the projects with liners to support the tunnel or equipment parts, such as TBM parts. This template will follow the same protocol by sending messages to tunnel construction to notify its existence. During excavation, the tunnel federate requires liners to support the tunnel; since the tunnel site can't store all the material required, it will send a message to request material. The supply federate will send the material to the tunnel federate, and at the end of the simulation the supply federate will have a complete schedule for the requests it received.
- Weather federate: Weather can greatly affect a tunnel project, especially in a cold weather environment such as Edmonton, Canada. This federate updates a number of weather parameters on daily basis using the date from the calendar federate. During simulation, this federate will send messages to the tunnel and shaft excavation template with the new weather parameters. These parameters include rain, temperature, and wind speed.

Users can develop tunnelling federation by utilizing a number of the federates we discussed earlier. At minimum, a user can develop a federation using the project federate, the shaft excavation federate or the tunnel excavation federate, and the calendar federate. The user can choose to use or not use other supporting federates in his/her federation.

Using HLA concepts can help facilitate the multi-user environment by providing each user with what he or she specifically requires; for example, the supply federate can be useful for managers, while the hand tunnel excavation federate can be useful for site engineers.

Figure 3-53 illustrates the tunnelling federation and shows the federates we propose.

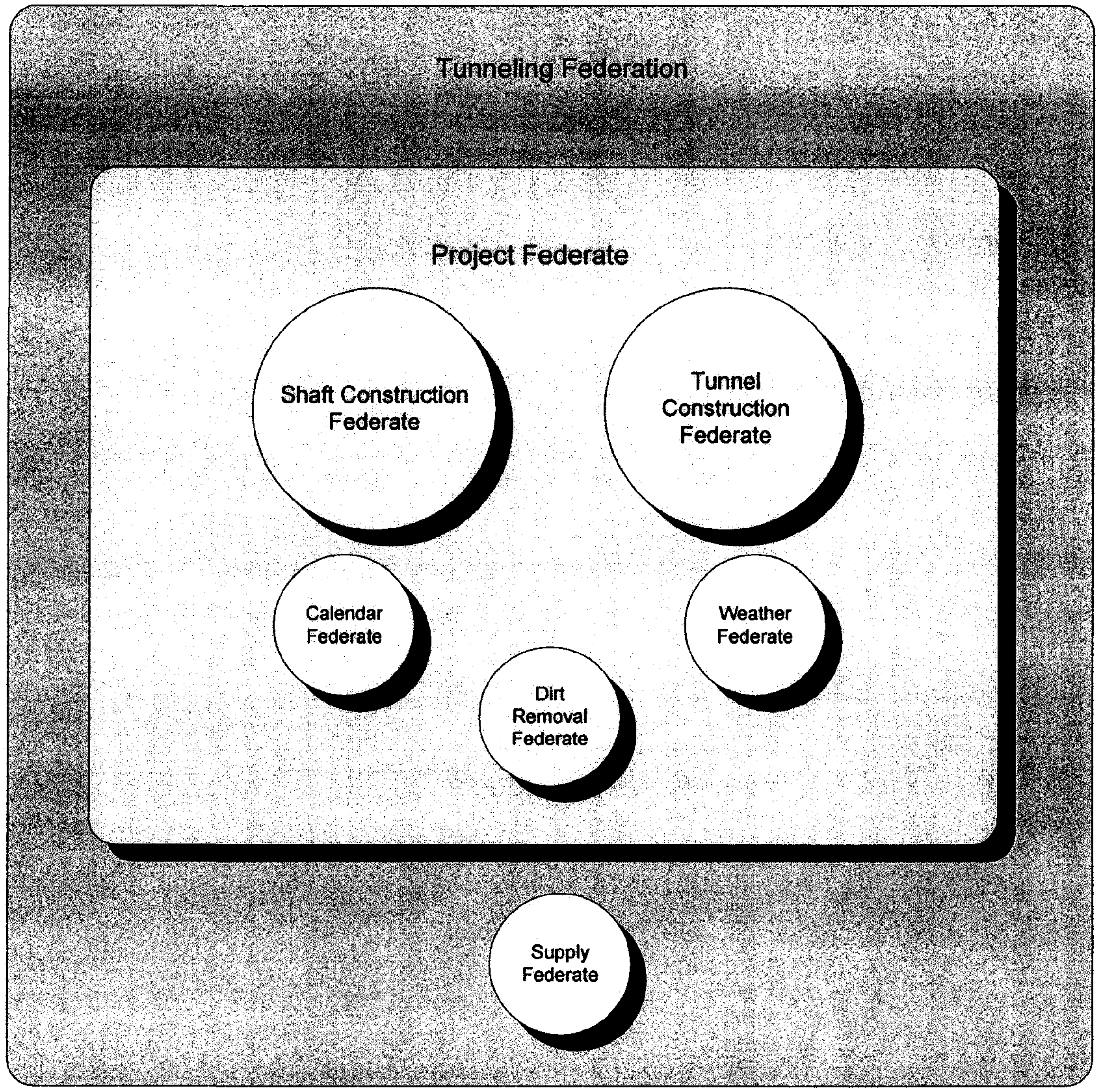


FIGURE 3-53 TUNNELLING FEDERATION

We used Simphony.NET to develop the scenario-based planning tool. In Simphony.NET we use templates consisting of a number of modelling elements to build simulation models. To implement the HLA federates concept in Simphony.NET, a set of templates was created. A template may represent a federate; also, a modelling element may represent a federate.

3.12 Scenario-based planning templates for tunnelling construction

To implement the framework we used Simphony.NET. Three templates were developed for the scenario-based planning tool for tunnelling construction, as shown in Figure 3-54. These templates are:

- Tunnelling template, used to simulate the tunnelling excavation operation. The outputs of this template are schedule, cost, and productivity for the tunnel excavation.
- Shaft construction template, used to simulate the shaft construction; it will have the same outputs as the tunnelling template.
- Support template, which has a number of elements, each of which represents a common feature uncovered in our study. These are: supply, used to simulate the material supply to the project; dirt removal, used to simulate the earth moving operation; calendar, used to introduce the schedule to the simulation model; weather generator, used to include weather effects in our model; and project, which allows the user to simulate a number of projects at the same time.

The three templates work collaboratively to help the project team to develop any tunnelling scenario they choose to explore in real time. Using this tool will enable the project team to select the most effective scenario from those proposed. The communication among these templates is achieved using global attributes and the event calendar used in discrete event simulation. The communication points will be discussed later in the next chapter.

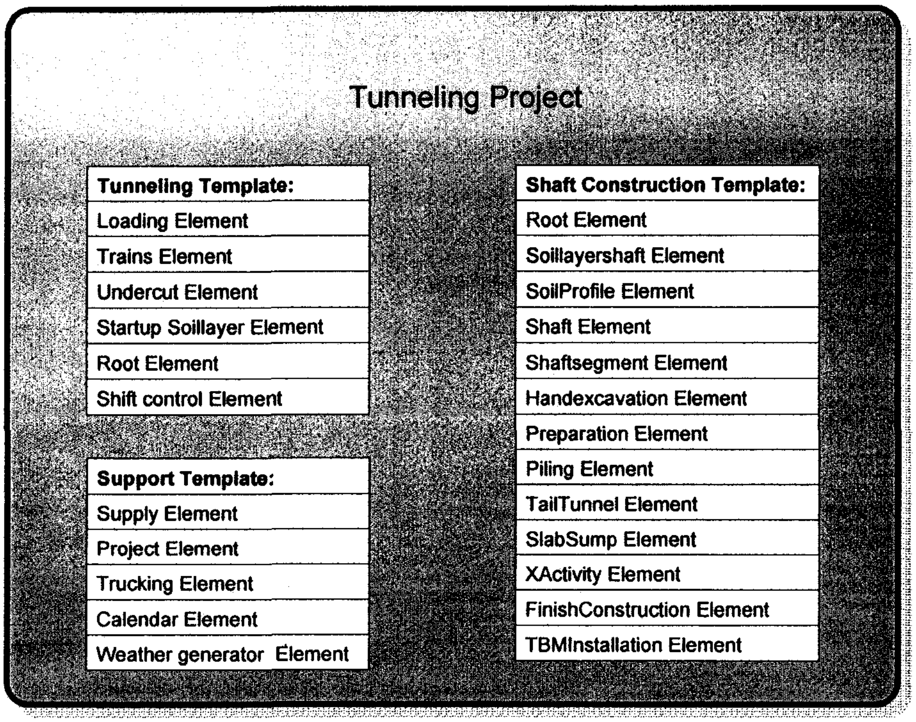


FIGURE 3-54 SCENARIO-BASED PLANNING TOOL TEMPLATES

3.13 Summary

In this chapter, we presented a scenario-based planning framework for tunnelling project development based on HLA concepts. In this chapter, we explored the tunnelling operation components and we also discussed the state-of-the-art in simulation planning applications. This showed the strength of simulation in project planning and the effectiveness of using Simphony.NET. It also showed the benefits of HLA concepts, and the platform is easy to use and implement. In the next chapter, we will discuss the implementation of the framework using Simphony.NET.

CHAPTER 4. SCENARIO-BASED PLANNING TEMPLATE

In this chapter, an implementation of the scenario-based planning framework based on the FIATECH vision applied to tunnel construction will be presented. The implementation we present includes a number of the FIATECH scenario-based planning features, such as integration and automation of schedule, cost, productivity, resource utilization, and material delivery.

We developed the scenario-based planning tool using Simphony.NET. The tool we developed consists of three parts, each of which is implemented as a simulation template: tunnelling template, shaft construction, and support template. The support template consists of a calendar element, project element, weather generator element, trucking element, and supply element.

We used the framework we presented in Chapter 3 as the basis to develop our tool. The tool allows the user to create simulation models for utility tunnel projects utilizing the shaft excavation and tunnel templates. We have also provided the user with supporting services to allow him/her to create cost estimates, project schedules, productivity analyses, and others. These templates are designed to accomplish some of the FIATECH scenario-based planning features. Figure 4-1 shows the scenario-based planning tool we developed; it also illustrates how we represent FIATECH scenario-based planning features in our tool.

The implementation of the framework in the utility tunnel domain is structured around two types of models. First, we need to be able to build models of the construction operation itself. To facilitate this, we provide two templates for tunnel operation modelling and shaft construction modelling. Secondly, we need to integrate various construction management features. These are implemented under the umbrella of a template called support template.

The tunnel and shaft templates allow the user to build a model of the project at hand using abstract simulation elements. The support template provides the services required to perform a calendar-based transformation of the simulation results, weather generation for each day, supply chain modelling, and others. These are conceptually shown in Figure 4-1.

Figure 4-1 shows the integrated functions of the model. The main component is the simulation model of the physical components of the tunnel project. This model interacts with other supporting models: in supply chain, the tunnel simulation model sends a request for material to the supply chain which relays the request by delivering the material; calendar requires the total day units in simulation units from the tunnel simulation model to be able to advance the date and notify the tunnel simulation model of the current date; weather generator informs the tunnel simulation model of the daily weather parameters concerning the model; earth moving operation monitors the dirt excavated and removes it from the tunnel site.

Figure 4-1 also shows some of the inputs to the simulation model and the main outputs it generates. For example, the calendar requires a list of the holidays to determine if the current day is a working day or not. Other inputs will be weather parameters for the area of construction, material supply duration, tunnel excavation activity durations, project starting date, resources unit rates, materials unit rates, equipment unit rates, and others.

The simulation model will generate a number of outputs such as: project total cost, which includes material costs, resource costs including crews and equipments, indirect costs, and dirt removal costs; project schedule, which shows the project starting and finishing date overall; and different components including productivity for tunnel excavation, and material supply schedule.

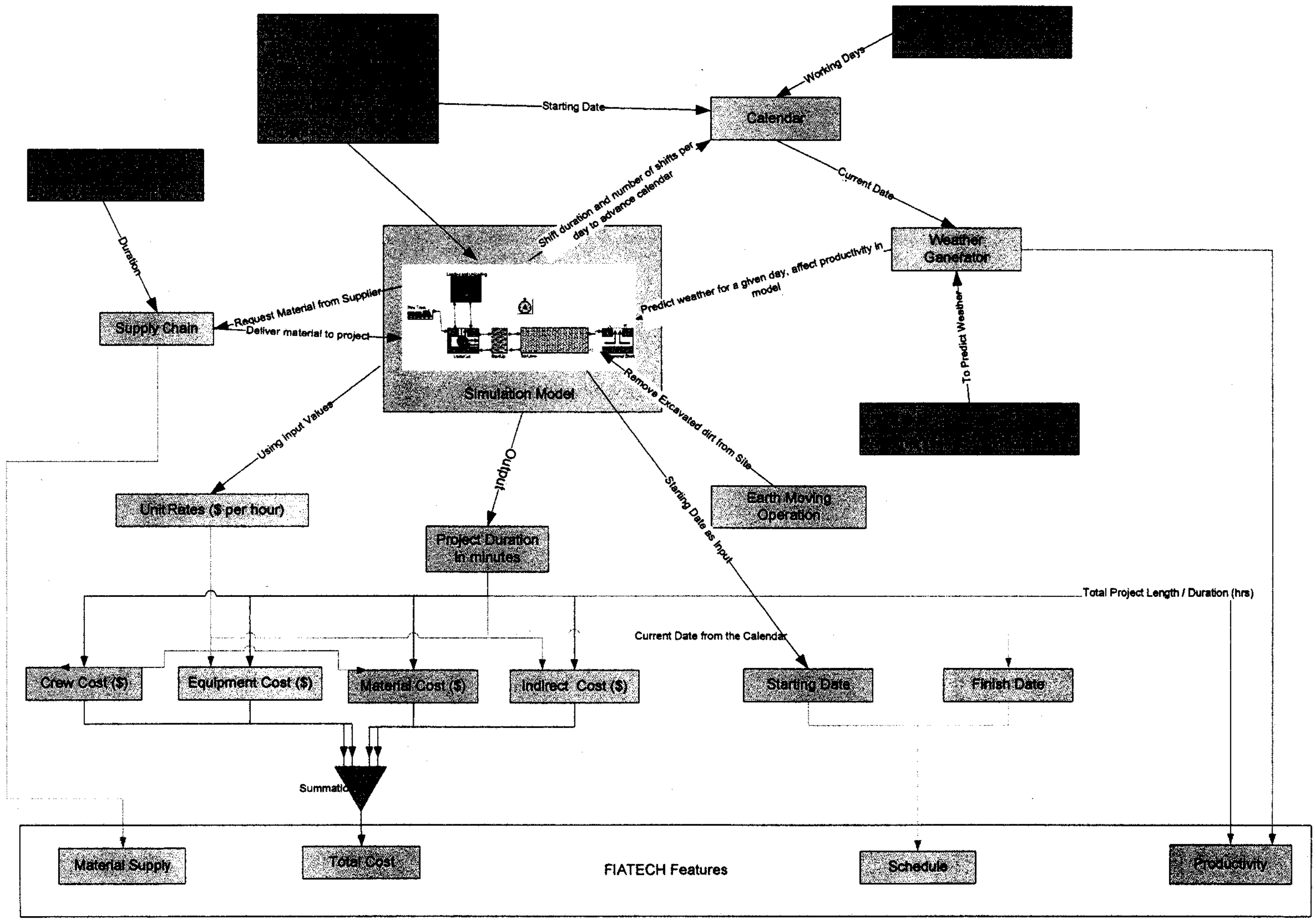


FIGURE 4-1 SCENARIO-BASED PLANNING TOOL CONCEPTUAL REPRESENTATION

4.01 FIATECH scenario-based planning features included in the simulation tool

As we pointed out before, our implementation uses FIATECH's vision for scenario-based planning and its features, which include cost, schedule, productivity, resources, and material delivery integration and automation.

To implement our framework for tunnel construction, we designed our system based on the findings of Chapter 3 and then incorporated the desired FIATECH features for scenario-based planning, as demonstrated in Figure 4-2.

In particular, to provide an integrated medium that facilitates rapid scenario-based planning, we conceptualized the modelling elements so as to map simulation information into cost, schedule, resources and other data required in decision modelling. The presentation of the results is in a typical form understood by construction practitioners.

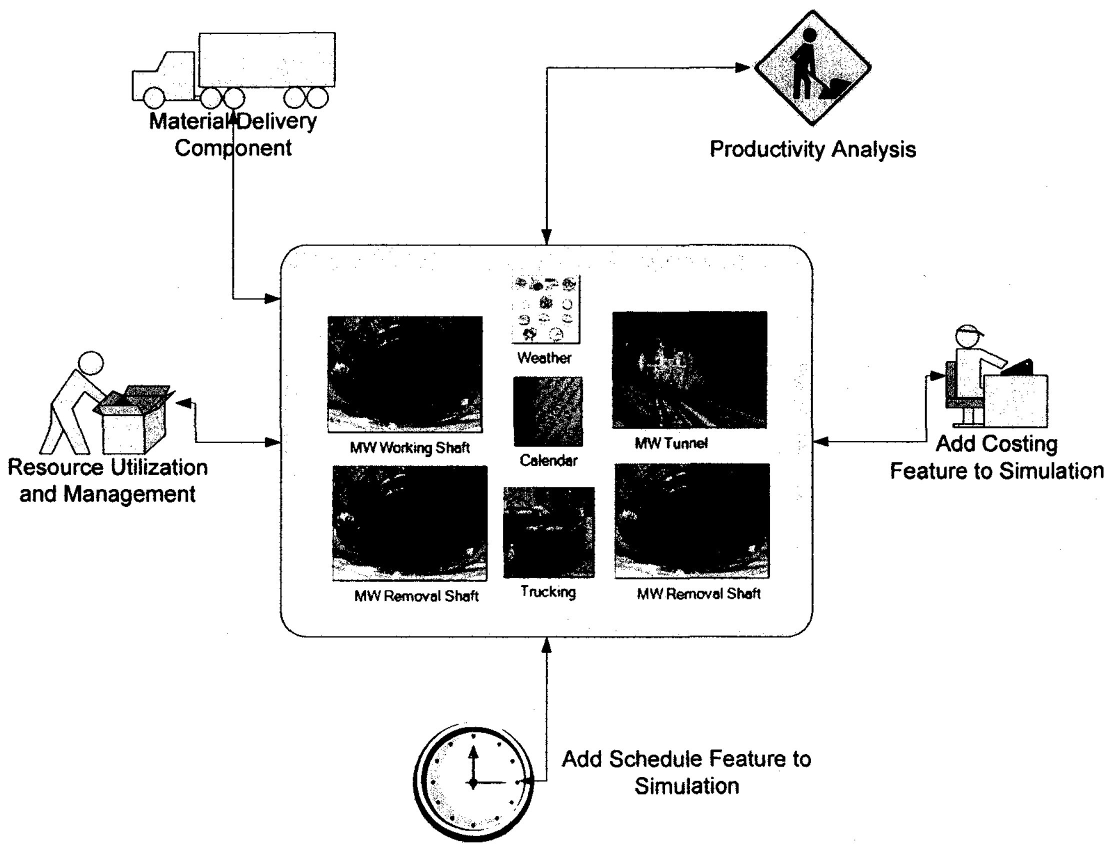


FIGURE 4-2 SCENARIO-BASED PLANNING TOOL WITH FIATECH FEATURES

4.02 Scenario-based planning workshop

The scenario-based planning simulation tool for tunnelling construction can be used during the scenario-based planning workshop (shown in Figure 4-3) through the following steps:

- The project team should be composed of key stakeholders involved in the project, such as the project manager, design team, consultant, foreman, and any relevant parties.
- The project team discusses project goals and components, and then proposes a number of scenarios. Each scenario should fulfill all project goals and should be distinguishable from the others. In other words, each scenario should represent a different future and not simply an expansion from a base case scenario.
- Using the scenario-based planning tool for tunnelling, a simulation model will be created to represent each scenario. The simulation model should include parts for tunnelling excavation, working shaft excavation, and removal shaft. Also include all supporting processes, such as material delivery, earth moving operations, and weather effect as required.
- Each model will be executed using Simphony.NET.
- After running the model, the results for each scenario will be reported to the project team during the workshop. These results include: (1) Total cost, which is an addition of the tunnel excavation cost, shafts excavation cost, and earth moving operation cost. The cost should be divided into direct cost and indirect cost. Direct cost includes labour, materials, and equipment cost. Indirect cost consists of any other cost; (2) Schedule, which identifies the start date and finish date for each component in the tunnelling project for evaluation; (3) Productivity values, which show the expected

advancement per hour or per shift. If material delivery is required, a schedule representing the material ordering will be shown.

- The project team will discuss the results and then select the best scenario, or propose a new scenario combined from the initially proposed scenarios. In most cases, the project team will combine a number of scenarios to come up with the most appropriate one. The new scenario will be modelled in the same way as the other scenarios, and the final cost, schedule, and productivity will be presented.

This process will be conducted in real time, which means the scenarios will be modelled and executed during the workshop, and the results will be reported during that period.

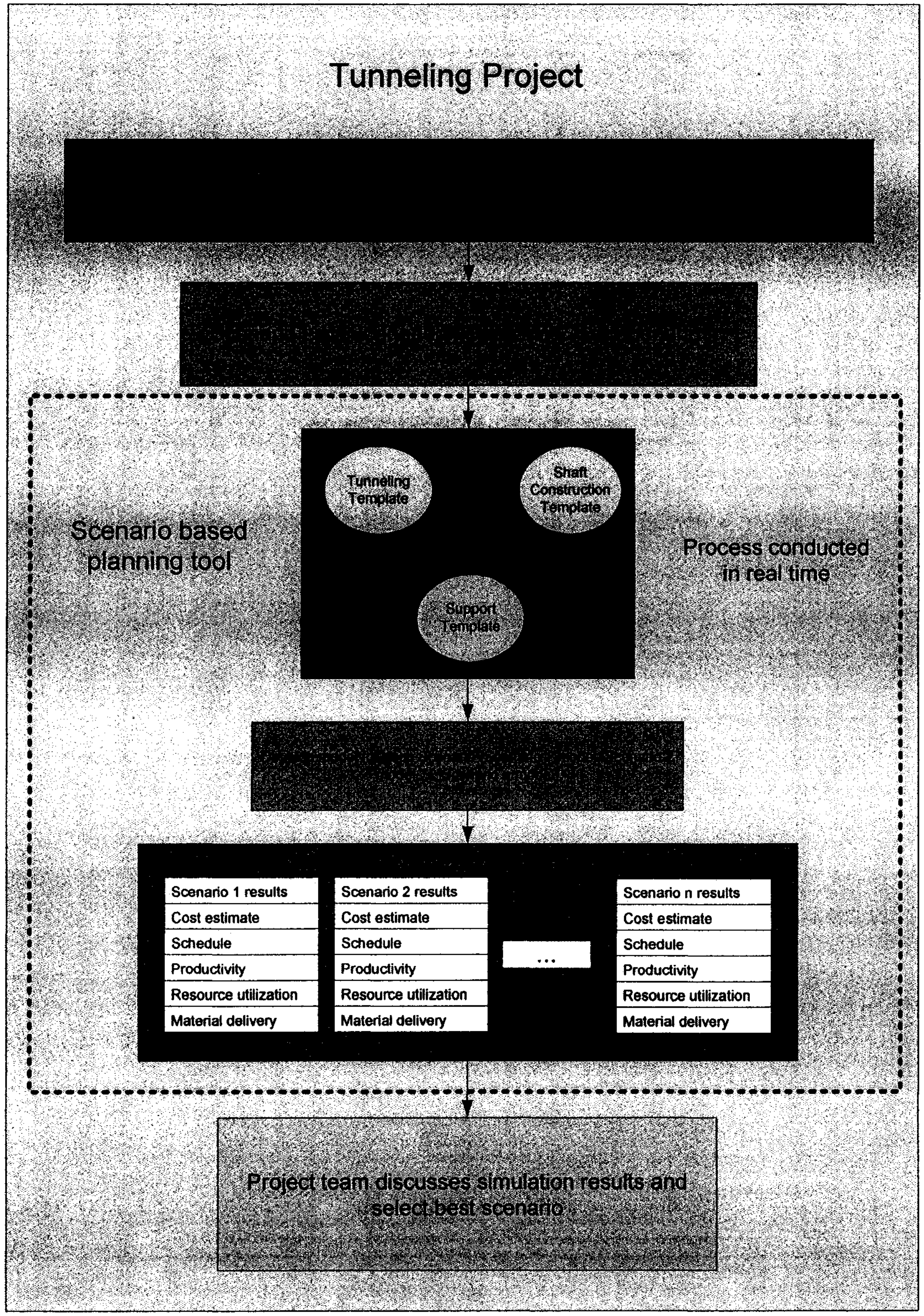


FIGURE 4-3 SCENARIO-BASED PLANNING PROCESS FOR TUNNELLING PROJECTS

4.03 Scenario-based planning tool for tunnel construction

As we mentioned previously, our tool consists of three templates: tunnel, shaft construction, and support. We designed the tool in this way to allow for integration, and to provide the user with an option to use the complete tool or part of the tool. For example, the user can use the tunnel template to develop a model for tunnel excavation only. The mechanics of the tool are illustrated in Figure 4-4. The project team starts with a scenario for a tunnel project. They use the tool, as shown in Figure 4-4, to create a simulation model representing the project.

To allow the user to implement some of the management services, we introduced the third and last template, the support template. This template consists of a number of elements: calendar, supply, project, trucking, calendar, and weather generator elements. The project team can use the calendar element for scheduling purposes. Weather generator will introduce the effects of weather into measures of productivity. The project elements used will allow the user to include number of tunnelling projects in the same simulation model. The supply element will allow the user to model the material delivery if s/he so chooses. The last element is used to model earth moving operations for excavating dirt from the project site. We built this template to be transferrable to simulation models other than tunnelling.

After building the model using the described templates, the project team can run the simulation and extract the results in form of a schedule, cost estimate, productivity, resource utilization, and material delivery. Then they can move to the next scenario. The templates will be described in the next sections.

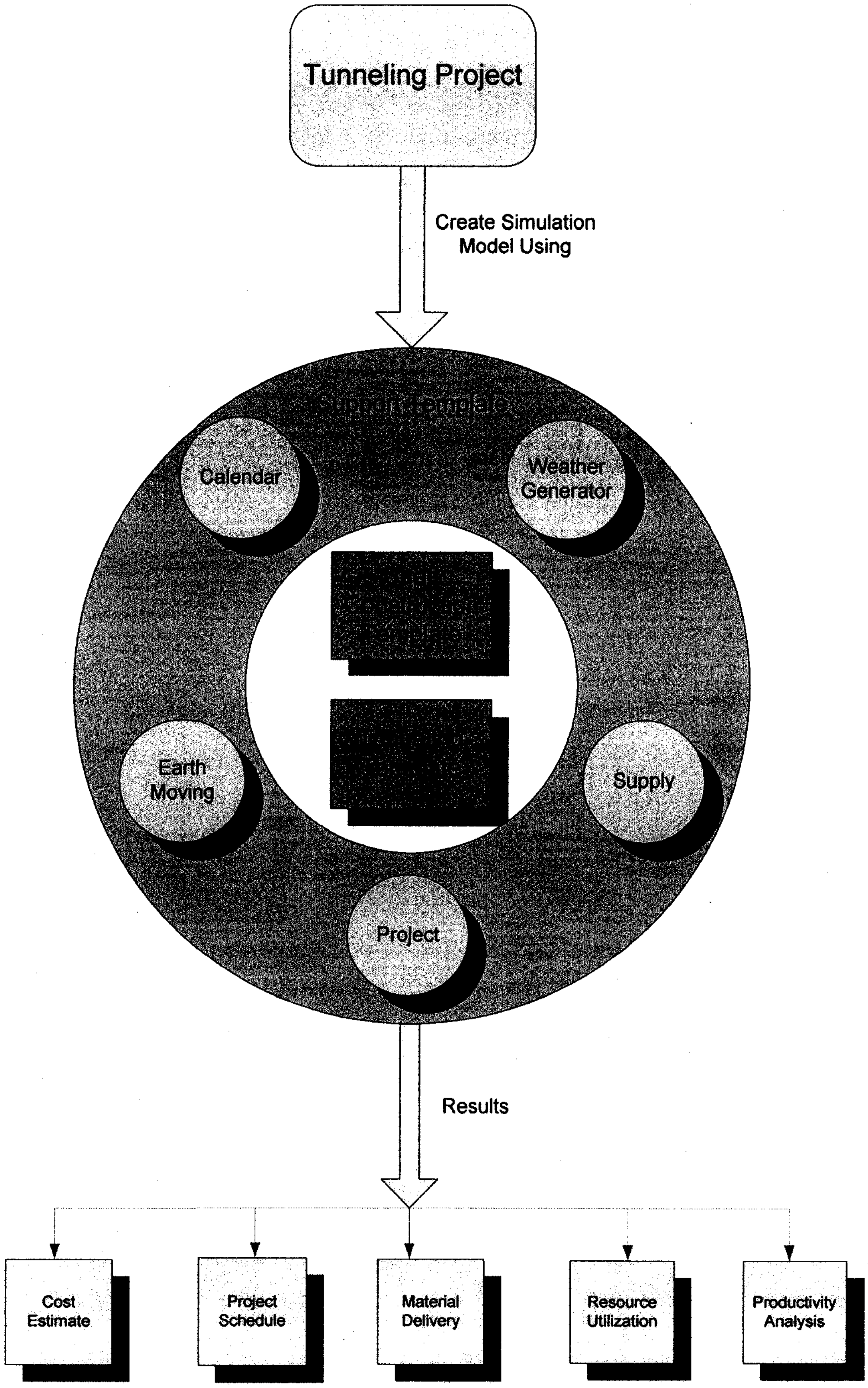


FIGURE 4-4 SCENARIO-BASED PLANNING TEMPLATE CONCEPTUAL REPRESENTATION

4.04 Tunnel excavation

A tunnelling project consists of a number of components, which may involve excavation work or support work. The main component in a tunnel project is the tunnel excavation, in which the workers use the TBM to excavate the soil layers of the tunnel. Tunnel excavation starts after the working shaft is constructed. Figure 4-5 illustrates the tunnel excavation components. The main resources required for tunnel excavation are a train to transfer the dirt excavated to the working shaft area, a crane to dump dirt from trains and load the train with tunnel lining material and others, and a TBM to excavate soil layers. The main part in tunnel excavation is the start-up soil layer section. In this section, tunnel production is minimal; during excavation of this section, the remaining body of the TBM is installed, consisting of conveyer belt and gantry, which slows down the process. Also, during this section, the crew can't use more than one dirt cart during excavation as the total length of the TBM can't accommodate a full train. Once the TBM is fully installed, the crew can use a full train to excavate, which usually can carry one section of tunnel's worth of dirt. After that, the project team needs to decide to use one or more trains. In the case of using two trains, they should build a switch in the working shaft area, which consists of shaft area, undercut, and tail tunnel. The next step is to excavate the remaining soil sections; this operation will be much faster since the TBM is completely installed. After excavating the tunnel sections, and once the TBM has reached the removal shaft, the crew will disassemble the TBM and remove it from the tunnel.

It is important to keep in mind that tunnel excavation requires many supporting activities to be successful. It requires material delivery, dirt removal, and equipment maintenance. To build a simulation model that fully represents tunnel excavation, we have to include the main physical components in our model as well as all supporting activities; we should also introduce the management dimension to the process by including cost and schedule.

To represent tunnel excavation in our tool, we developed a tunnel template. This template and its elements will be discussed in the following sections.

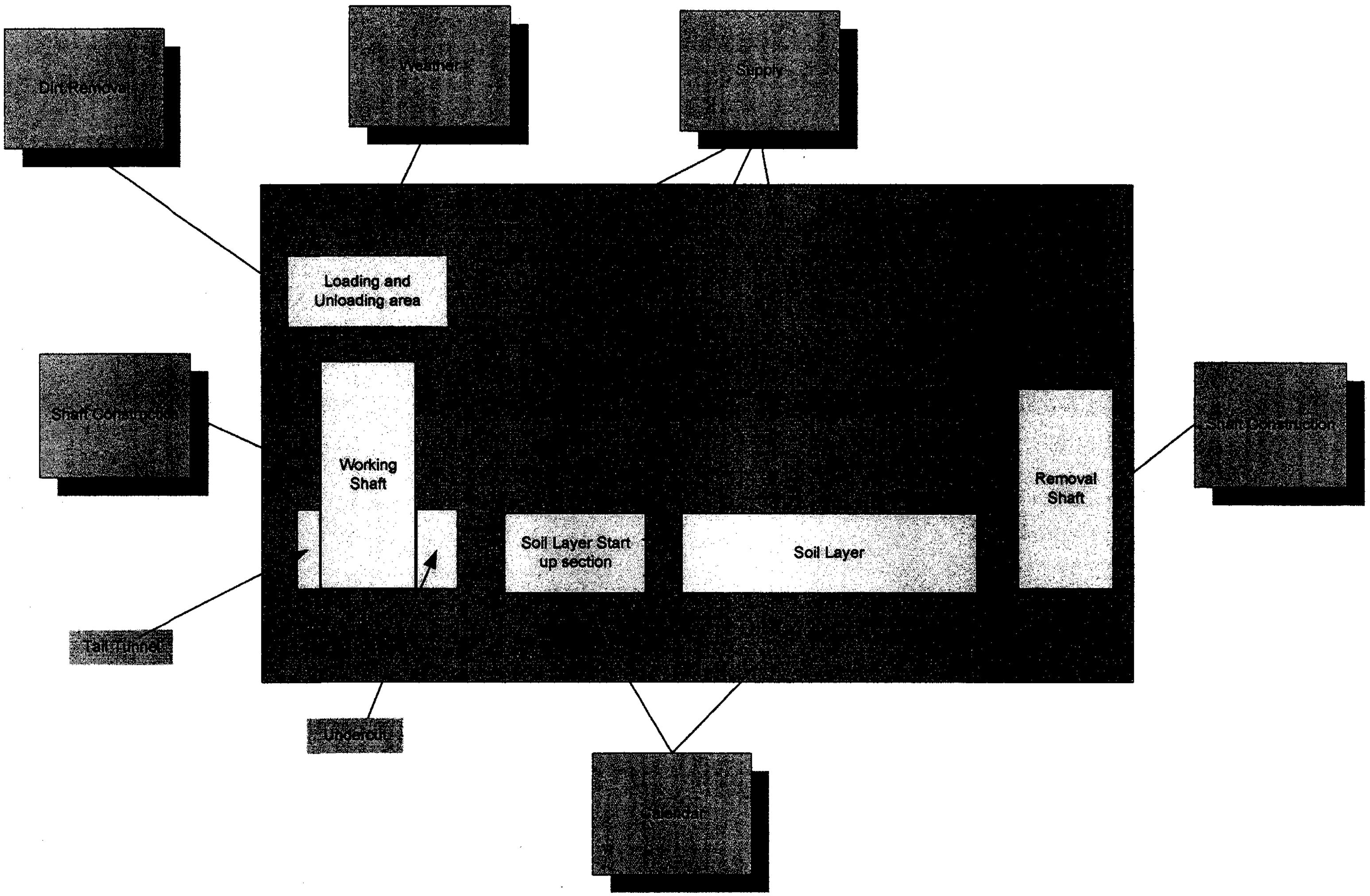


FIGURE 4-5 TUNNEL CONSTRUCTION COMPONENTS

4.05 Tunnelling template

After close study of tunnelling operations, a SPS template was developed using *Simphony* (Hajjar and AbouRizk 1999). This template is used to model the tunnel excavation, starting from the working shaft to the removal shaft. This template can model one-way tunnelling and two-way tunnelling. To cover all tunnelling activities, this template consists of seven elements: Loading, Trains, Undercut, Startup, SoilLayer, Root, and Shift control (see Figure 4-6).

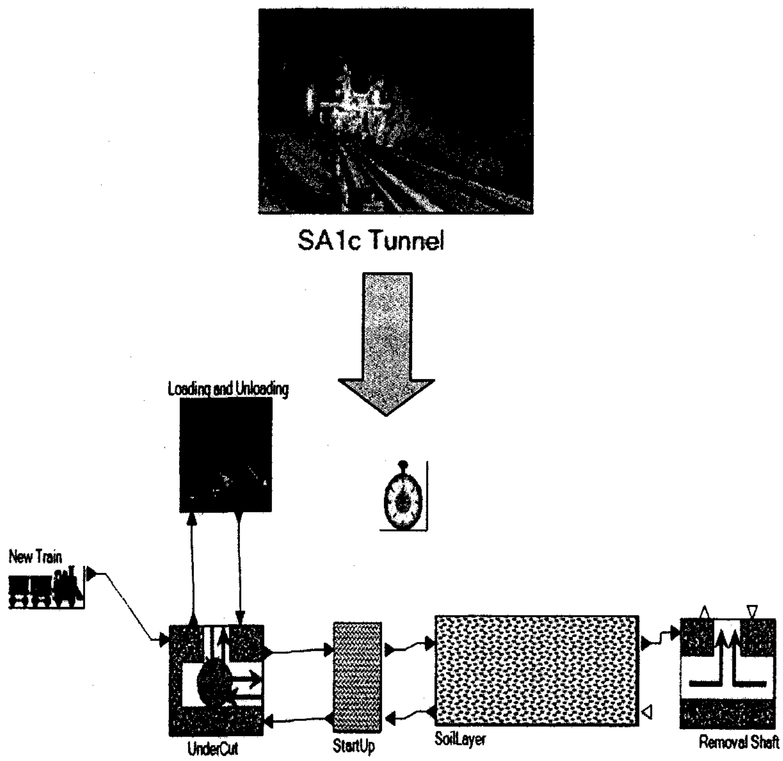


FIGURE 4-6 TUNNELLING ELEMENTS

4.05.1 Root element

This is the parent element that will hold all other elements related to the tunnel template (see Figure 4-6). This element has a number of parameters, outputs, and statistics as follow:

4.05.1.1 Parameters

- Description: allows the user to define the project name
- Number of shifts: how many shifts the project will operate per day
- Shift Duration: how many working hours per shift
- Start up: enables the user to define the length of the start up element
- Number of trains east: allows the user to input how many trains to work in the east side of the tunnel
- Number of trains west: the same as in Number of trains east, put to the west side
- Equipment cost: the cost per hour of the above the ground equipment, such as crane and loader
- Indirect cost: the project indirect cost per hour, such as electricity, water, management

4.05.1.2 Outputs

- Start Time: the simulation time at the start of tunnelling
- Start Date: the date at the start of tunnelling
- Finish Time: the simulation time when the project is completed
- Finish Date: the date when the project is completed
- Total Length: the project total length in meters
- Total Finished Length: the total finished length so far
- Total Equipment Cost: the total project equipment cost, including TBM, crane, and loaders
- Total Indirect Cost: the total indirect cost calculated based on the tunnel duration, which equals the finish time minus start time

- Total Material Cost: the cost of all materials used in the project calculated using material unit cost per meter of the project length
- Direct Cost: the cost of all components of the project, including the labourers, material, and equipment costs
- Total Cost: the direct cost plus the indirect cost

4.05.1.3 Statistics

- Advance Rate: the overall project productivity per hour
- Advance Rate per Shift: the overall productivity per shift

4.05.2 Train element

This element generates the trains used in the tunnelling process. This element will generate just one train, but the train number can be increased through the root element based on the user's desire. This element has a number of parameters as follows:

4.05.2.1 Parameters

- Car Capacity: dirt car size in cubic meters
- Number of Dirt Cars: dirt cars in the train for carrying dirt from tunnel face to working shaft
- Number of Material Cars: cars needed to carry material to tunnel face
- Speed Empty: train speed when it is empty in km/h
- Speed Loaded: train speed when it is loaded in km/h
- Shaft Construction: control tunnelling start based on construction of working shaft; 'Yes' means wait for working shaft; 'No' means working shaft construction is complete.
- Direction: direction in which this train will be working, either east or west.

4.05.3 Undercut element

This element represents the shaft area where trains travel to and from the TBM; this area includes undercut, tail tunnel, and shaft lower part. This element has a number of parameters as follow:

- Switch: to be able to use more than one train, a switch should be built after installing the TBM. This parameter shows if the switch is completed or not yet.
- Switch Install: duration to install switch in minutes.
- Track East: number of tracks to east side of the tunnel, usually one track.
- Track West: number of tracks going to the west side of the tunnel if the tunnel supports two-way tunnelling.
- Undercut Tracks: number of shafts in shaft undercut area; once tunnelling starts, it is usually one track. After installing a switch, it goes to two.
- Type: users define the type of shaft: if it is a working shaft, the type could be one-way tunnel or two-way tunnel; if it is a removal shaft, the type should be defined as removal shaft.

4.05.4 Loading element

This element represents surface area. It includes dirt and material handling between the surface area and shaft lower area. Like the other elements, this element has a number of parameters and one output. These include:

4.05.4.1 Parameters

- Number of Cranes: cranes available to handle dumping of dirt from train and loading material into train
- Crane MBF: the mean between failures in minutes. This parameter is used to simulate crane breakdowns.

- Crane MBR: the mean between repairs in minutes, used to sample duration for crane repairs.
- Dirt Capacity: the maximum size, in cubic meters, of the soil stockpile the tunnelling site can store during operation.
- Loader: number of loaders available on site
- Load Time: time to load material in train in minutes.
- Unload Time: used to sample the duration of dirt dumping from the train in minutes.
- Number of Liners: represents available material units for lining the tunnel after one section has been excavated. Liners can be either concrete liner or rib and lagging.
- Supply: the simulation model will define if a supplier for liners is present or not. If the value is 'Yes' a number of liners will be part of the simulation and could control the operation if suppliers can keep up with tunnel production. If the value is 'No', it means liner suppliers are not part of the simulation.

4.05.4.2 Output

This element has one output, which is excavated dirt stockpiled on site. This number changes based on tunnelling production and trucking operation if available.

4.05.5 Shift control element

In this element shift start-up and crew breaks during a shift are presented. Crew breaks include lunch and coffee. This element has a number of inputs and one output shown below:

4.05.5.1 Parameters

- Start Shift: time of day when shift starts
- Finish Shift: time of day when shift finishes

- Coffee Break: duration of coffee break in minutes
- Coffee Break Start: time of day when coffee break starts
- Lunch Break: lunch break duration in minutes
- Lunch Break Start: time of day lunch break starts
- Mobilization Time: duration of mobilization in minutes
- Start Mobilization: when to start mobilization after shift start in minutes

4.05.5.2 Output

The output of this element is the number of shifts tacked to finish tunnelling.

4.05.6 SoilLayer element

This element is the key element in this template. It encapsulates the major TBM excavation processes, including excavating soil section, installing liners, installing track, and performing surveying. At this point tunnelling will be at full capacity. This element has a number of parameters, outputs, and statistics, as shown below:

4.05.6.1 Parameters

- Advanced Rate: represents the time the TBM will need to finish excavating one tunnel section, normally 1 m.
- Crew Cost: represents crew unit rate per hour
- Equipment Cost: equipment used inside the tunnel, including TBM and rate per hour
- Finished Length: shows the finished excavated length so far
- Length: the soil segment length; soil segment is defined based on its type
- Number Section for Track: sections remaining to be excavated to install train track

- Soil Direction: direction of section, west or east
- Soil Type: this describes soil type of the soil section to be excavated, such as, clay, rocks, etc.
- Supply: the same as loading element. In this case the supplier is TBM parts; since some of TBM parts are not available on hand, we need to order them. In the simulation, if users define a supplier for the TBM, the SoilLayer element will find out and set this value to 'Yes'; otherwise, it is 'o'. This parameter will be checked in case of TBM breakdown.
- Supply Rate: in this parameter, users define the frequency for requesting TBM parts in the event of TBM breakdown.
- Survey Interval: how many tunnel sections need to be excavated before a survey is required
- Survey Time: surveying duration, in which excavation will be down
- Swell Factor: soil swell factor
- TBM Diameter: used to calculate the excavated soil volume per section
- TBM Lining Time: time to install liners
- TBM Lining Type: lining type used in the tunnel, which can be either concrete liners or rib and lagging
- TBM MBF: the mean between failures used to define the next TBM failure
- TBM MBR: the mean time between repairs used to find time to fix the TBM
- TBM Name
- TBM Resetting Time

- TBM Working Section: the length of the excavated section, usually 1 m for concrete liners and 4 ft for rib and lagging
- Track Installing Time: time to install track for train
- Tunnel Alignment: whether tunnel segment is straight or curved

4.05.6.2 Output

- Finish Date: the date when soil segment excavation finishes
- Start Date: the date when soil segment excavation begins
- Finish Time: the simulation time when soil segment excavation finishes
- Start Time: the simulation time when soil segment excavation started
- Total Crew Cost: the total crew cost calculated based on crew rate per hour multiplied by soil segment excavation total duration in hours
- Total Equipment Cost: the total equipment cost calculated based on equipment rate per hour multiplied by soil segment excavation total duration in hours

4.05.6.3 Statistic

- Production rate: shows excavation rate as meters per hour

4.05.7 Startup element

This element is mostly the same as the SoilLayer element, except in this element TBM installation will be finished by installing the conveyer belt and installing the gantry to support it. This element has all SoilLayer parameters, outputs, and statistics in addition to the followings parameters:

- Gantry Section Length: the gantry will be installed in sections; this input specifies the length of each section
- Gantry Time: duration to install gantry section

- Conveyor Section Length: the same as in gantry installation; it must be installed in sections due to limitations in undercut and tail tunnel lengths
- Time Conveyer: time to install conveyer section
- TBM Length: the TBM length in meters
- TBM Gantry Length: the total length of conveyor belts that will be used in tunnelling; in most cases equal to the train total length

4.06 Supporting operations

In any successful project, a number of supporting activities play a crucial role. Based on our site visits and tunnel project study, in a tunnelling project these activities are: dirt removal, material supply, and weather effect. See Figure 4-7.

Dirt removal refers to hauling the excavated dirt from the tunnel sections to a dumping area using trucks. In many cases, the tunnel site is limited in area, so the area reserved for stockpiling the dirt is also limited in area. Over time, we have to control the tunnelling operation in case we cannot store any more, forcing the tunnel excavation operation to stop until we have space.

Material supply refers to those materials needed to tunnel or for shaft excavation. Most of the time, the same supplier is used for an entire tunnel project, which leads to limited supply availability due to the volume of the required material and may force the project to stop. In some cases, the supplies needed are equipment parts, especially for the TBM, which may require several days to be delivered and will affect our progress.

The last major activity is weather effect, which may cause a lot of problems, especially for cold weather areas such as the city of Edmonton. Tunnel projects may be affected by weather in several ways: (1) due to high winds, the tunnel project will shut down since the crane can't operate under those conditions; (2) wet weather may affect the dirt dumping by forcing the crew to clean the dirt cart, which will add more time to the excavation cycle. As a result, the overall production will be affected; (3) finally, severe cold weather will force the tunnel to shut down.

Managerial activities, such as cost estimate, project schedule, and productivity calculations, should be included in any tool design. To account for these activities, we built a support template as a component in our tool. This template will be discussed in the following sections.

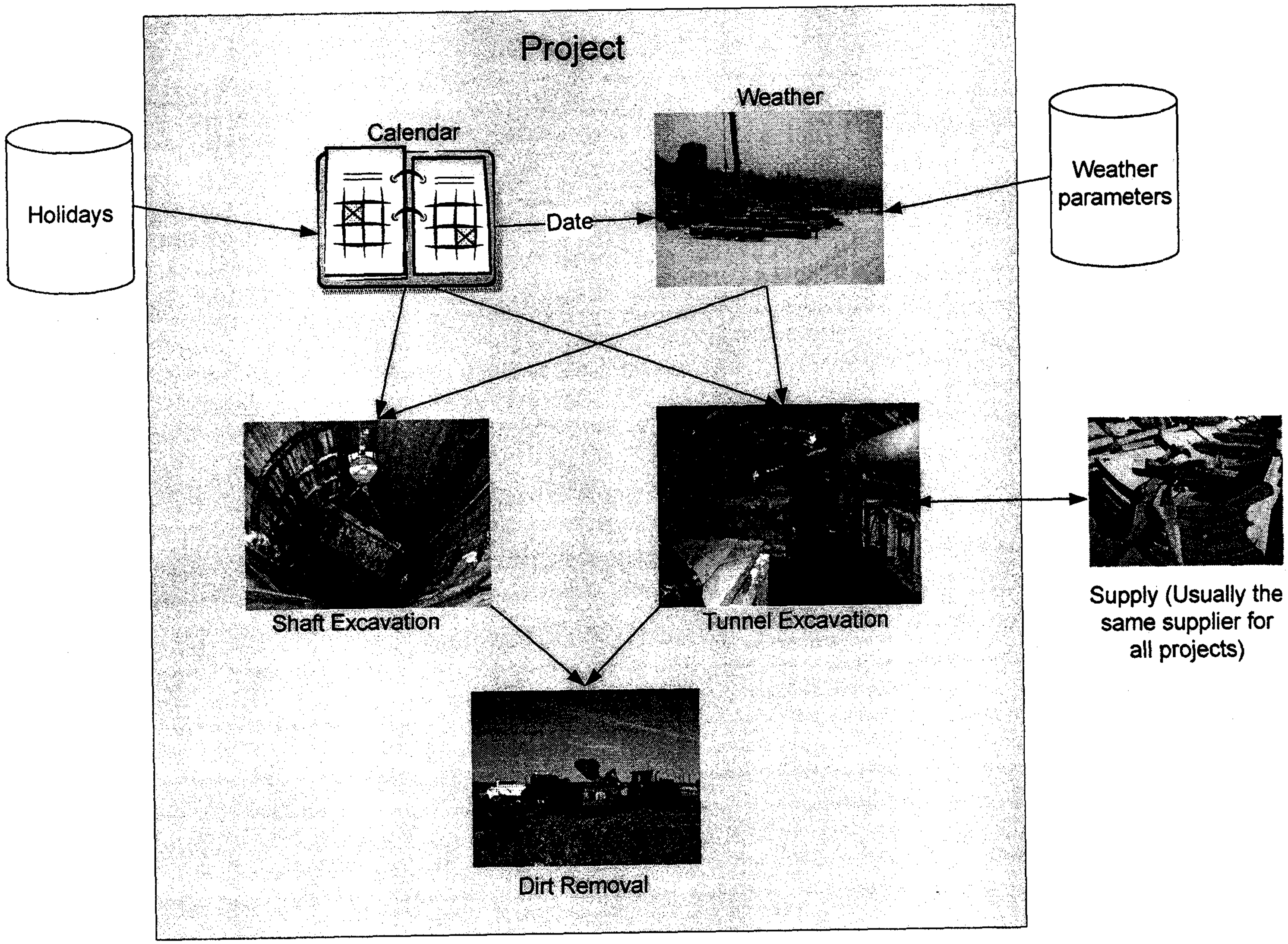


FIGURE 4-7 SUPPORTING OPERATIONS

4.07 Support template

This template was developed to support the tunnelling template and to enable the user to run a number of projects at the same time. These template elements can be used for any simulation model, including tunnelling. This template has five elements: supply, project, trucking, calendar, and weather generator (see Figure 4-8). To be able to use the trucking, calendar, and weather generator elements, the user must create these as child elements of a project element. The following is a description of each element:

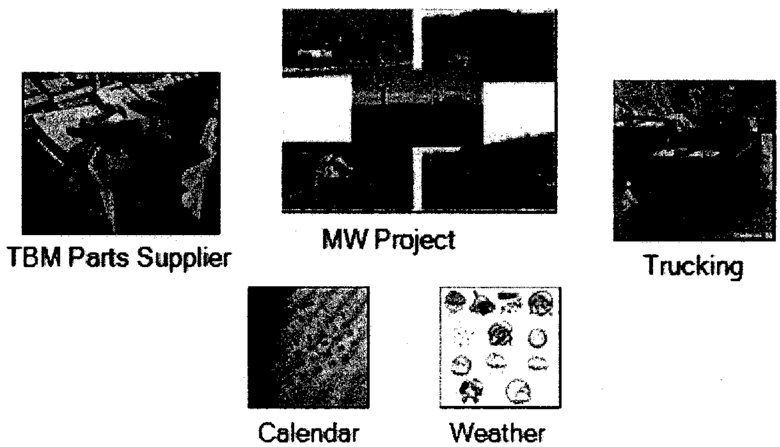


FIGURE 4-8 SUPPORT TEMPLATE ELEMENTS

4.07.1 Project element

This element encapsulates a project simulation model. This element will enable the user to create multiple tunnelling models at the same time, and for each tunnel the modeller can use calendar, weather generator and trucking elements. Project element has one parameter and nine outputs as shown:

4.07.1.1 Parameters

The only parameter is project name, which will be used by other child elements in the project element.

4.07.1.2 Output

- Start Date: the date when the project started
- Finish Date: the date when the project finished
- Total Crew Cost: the total crew cost for all the activities of the tunnelling project in the child window of the project element; includes the tunnelling excavation and any shafts constructed
- Total Equipment Cost: a count for all equipment costs included in the project, such as TBM, crane, and loaders
- Total Material Cost: shows cost for all materials used in constructing the tunnel and its shafts, including the liners and rib and lagging
- Total Indirect Cost: indirect cost for the tunnel and its shafts
- Direct Cost: the project's direct cost, including total crew cost, total material cost, total equipment cost, and dirt disposal cost
- Total Cost: the sum of the direct and indirect cost

4.07.2 Supply element

This element is used for a supplier of tunnelling materials, such as liner and rib and lagging; it is also used for supplying the TBM unavailable parts needed to fix it. Supply element could be used for other types of material suppliers. The following shows this element's parameters and outputs:

4.07.2.1 Parameters

- Supply Type: the user can define the supplier type. In our case of tunnelling simulation, we have three types of suppliers implemented: concrete liners, rib and lagging, and TBM parts.
- Duration: how long it will take to deliver the required material. The user does not need to input this value as it will be defined by the simulation.

- Quantity: how many units required. Here also the user does not need to input this value for the tunnelling simulation.

4.07.2.2 Output

This element has one output, which is a supply record. This output is a table showing all the requested parts from all projects running. The table shows the project name, quantity, date requested, date delivered, and for TBM parts TBM name. See Figure 4-9.

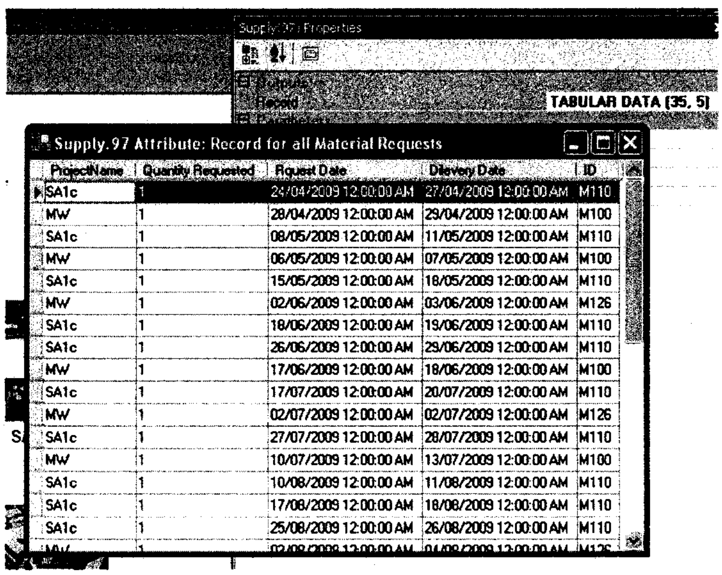


FIGURE 4-9 SUPPLY RECORD OUTPUT

4.07.3 Trucking element

This element represents the earth moving operation of the tunnel, which takes excavated dirt from the tunnel site to one dumping site. To activate it, it should be created as child element in the Project element. It communicates with the Loading element from the tunnelling template and moves dirt from there to the dumping site to allow the tunnelling operation to continue. It has a number of parameters and two outputs, as shown:

4.07.3.1 Parameters

- Loading Time: time to load truck at tunnelling site in minutes

- Dumping Time: time to dump load at dumping site in minutes
- Hauling Length: the distance between the tunnelling site and the dumping site while the truck is loaded, in km
- Returning Length: the distance between the dumping site and the loading site while truck is empty, in km
- Number Trucks: number of trucks used in the operation
- Truck Size: truck size in cubic meters
- Project Name: the project name the trucking element is associated with
- Speed Empty: truck speed while empty, in km/hr
- Speed Loaded: truck speed while loaded in km/hr
- Cost: truck unit cost per hour.
- Dirt Cost: the cost to dump dirt in dumping site per cubic meter

4.07.3.2 Output

- Dirt Quantity: the total transported dirt in cubic meters
- Dirt Total Cost: the total cost of the dirt removal from tunnelling site calculated based on the duration of the process multiplied by truck unit cost added to the dumping site cost

4.07.4 Calendar element

The calendar element is used to convert the simulation time into dates for each project. Users can use a number of calendars in the same simulation model, but must create each one of them as a child element of a project element. It works by publishing the current date as global variable that can be accessed by any element in the simulation model. This element was originally developed by Shahin (2007) using the legacy version of *Simphony*; we redeveloped it using the new version of *Simphony*. This element has a number of parameters and outputs, discussed below:

4.07.4.1 Parameters

- NDayUnits: number of time units in the day. In the case of tunnelling, this is the shift duration multiplied by number of shifts multiplied by 60 to convert it to minutes.
- Project Name: use project name only as a child element of the Project element; if users want to use it for the whole simulation model, keep Project Name empty.
- Start Date: defines the date when the project will start

4.07.4.2 Output

- Current Date: shows the current date at any point of time in the simulation run
- Project Finish Date: shows the date when the project finishes
- Number of Calendar Date: number of days that have passed since the project started until the project finishes
- Number of Vacation Days: how many vacation days are accounted for during the project's life
- Number of Working Days: represents how many working days passed during the project's life
- Is Holiday: shows if the current date is a holiday or not; this is specified by reading holiday dates from a database.

4.07.5 Weather generator

This element is used to predict different weather parameters, such as temperature, humidity, precipitation, frost depth, and wind speed. This element was originally developed by Shahin (2007) using the legacy version of *Simphony*; we redeveloped it using the new version of *Simphony*. This element should be used with the Calendar element. As with most elements, it has a number of parameters, outputs, and statistics as follows:

4.07.5.1 Parameters

- Weather Station: location of the weather station—same as the project location. In this model we have two weather stations: Edmonton and Fort McMurray.
- Project Name: the same as in Calendar. If the user wants to link the weather to a specific project, the project name should be used.

4.07.5.2 Output

- Tmax: current day expected high temperature
- Tmin: current day expected low temperature
- Wspeed: current day wind speed
- RHmax: maximum relative humidity for the current day
- RHmin: minimum relative humidity for the current day
- Precip: amount of precipitation expected for the current day
- FrostD: depth of the frost in the ground

4.07.5.3 Statistics

- Tmax: collects all expected maximum temperatures during the project's life
- Tmin: collects minimum temperature for all days included in the project's life
- Wspeed: shows the wind speed predicted for each day of project's life
- RHmax: collects all expected maximum relative humidity during the project's life

- RHmin: shows the minimum relative humidity values predicted during the project's life
- Precip: collects all precipitation amounts for each day of the project's life
- FrostD: depth of frost in ground for every day during the project's life

4.08 Shaft construction

To build a tunnel, the first step is to build a working shaft. The working shaft is usually circular in shape, although in some cases it is square. Crews use drills to excavate a circular shaft, and then use hand tunnelling to expand it to the desired diameter. In the case of square shafts, they usually use hand tunnelling or a backhoe. Once the shaft reaches the desired depth, the crew starts excavating the tail tunnel and the undercut. After building the tail tunnel and undercut, the TBM can be assembled to start tunnel excavation. See Figure 4-10.

In our tool, we built a shaft excavation template to model shaft excavation. In the following section, we will describe this template.

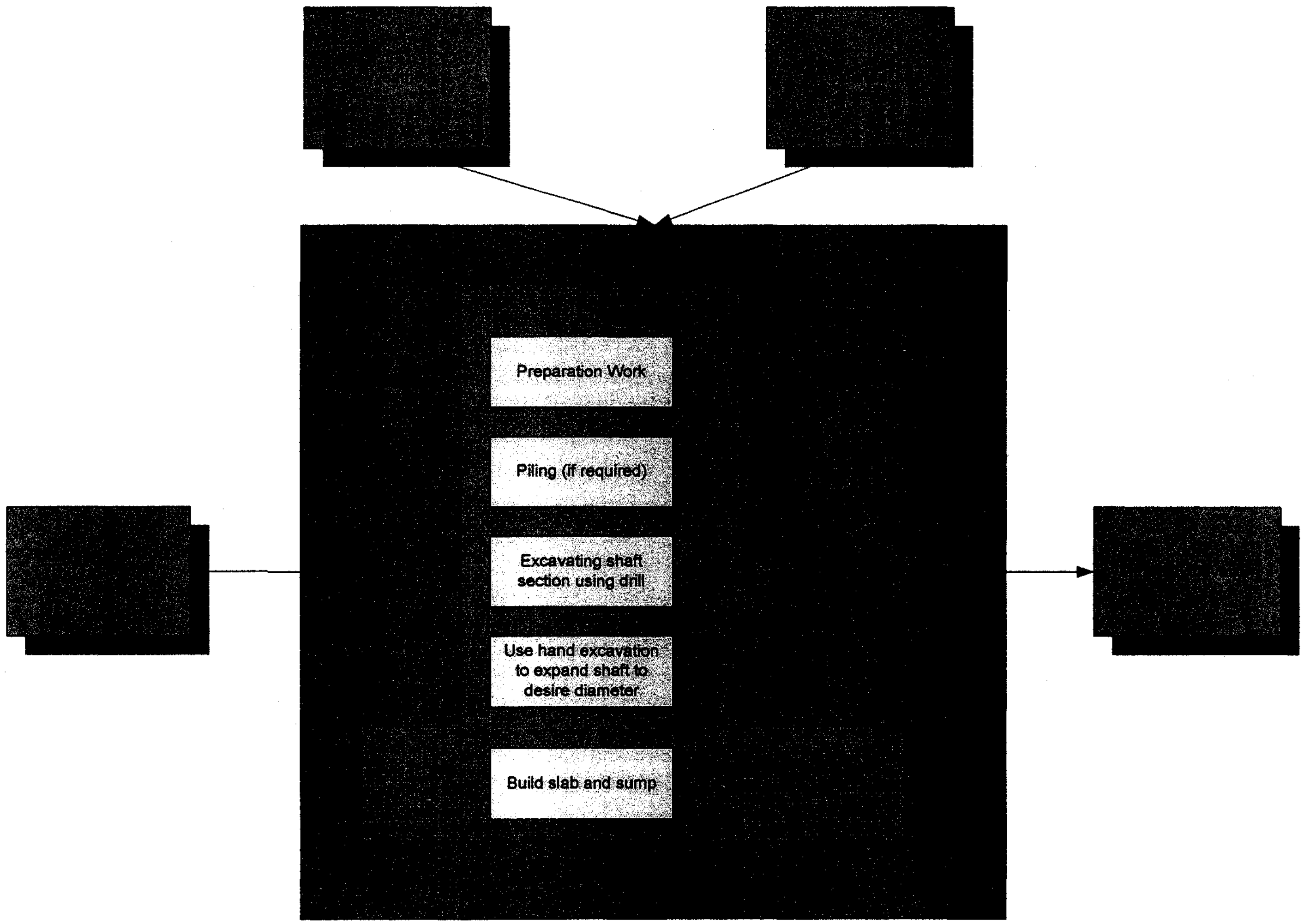


FIGURE 4-10 SHAFT CONSTRUCTION COMPONENTS

4.09 Shaft construction template

This template is based on a template developed by Zhou (2006). This template consists of 14 elements: Root, Soillayershaft, SoilProfile, Shaft, Shaftsegment, Handexcavation, Preparation, Piling, TailTunnel, SlabSump, XActivity, FinishConstruction, and TBMInstallation. The last two elements are new elements introduced to be able to communicate with the tunnelling template in case the shaft we are constructing is a working shaft. The purpose of this template is to model the shaft excavation process, which can have three types of shafts (working shaft, removal shaft, and safety shaft). Also, the template supports the excavation of circular and rectangular shape shafts.

4.09.1 FinishConstruction element

This element has no parameters, output, or statistics. The purpose for this element is to notify the tunnelling excavation template that the working shaft is done and the TBM can start excavating. Figure 4-11 shows the code used to create the communication between shaft construction and tunnelling construction.

```
Dim Root As CFCSim_ModelingElementInstance
for each Root in SimEnvironment.Elements.Values
    if Root.ElementType = "CEM_Tunnel_Code_Trains" then
        if Root("ProjectName").Value = ob.Parent.Parent("ProjectName").Value then
            if ob.Parent.Parent("ShaftType").Value = "Working Shaft" then
                Root("ShaftConstruction").Value = "Yes"
                Root.ScheduleEvent(ob.AddEntity,"CreateTrain",0)
            end if
        end if
    end if
next
```

FIGURE 4-11 COMMUNICATION CODE BETWEEN SHAFT CONSTRUCTION AND TUNNEL CONSTRUCTION

4.09.2 TBMInstallation element

This element was added to the shaft construction to represent the assembly or disassembly of the TBM. This element can be used for a working shaft only if it is defined as assembling and for a removal shaft if it is defined as disassembling.

This element has two parameters: (1) description, to define for the shaft as assembling or dissembling; (2) duration, which is used to define the process duration, in minutes.

4.10 Communication points between templates

The scenario-based planning tool we introduced integrates three templates. This integration will allow the user to use these templates in combination or separately. To achieve the integration, we presented a number of communication points to our system. A communication point enables templates to interact with each other. The concept we used for communication points is inspired by the HLA concept.

As an example for a communication point, in excavating a tunnel the starting point will be to excavate a working shaft. The first step in the simulation model is to figure out if a working shaft exists in our model or not. An existing tunnel excavation can't start until the shaft excavation is done. Another example would be the communication between the supply element and the tunnelling template. During this communication, the simulation model will find out if the material supply is required or not. If the supply is required, two-way communication will occur during project construction. A very important communication point would be between the Calendar element and shaft construction template communication point, and the Calendar element and the tunnel template communication point, in which the Calendar element defines how many simulation time units are needed to advance the date. Normally, a project will have the same shift duration and number of shifts per day, but sometimes the shift duration and number of shifts per day changes from shaft excavation to the tunnel excavation, so our calendar should also be updated during simulation. There are 10 main communication points included in our tool to facilitate the integration among different templates. See Figure 4-12 for illustration. These communication points will discussed in the next sections.

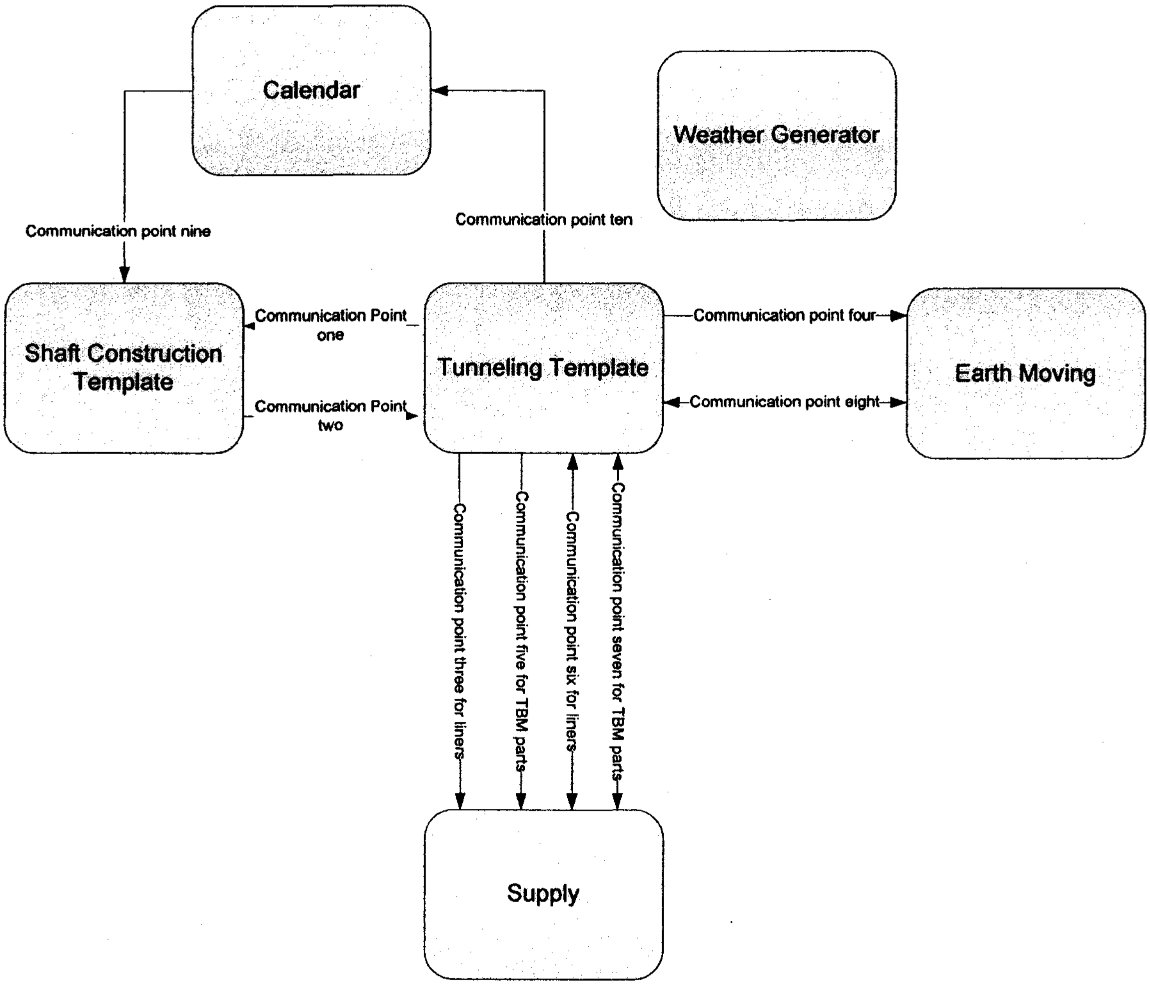


FIGURE 4-12 SYSTEM COMMUNICATION POINTS

4.10.1 Communication point 1

This point connects the tunnelling template with the shaft construction template. During the simulation execution, the tunnelling template will search the modelling area to define whether or not a working shaft is required for the tunnel. If yes, the tunnelling excavation cannot start until the shaft construction is done. If no, the tunnel excavation can start. This is done through the Train element of the tunnelling template, which has a parameter called Shaft Construction. Figure 4-13 shows the code used for the communication point 1.

```
Case "Check"
    Dim Root As CFCSim_ModelingElementInstance
    for each Root in SimEnvironment.Elements.Values
        if Root.ElementType = "CEM_Shaft_Construction_Root" then
            if Root("ProjectName").Value = ob("ProjectName").Value then
                x = x+1
                if Root("ShaftType").Value  = "Working Shaft"  then
                    if Root("FinishTime").Value >= 0 then
                        ob("ShaftConstruction").Value = "Yes"
                    end if
                end if
            end if
        end if
    next
```

FIGURE 4-13 COMMUNICATION POINT 1

4.10.2 Communication point 2

This point is the complementary point for the first one. We discussed it under the FinishConstruction element of the shaft construction template. If we have a working shaft, once it finishes construction the tunnelling excavation can start. See Figure 4-11.

4.10.3 Communication point 3

This point is used to define whether or not liner material supply is required in the model. The communication happens between the Loading element from the tunnelling template and the Supply element from the support template.

The loading element will search the model, and if it finds an element called Supply and the supply type parameter is Liners, then a liner supply is required. Otherwise, it is not required. Figure 4-14 shows the code used to create this communication point.

```
for each Root in SimEnvironment.Elements.Values
    if Root.ElementType = "Supply" then
        if Root("SupplierType").Value = "Liners" then
            ob("Supply").Value = "Yes"
        end if
    end if
next
```

FIGURE 4-14 COMMUNICATION POINT 3

4.10.4 Communication point 4

The Loading element in the tunnel template will communicate with the Trucking element of the support template to define whether or not the earth moving operation is required. If it is required, then the user should define the site's dirt stockpile capacity.

The code used for this point is shown in Figure 4-15.

```
for each Elmnt in SimEnvironment.Elements.Values
    if Elmnt.ElementType = "Trucking" then
        if Elmnt("ProjectName").Value = ob("Name").Value then
            ob("Check").Value = "Yes"
        end if
    end if
next
```

FIGURE 4-15 COMMUNICATION POINT 4

4.10.5 Communication point 5

This point is used to define whether or not a TBM part will be requested from a supplier To achieve this point, the Startup element and SoilLayer element of the tunnelling template will search the model for a Supply element of the support template which has a supply type of TBM parts. If it exists, that means the model should include the supply of TBM parts. Figure 4-16 shows the code used to allow the parts supply.

```
for each Root in SimEnvironment.Elements.Values
    if Root.ElementType = "Supply" then
        if Root("SupplierType").Value = "TBM" then
            ob("Supply").Value = "Yes"
        end if
    end if
next
```

FIGURE 4-16 COMMUNICATION POINT 5

4.10.6 Communication point 6

In case a liner supply is required, a communication occurs during simulation. Usually the tunnel starts with a number of liners on hand, and during construction the number decreases based on the productivity achieved. Based on the productivity and the time required to produce the liners, a threshold will be calculated. At any time this threshold is reached, the manager should request liners. In our model, the Loading and Unloading elements will send a message to the Supply element requesting a number of liners. Once the message arrives, the Supply element will record the request date and start producing liners., When the total number of liners required is reached, the Supply element records the finish date and send a message with the load to the Loading and Unloading elements. This process continues during the simulation.

The code used for requesting liners is shown in Figure 4-17; Figure 4-18 presents the delivery code.

```
for each Supply in SimEnvironment.Elements.Values
    if Supply.ElementType = "Supply" then
        if Supply("SupplierType").Value = entity("LinerType") then
            if ob("NumberofLiners").Value <= 50 and ob("SendRequest").Value = "No" then
                Entity("ProjectName") = ob("Name").Value
                ob("SendRequest").Value = "Yes"
                Entity("EventDuration") = 0
                Entity("Event") = "CheckLiner"
                Entity("ElementType") = "CEM_Tunnel_Code_Loading"
                Entity("MaterialName") = "NumberofLiners"
                Entity("Request") = "SendRequest"
                if (ob.Parent("TotalLength").Value-ob.Parent("TotalFinishedLength").Value-ob("Numb
                    Entity("Quantity") = ob.Parent("TotalLength").Value-ob.Parent("TotalFinishedLe
                else
                    Entity("Quantity") = 100
                end if
                Entity("ID") = ob.ID
                Supply("Quantity").Value = Entity("Quantity")
                if Entity("Quantity") > 0 then
                Supply.ScheduleEvent(Entity,"OrderMaterial",0)
                end if
            end if
        end if
    end if
next
```

FIGURE 4-17 REQUEST LINERS

```
for each Load in SimEnvironment.Elements.Values
    if load.ElementType = Entity("ElementType") then
        if Load("Name").Value = Entity("ProjectName") and Load.ID = Entity("ID") then
            Load(Entity("MaterialName")).Value = Load(Entity("MaterialName")).Value + Entity("Quantity")
            Load(Entity("Request")).Value = "No"
            ob("Record").SetValueRC(Entity("NumRequest")- 1 ,3 ,SimEnvironment.Gattr("CurrentDate" & Ent
            Load.ScheduleEvent(Entity,Entity("Event"),Entity("EventDuration"))
        end if
    end if
next
```

FIGURE 4-18 DELIVER LINERS

The results from the Supply element for liners will include the project name, since we can have many projects running at the same time. Request date represents delivery date and amount requested (see Figure 4-19).

Supply.96 Attribute: Record for all Material Requests

ProjectName	Quantity Requested	Rquest Date	Dilevery Date	ID
SA1c	100	19/02/2009 12:00:00 AM	20/02/2009 12:00:00 AM	330
SA1c	100	19/03/2009 12:00:00 AM	20/03/2009 12:00:00 AM	330
SA1c	100	13/04/2009 12:00:00 AM	14/04/2009 12:00:00 AM	330
MW	100	13/04/2009 12:00:00 AM	14/04/2009 12:00:00 AM	154
SA1c	100	29/04/2009 12:00:00 AM	30/04/2009 12:00:00 AM	330
MW	100	04/05/2009 12:00:00 AM	05/05/2009 12:00:00 AM	154
SA1c	100	18/05/2009 12:00:00 AM	19/05/2009 12:00:00 AM	330
SA1c	100	01/06/2009 12:00:00 AM	02/06/2009 12:00:00 AM	330
SA1c	100	18/06/2009 12:00:00 AM	19/06/2009 12:00:00 AM	330
MW	100	05/06/2009 12:00:00 AM	08/06/2009 12:00:00 AM	154
SA1c	100	02/07/2009 12:00:00 AM	03/07/2009 12:00:00 AM	330
MW	100	22/06/2009 12:00:00 AM	23/06/2009 12:00:00 AM	154
MW	100	26/06/2009 12:00:00 AM	29/06/2009 12:00:00 AM	154
SA1c	100	17/07/2009 12:00:00 AM	20/07/2009 12:00:00 AM	330
MW	100	01/07/2009 12:00:00 AM	02/07/2009 12:00:00 AM	154
MW	100	07/07/2009 12:00:00 AM	08/07/2009 12:00:00 AM	154
MW	100	13/07/2009 12:00:00 AM	14/07/2009 12:00:00 AM	154
SA1c	100	06/08/2009 12:00:00 AM	07/08/2009 12:00:00 AM	330
MW	100	17/07/2009 12:00:00 AM	20/07/2009 12:00:00 AM	154
MW	100	22/07/2009 12:00:00 AM	23/07/2009 12:00:00 AM	154

FIGURE 4-19 LINERS SUPPLY RECORD

To differentiate between projects, we tagged the messenger with the element ID. When the delivery occurs, the Supply element will send it to the element has the ID of the messenger.

4.10.7 Communication point 7

This point the same as number six except it is for TBM parts. In this case the Startup element and SoilLayer element will send a messenger to the Supply element representing the TBM part supplier requesting a part based on the breakdown data we collected. Not all breakdowns require a part from the supplier. The Supplier element will record the request date, delivery date, project name, TBM name, and quantity.

Figure 4-20 shows the code used for requesting TBM parts.

```
Case "RequestPart"

for each Supply in SimEnvironment.Elements.Values
if Supply.ElementType = "Supply" then
    if Supply("SupplierType").Value = "TBM" then
        if ob("SendRequest").Value = "No" then
            Entity("ProjectName") = ob("Name").Value
            ob("SendRequest").Value = "Yes"
            Entity("EventDuration") = ob("TBM_MBR").Value
            Entity("Event") = "TBMUp"
            Entity("ElementType") = "CEM_Tunnel_Code_SoilLayer"
            Entity("MaterialName") = "NumberofParts"
            Entity("Request") = "SendRequest"
            Entity("Quantity") = 1
            Entity("TBM_Name") = ob("TBM_Name").Value
            Entity("ID") = ob.ID
            Supply("Quantity").Value = 1
            Supply.ScheduleEvent(Entity,"OrderMaterial",0)
        end if
    end if
    end if
next
```

FIGURE 4-20 REQUEST TBM PARTS

For the Supply element to know where to send the parts, we use the element ID and the event name. In the case of TBM parts, the event should be TBMup, meaning the TBM has been fixed and ready to work.

4.10.8 Communication point 8

This communication point occurs between the Loading element and the Trucking element. The interaction between tunnelling operations and earth moving operations happens when loading trucks. So, when the truck arrives, the Trucking element sends the truck to the Loading element, where the loader will load the truck and the total capacity of the truck will be removed from the dirt stockpile. After loading the truck, the Loading element sends it back to the Trucking element, where it continues its operation.

Figures 4-21 and 4-22 show the code used for the communication between the Loading element and the Trucking element.

```
for each Elmnt in SimEnvironment.Elements.Values
    if Elmnt.ElementType = "CEM_Tunnel_Code_Loading" then
        if Elmnt("Name").Value = ob("ProjectName").Value then
            Elmnt.File("Load").Add(Entity,1)
            Elmnt.ScheduleEvent(Entity,"Loading",0)
        end if
    end if
next
```

FIGURE 4-21TRUCKING ELEMENT SENDS TRUCK TO LOADING ELEMENT

```
for each Elmnt in SimEnvironment.Elements.Values
    if Elmnt.ElementType = "Trucking" then
        if Elmnt("ProjectName").Value = ob("Name").Value then
            Elmnt.ScheduleEvent(Entity,"Hauling", 0)
        end if
    end if
next
```

FIGURE 4-22 LOADING ELEMENT SENDS TRUCK TO TRUCKING ELEMENT

4.10.9 Communication point 9

This point of communication occurs between the shaft construction template and the Calendar element. During the pre-simulation, the Calendar element will search the modelling area for the Shaft Construction root element with the same project name as the Calendar element. If an element exists, it checks the shaft type. If it is a working shaft, then the Calendar element will use the shift duration and number of shifts for that shaft construction as the day duration. See Figure 4-23.

```
dim element as CFCSim_ModelingElementInstance
for each element in SimEnvironment.Elements.Values
    if element.ElementType = "CEM_Shaft_Construction_Root" then
        if element("ProjectName").Value = ob("ProjectName").Value then
            ob("NDayUnits").Value = element("NumShifts").Value * element("ShiftLength").Value * 60
        end if
    end if
next
```

FIGURE 4-23 CALENDAR ELEMENT COMMUNICATES WITH SHAFT CONSTRUCTION ELEMENT TO DEFINE DAY DURATION IN MIN

4.10.10 Communication point 10

When the excavation starts, the Train element in the tunnelling template updates the day duration based on the tunnel shift duration and number of shifts. See Figure 4-24.

```
If  SimEnvironment.Gattr.Exists("NDayUnits"& ob.Parent("Description").Value) Then
    SimEnvironment.Gattr("NDayUnits"& ob.Parent("Description").Value) = ob.Parent("ShiftLength").Value*
end if
```

FIGURE 4-24 TRAIN ELEMENT UPDATES DAY DURATION

4.11 Example

To illustrate the previous discussion, we will assume the following situation: the project team has to decide to use either one-way tunnelling or two-way tunnelling to excavate 2 km of a storm tunnel with an internal diameter of 2.5 m and an external diameter of 2.9 m.

4.11.1 Scenario 1: One-way tunnelling

Tunnelling parameters are shown in Table 4-1. In this case, the project team decided to simulate the tunnel excavation section only without shaft excavation. The simulation required material supply for both tunnel liners and TBM parts. Dirt removal should be included also. The project team decided to select the desirable method based on the criteria of cost, schedule and productivity. Cost unit rates are shown in Table 4-2. The project start date is January 1, 2009. Figure 4-25 illustrates the simulation model for Scenario 1.

TABLE 4-1 TUNNEL PARAMETERS

Parameter	2.9 m Dim tunnel
Advance Rate	Beta(30,20,1.5,8)
Swell factor	1.35
Lining time	10-15 min
Track Installation	5-15 min
Track Interval	6 m
Surveying Duration	120-180 min
Surveying Interval	200 m
Number of trains	2
Number of train cars	5 dirt, 1 material
Cars Capacity	1.8 m^3
TBM Length	6 m
TBM Total Length	42 m
Conveyer section length	4 m
Gantry Section Length	4 m
Installing Gantry and Conveyer section	240 min
Number of shifts	1
Shift Duration	600 min
Loading material	Triangular(4,7,10) min
Unloading dirt	Triangular(7,10,13) min
Material Delivery time	600 min

TABLE 4-2 COST UNIT RATES

Component	Unit Cost
Tunnelling overall	
Crane cost per hour	\$200
Material cost per m	\$1,750
Indirect cost per hour	\$240
Soil section 2.9 m dim	
Equipment cost per hour	\$350
Crew cost per hour	\$500
Trucking	
Dump cost per m^3	\$35

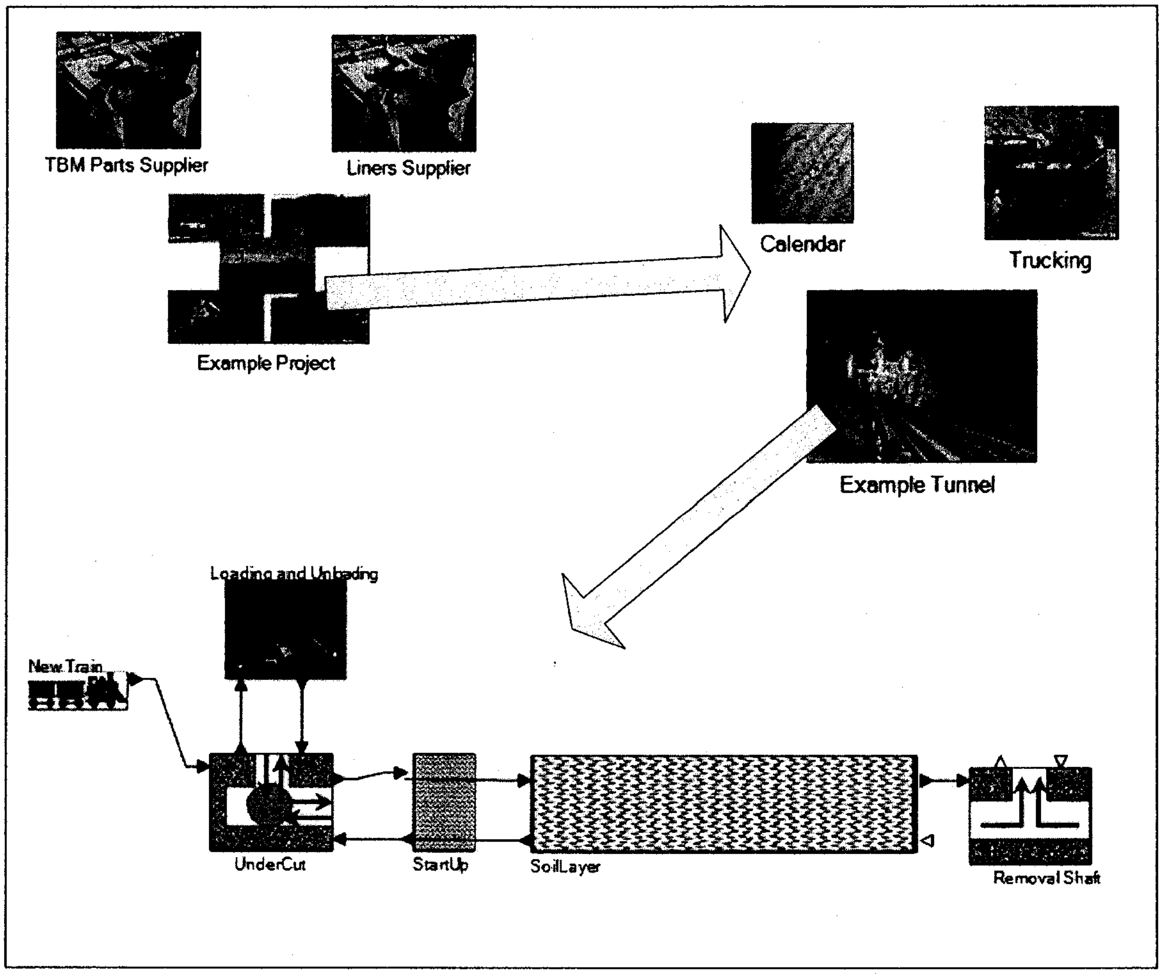


FIGURE 4-25 SCENARIO 1 SIMULATION MODEL

After running the simulation, the results shows a total cost of $6,393,894.00, with a start date of 1/1/2009 and a finishing date of 4/9/2009. Productivity is 1.13 m/hr or 11.36 m/shift

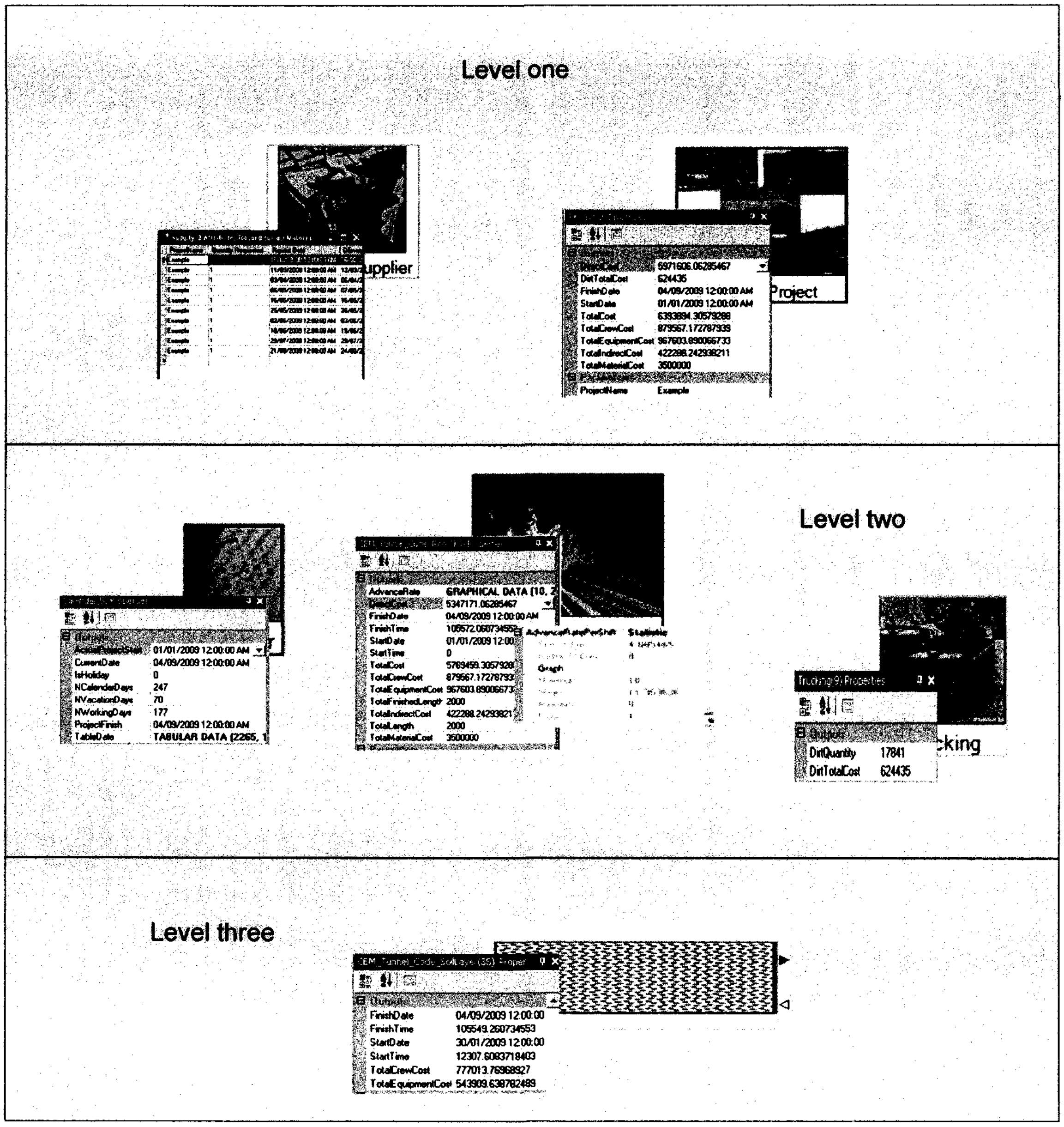


FIGURE 4-26 SIMULATION COST AND SCHEDULE RESULTS FOR SCENARIO1

4.11.2 Scenario 2: Two-way tunnel.

The tunnelling parameters are the same as those shown in Table 4-1. Since we are planning to use the same equipment and two crews with each same as the crew in the first scenario, the only change we have is indirect cost at $350. Figure 4-27 shows the Scenario 2 simulation model. The simulation model is similar, except in the tunnel excavation section we have two-way excavated sections, with each of them at 1 km.

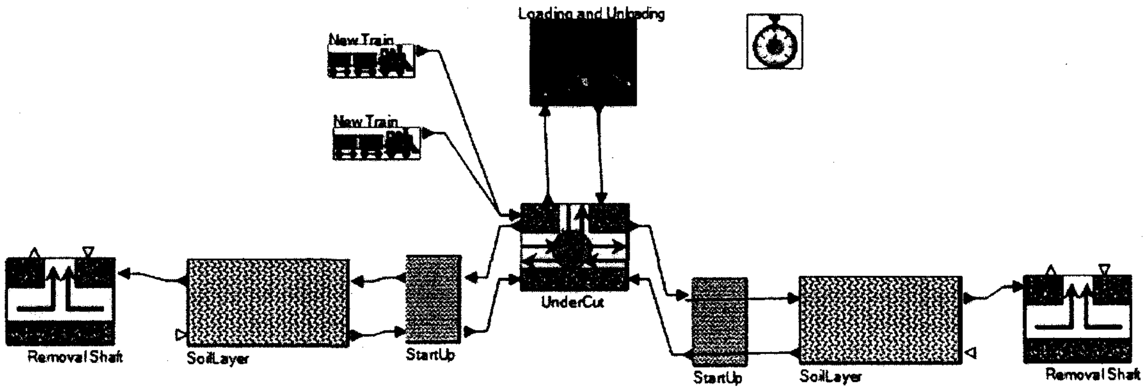


FIGURE 4-27 SCENARIO 2 SIMULATION MODEL

After running the simulation model, the total cost came to $7,052,496.00, with a starting date of 1/1/2009 and a finishing date of 6/7/2009,. Productivity was 1.51 m/hr or 15.15 m/shift.

Comparing the results, Scenario 1 has a lower cost, while Scenario 2 shows a faster finishing date and higher productivity. Based on these results, the project team has to decide between the scenarios based on the project's constraints.

4.12 Model Validation

To validate our templates we used EL-Smith and SW2&3 Tunnel.

EL-Smith is a tunnelling project carried out by the City of Edmonton, beginning in early 2007. During the period between May and June 2007, we collected data representing excavation time, liner installation, track installation and dirt unloading and material lading, and others.

The project's total length is 550 m. At the time of the study the total finished length was 186 m and the remaining length was 364 m. The crew used one train with 2 dirt cars with capacity of 4.6 m^3 and one material car. The average production was found to be 0.7 m/h; lining time was 10-15 min; track installation was 10-15 min; dirt dumping time was 9 min; loading material 6 min. The TBM excavation section is 1.2 m, and to excavate 1 m of soil the TBM takes 15 to 30 min. The average shift duration was 12 h, and the average production was 8.4 m/shift.

Using the data collected from the site, we developed a simulation model. After running the model, the results showed that production rate is 0.744 m/h, and 8.9 m/shift. This compares to 0.7 and 8.4 respectively, which represents a 6.3% difference from the actual.

We used SW2&3 scenario 5a as the second example to validate our template. In this scenario the project team suggested continuous tunnelling all the way. The total length was at the time of analysis 1205 m of soft ground with a production rate of 3.74 m/shift. Note that tunnelling under the creek is prohibited during the period from April to September. The simulation model we have assumes the use of two shifts at 10 h/shift. We used the same input parameters as the original simulation. The input parameters for this scenario are shown in Table 4-3.

TABLE 4-3 SW2&3 SCENARIO 5A INPUT PARAMETERS

Component	Unit Cost
Advance Rate	Triangular (0.44,0.55, 0.7) min
Lining time	Triangular(15,18,25) min
Track Installation	15 min
Resetting Time	15 min
Track Interval	6 m
Surveying Duration	120-180 min
Surveying Interval	15m
Number of trains	2

Number of train cars	4 dirt, 1 material
Train cars Capacity	4.2 m3
Loading material, and unloading dirt time	Triangular(3,5,7) min
Swell Factor	1.35
TBM MTBF	Exp(3000) min
TBM MTTR	60 min
Crane MTBF	Exp(9000) min
Crane MTTR	Uniform(60,240) min

We developed the simulation model using the new tunnelling template. After running the model, we found out that we would be unable to complete the tunnel before the end of March. The actual finishing date will be May 26, 2007, which will violate the constraint against tunnelling under the creek. So, we will have to continue digging until we reach the creek, (April 27, 2007, based on the simulation), then shut down the project until the beginning of October 2007 when we can restart again. We will finish, based on the simulation model, by October 30, 2007. The results we found match the results obtained from the simulation template and Microsoft Project.

4.13 The current tunnel simulation template versus the newly developed one

The new tunnelling template has a number of advantages over the current templates. The new tunnelling template builds upon the rules of SPS, while the old one was built using a user elements methodology. In user elements, the tunnelling template is a shell to encapsulate a model using general purpose modelling elements, leading to lengthy execution time and greater complexity for the user to handle. The new template provides a new concept to the tunnelling simulation called Start up, where the advancement rate in the early stage of the tunnelling project is low due to the installation of the TBM and the train switch. The old tunnelling template doesn't have this concept; we assumed the tunnelling advancement rate was the same from the start until the end. In the new template, we allow the user to define the finished length if simulation is needed during construction, whereas this was not possible in the old one.

The new template provides us with a cost estimate, while the old one does not.

The new template provides us with a schedule by using the Calendar element, not possible in the old template. As well, the old templates cannot work together; they have to work separately, while the new ones can work together and separately. Furthermore, we did not previously have an earth moving operation simulation.

The new tool allows us to simulate a number of tunnelling projects in the same model, using the Project element from the support template. In the old template, we were not able to do that, since the Shift Control element in the tunnelling template cannot be created more than once.

4.14 Summary

In this chapter, we demonstrated the tool we developed based on the scenario based-planning framework for tunnelling construction. This tool consists of three Simphony.NET SPS templates: tunnelling, shaft construction, and support. The templates can work together or separately. Also, we presented the communication points that will allow these templates to work together. In this chapter, we presented a proposed scenario-based planning process for tunnelling project planning. This process will use the developed tool as an evaluation tool for each scenario and can be generalized for any construction project.

CHAPTER 5. CASE STUDY: MILL WOODS DOUBLE BARREL (MWDB) SCENARIO-BASED PLANNING

In this chapter we will present an actual project that will be constructed in Edmonton, Alberta, Canada. We will use the developed scenario-based planning tool, presented in Chapter 4 and based on the framework discussed in Chapter 3, to evaluate a number of scenarios proposed by the project team. This exercise was done in a real-time setting: the project team proposed number of scenarios, and then we developed a simulation model for each scenario and ran each one of them, providing the project team with the results. In this chapter, we will discuss the project, the proposed scenarios, and then the final results based on the simulation tool we developed.

5.01 Project Information

The case study involves constructing multiple tunnels under the umbrella of two projects: the South Edmonton Sanitary System (SESS) SA1 project to provide sanitary services to Ellerslie area and the Mill Woods Double Barrel (MWDB) project for flood reduction in the neighbourhood of Mill Woods. Our focus was on the MWDB project.

The SA1 project is part of the SESS concept, which conveys South Edmonton sewage flows to the Alberta Capital Region Wastewater Treatment Plant (ACRWTP) for their ultimate processing. The SESS concept is made up of three trunk systems: the SW, SE, and SA trunks. The SW trunk is a deep trunk that serves the Heritage Valley and Windermere areas and an area west of the North Saskatchewan River (NSR), the SESS SE trunk serves the area covered by the Ellerslie and part of the Ellerslie East areas, and the SA trunk is expected to collect flows from the SESS SW and SE trunks (and possibly the regional flow from the SERTS South system) and deliver them to the ACRWTP (See Figure 5-1).

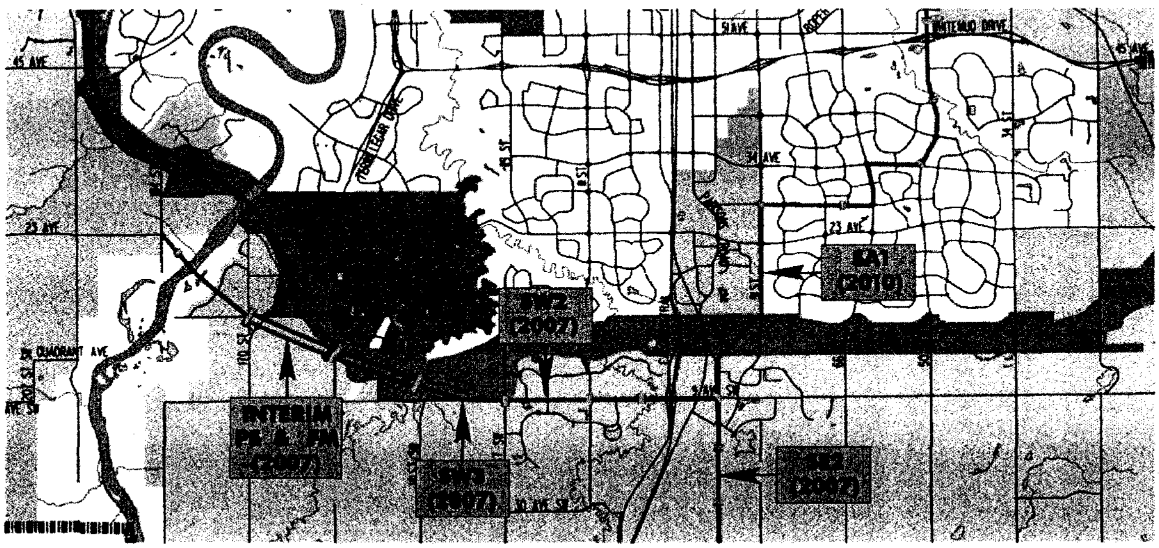


FIGURE 5-1 SESS CONCEPT

The objective of the MWDB project is to upgrade drainage facilities that will result in reduced risk of flooding in Mill Woods priority neighbourhoods. "Reduced risk of flooding" refers to approximately 80% to 90% less flooding being experienced in the future based on the reference storm event of July 2004. In the study area, a major storm-water bottleneck exists at 30 Avenue and 91 Street (one 1950 mm and two 2775 mm diameter double barrel pipes discharge into one 2775 mm diameter double barrel on 30 Avenue). The objective is to increase storm water outlet capacity; the recommended concept design was to replace the DB with a new tunnel to increase the level of service to Mill Woods and to convert the existing DB into sanitary use as an outlet for the SESS area.

Major project components include the installation of new storm trunks, conversion of double barrel to sanitary trunk, the installation of SESS SA1, and 10 connections and tie-ins. A concept review was conducted by Stantec Consulting Ltd., and recommendations to SSSF (December 13, 2007) included the following:

- Design and develop costs for the concept to convert the Mill Woods Double Barrel to a sanitary outlet for SESS.

- Install 3500 mm diameter storm sewer along 30 Avenue from 91 Street to Calgary Trail (length = 1.85 km; refer to Figure 5-2).
- Install 2900 mm diameter storm sewer from 91 Street and 30 Avenue to Knottwood Road and 85 Street (length = 1.7 km).
- Design the necessary re-connections to the new storm trunks and to convert the existing DB to full sanitary tunnel.

- Construct SESS Stage SA1b:
  - Install 2350 mm diameter sanitary trunk from approximately 9 Avenue to 23 Avenue (length = 1.4 km).
  - During preliminary design, determine if stage SA1c (23 Avenue to 28 Avenue) needs to be constructed (length = 0.8 km).
  - Develop a fair and equitable cost sharing arrangement between SSSF and the City regarding the MWDB conversion cost (amount to be determined); cost sharing formula to be based on appropriate allocation of benefits.
- Additional local flood relief measures within priority Mill Woods neighbourhoods will be required (not in current scope of the project).

The geotechnical composition at tunnel elevation along 91 Street from 9 Avenue to 23 Avenue, according to Thurber Engineering, is mainly sand. The rest of the 91 Street (SA1c and DB replacement sections) ground is comprised of bedrock, clay, etc. No bore holes so far have been dug along 30 Avenue, as the geotechnical investigation was conducted for SESS project alignment and the 91 DB portion of the flood study.

The budget on this project is approximately $49 million. Project milestones have been discussed and confirmed as follows:

- Preliminary design completed by May 31, 2008.

- Construction starts on June 1, 2008 with SA1b and should be completed by December 2010.
- Construction of MWDB starts in January 2009 and should be completed by December 2010.

Figure 5-2 shows the project and tunnel locations.

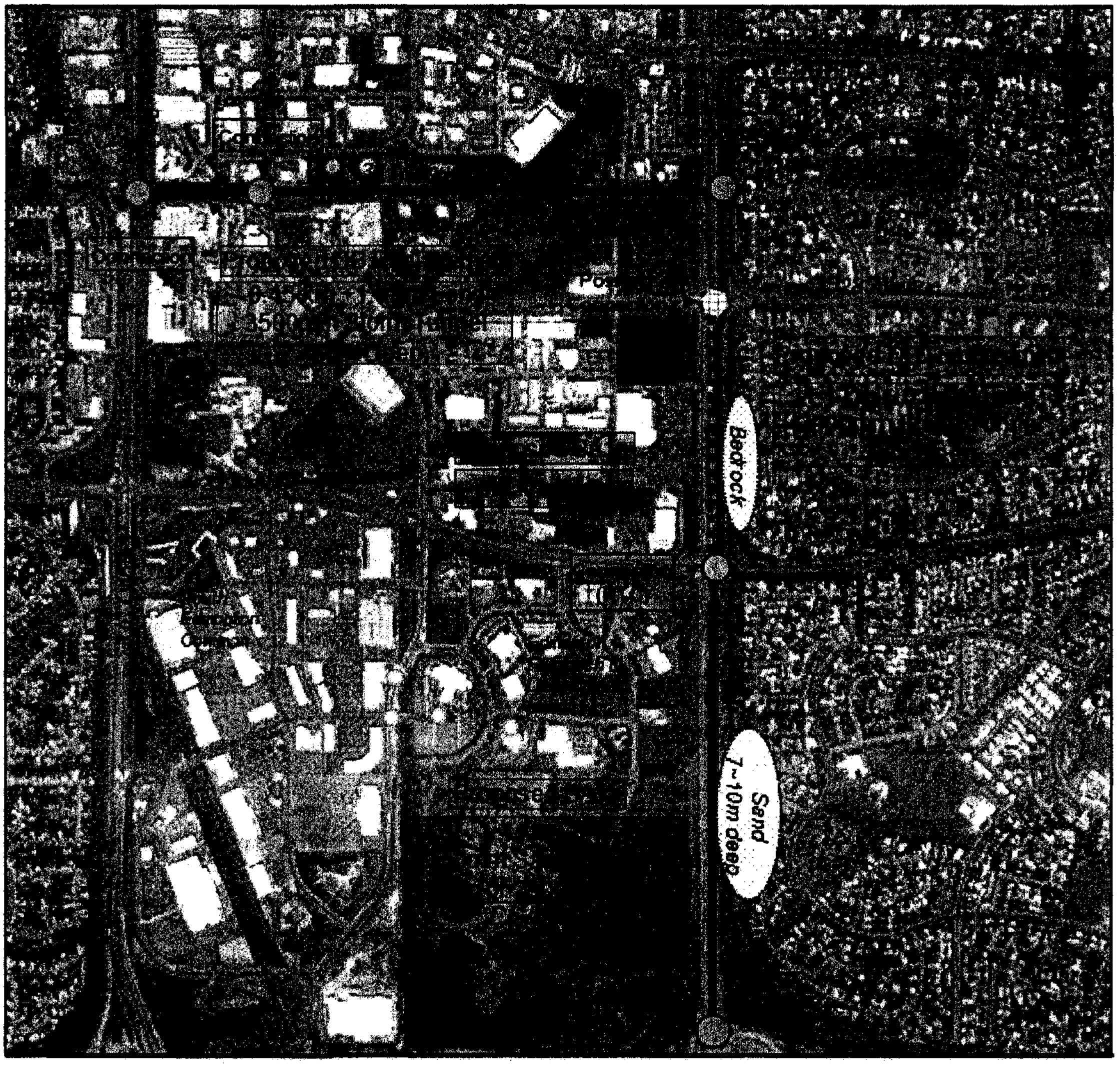


FIGURE 5-2 MWDB/ SESS SA1 PLAN OVERVIEW

5.02 MWDB scenario analysis

During the preconstruction analysis, the project team met and proposed two possible scenarios. For each scenario, the project team further proposed sub-scenarios, as follow:

- Running two ways tunnelling using a 10 m diameter working shaft, the two tunnels on an angle which required more space to a accommodate trains (two for each side) and simplify assembling TBM (see Figure 5-3)
    - o Assume the material loading time is 7 min and unloading dirt is 10 min per car.
    - o Eliminate the loading and the unloading time, to reduce cycle time for trains which will affect productivity.
- Running two separate tunnels (see Figure 5-9)
    - o Assume the loading time and unloading time for the 3.5 m diameter tunnel are 7 min and 10 min respectively, and 5 min for the 2.9 m diameter tunnel. In this case, the tunnels will have different working shafts: 37 m deep for the 3.5 m tunnel and 20 m deep for the 2.9 m tunnel, which will consequently affect crane time.
    - o Eliminate the loading and the unloading time for both tunnels, by eliminating loading and unloading time. Crane operation is not the controlling process in the tunnel excavation.
    - o Use one crane for both tunnels.

A simulation model was built for each scenario using our proposed templates, and the simulation models were developed in real time during the workshop. Tables 5-1 and 5-2 show input data for the simulation models to calculate the productivity and the duration for scenario 1 and scenario 2 respectively. Table 5-3 shows the input parameters for the cost estimate. These values are based on historical data collected form a number of tunnelling projects done by the City of Edmonton Drainage Services department.

TABLE 5-1 SIMULATION PARAMETERS: SCENARIO 1

Parameter	*3.5 m diameter tunnel*	2.9 m diameter tunnel
Advance Rate	30-45 min	15-30 min
Lining time	15 min	15 min
Track Installation	15 min	15 min
Track Interval	6 m	6 m
Surveying Duration	120-180 min	120-180 min
Surveying Interval	200 m	200 m
Number of trains	2	2
Number of train cars	5 dirt, 1 material	5 dirt, 1 material
Loading material and unloading dirt time	7 min and 10 min respectively	7 min and 10 min respectively

TABLE 5-2 SIMULATION PARAMETERS: SCENARIO 2

Parameter	*3.5 m diameter tunnel*	2.9 m diameter tunnel
Advance Rate	30-45 min	15-30 min
Lining time	15 min	15 min
Track Installation	15 min	15 min
Track Interval	6 m	6 m
Surveying Duration	120-180 min	120-180 min
Surveying Interval	200 m	200 m
Number of trains	2	2
Number of train cars	5 dirt, 1 material	5 dirt, 1 material
Loading material and unloading dirt time	7 min and 10 min respectively	5 min and 5 min respectively

TABLE 5-3 COST UNIT RATES

Component	Unit Cost
10 m diameter shaft	
Crew cost per hour	$271
Equipment cost per hour	$688
Material cost including piles per m	$22440
Indirect cost per hour	$200
6 m diameter shaft	
Crew cost per hour	$271
Equipment cost per hour	$483
Material cost including piles per m	$12841
Indirect cost per hour	$200
4.5 m shaft	
Crew cost per hour	$259
Equipment cost per hour	$267
Material cost per m	$1669
Indirect cost per hour	$200
Tunnelling overall	
Crane cost per hour	$223
Material cost per m	$2000 for 3.5 m tunnel and $1505 for 2.9m tunnel
Indirect cost per hour	$419 when combined $ when separate 240
Soil section 3.5 m diameter	
Equipment cost per hour	$801
Crew cost per hour	$564

Soil section 2.9 m diameter	
Equipment cost per hour	\$442
Crew cost per hour	\$523
Trucking	
Dump cost per m^3	\$22.56

5.03 Scenario 1: Running two-way tunnelling using a 10 m diameter working shaft

In this scenario, the project team proposed two-way tunnelling using a 10 m diameter,

37 m deep working shaft for both sides, as shown in Figure 5-3. The major project components are:

- 10 m diameter working shaft 37 m deep
- 6 m diameter removal shaft 37 m deep for the 3.5 m tunnel
- 4.5 m diameter removal shaft 20 m deep
- 3.5 m diameter straight tunnel start up of 100 m
- 3.5 m diameter straight tunnel of 1680 m
- 2.9 m diameter straight tunnel start up of 100 m
- 2.9 m diameter straight tunnel of 1080 m
- 2.9 m diameter curved tunnel of 600 m

Two new scenarios were presented based on material handling at the working shaft.

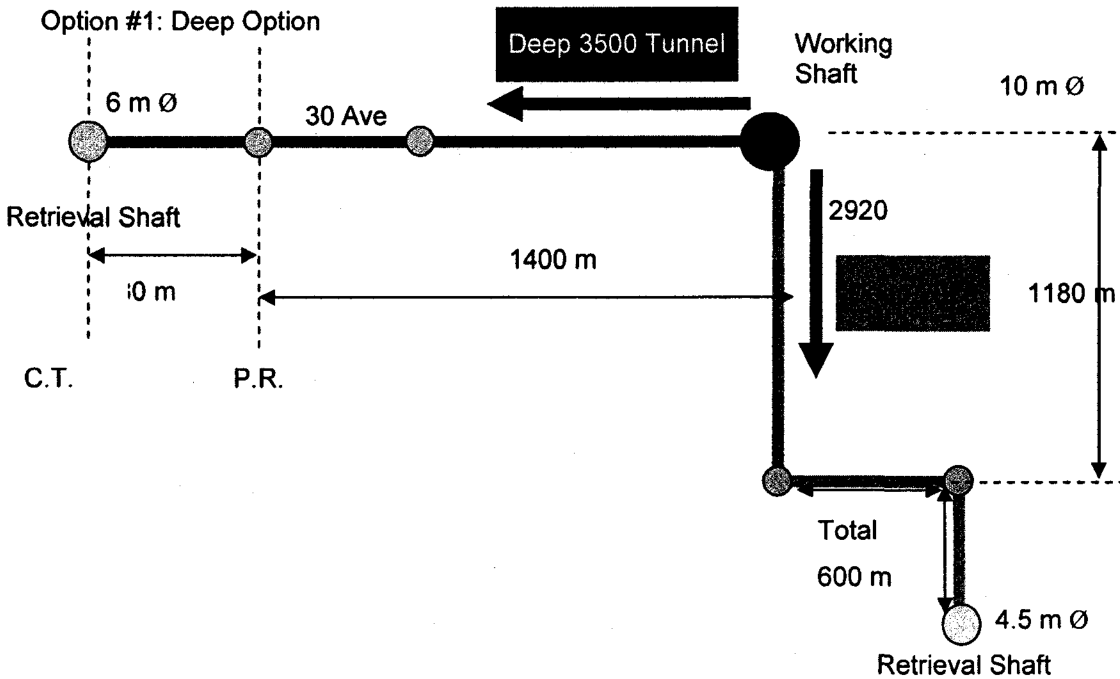


FIGURE 5-3 SCENARIO 1: TWO-WAY TUNNELLING

5.03.1 Scenario 1a: Two-way tunnelling using loading time of 10 min and unloading time of 7 min

A simulation model was developed for this scenario based on the input data from Tables 5-1 and 5-2; Figures 5-4 to 5-7 show the simulation model. The total cost based on the simulation run is $21.4 million. The project expected to begin on January 1, 2009 and finish on October 27, 2010, based on the simulation model. Tables 5-4, 5-5, and 5-6. Table 5-4 present the total cost for major components included in the project; Table 5-5 shows the schedule for each component, while Table 5-6 includes the tunnelling productivity for each soil segment.

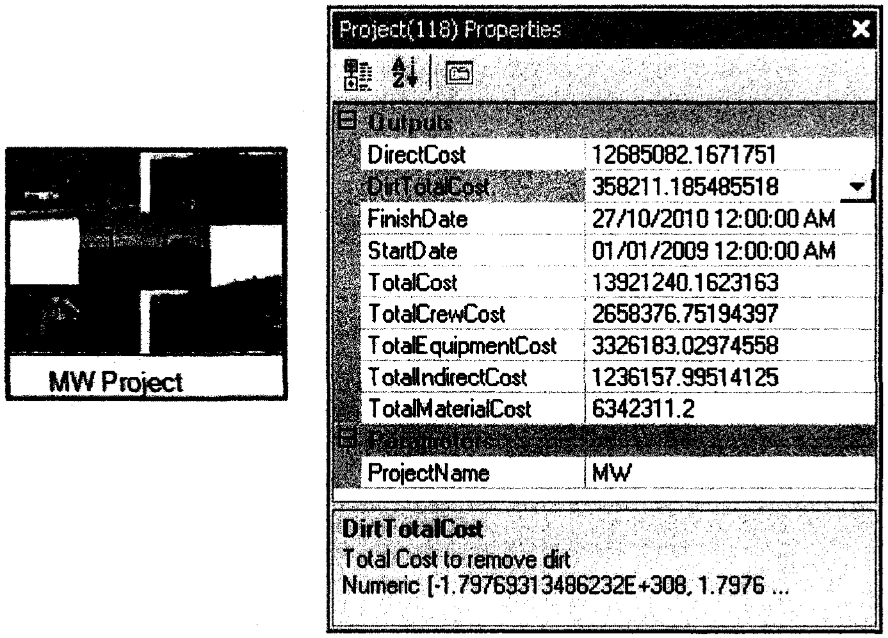


FIGURE 5-4 SCENARIO 1 SIMULATION MODEL (1)

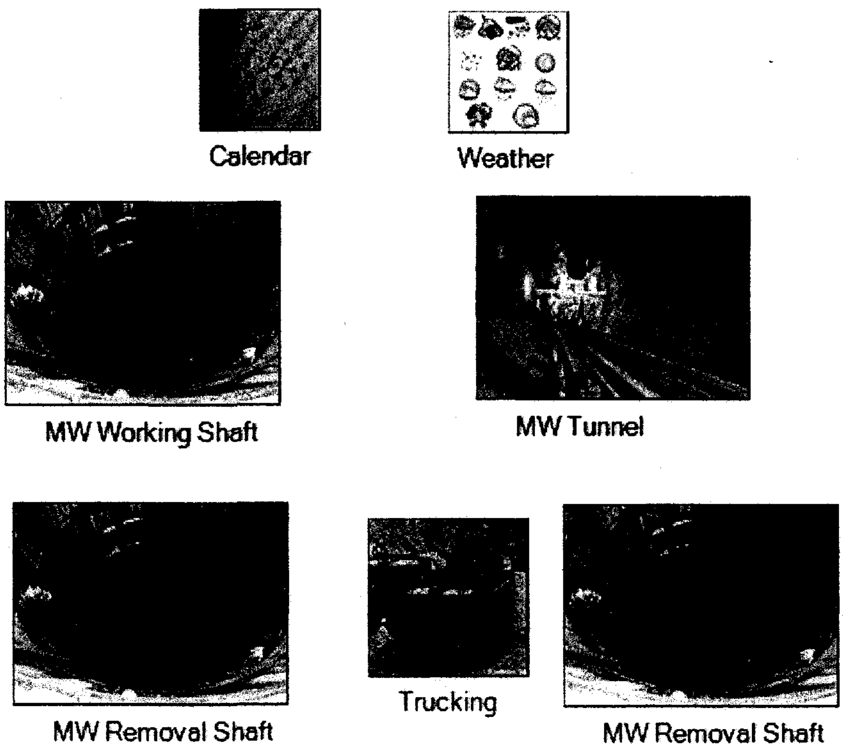


FIGURE 5-5 SCENARIO 1 SIMULATION MODEL (2)

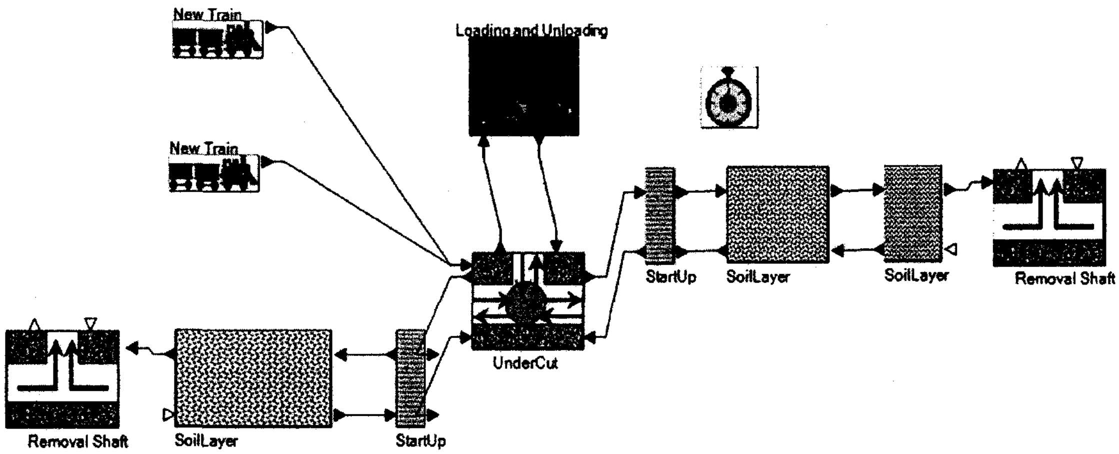


FIGURE 5-6 SCENARIO 1 SIMULATION MODEL (3)

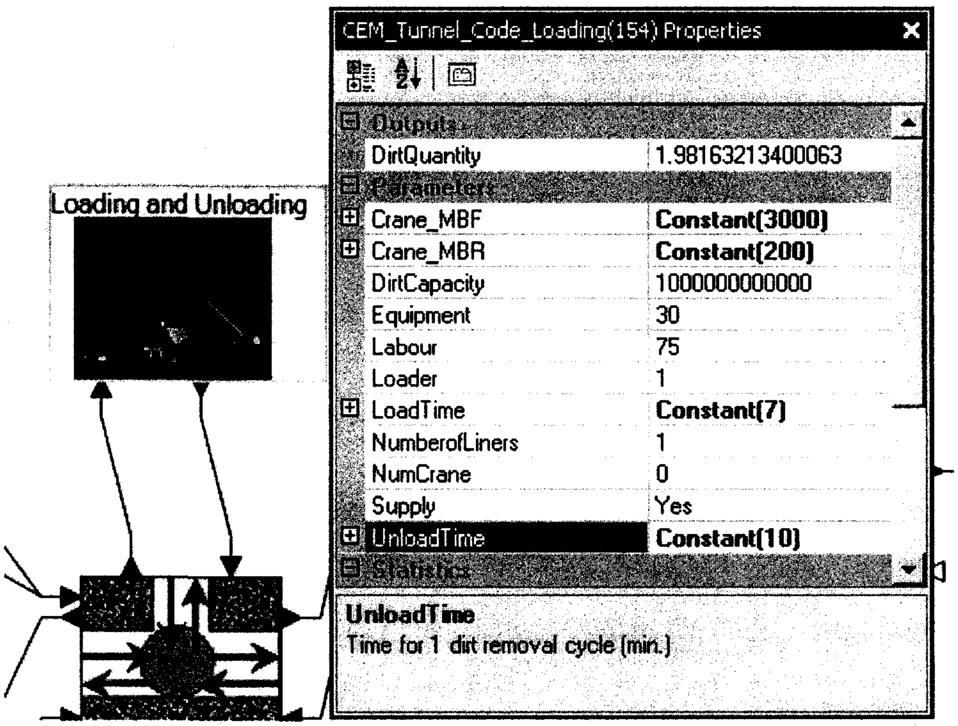


FIGURE 5-7 SCENARIO 1A SIMULATION MODEL: LOADING AND UNLOADING TIME.

TABLE 5-4 SCENARIO 1A COST

Component	Cost
10 m diameter working shaft 37 m deep	$1,588,990
6 m diameter removal shaft 37m deep for the 3.5 m tunnel.	$885,418
4.5 m diameter removal shaft 20 m deep	$169,065
3.5 m diameter straight tunnel start up of 100 m	$461,661
3.5 m diameter straight tunnel of 1680 m	$4,618,968
2.9 m diameter straight tunnel start up of 100 m	$563,465
2.9 m diameter straight tunnel of 1080 m	$2,133,594
2.9 m diameter curved tunnel of 600 m	$1,168,368
Tunnel total material and indirect cost	$8,052,407
Trucking	$880,178
Crane	$893,897
Total Cost	**$21,416,011**

TABLE 5-5 SCENARIO 1A SCHEDULE

Component	*Start Date*	Finish Date
10 m diameter working shaft 37 m deep	01/01/2009	13/04/2009
6 m diameter removal shaft 37 m deep for the 3.5 m tunnel	01/01/2009	10/03/2009
4.5 m diameter removal shaft 20 m deep	01/01/2009	03/02/2009
3.5 m diameter straight tunnel start up of 100 m	18/05/2009	03/07/2009
3.5 m diameter straight tunnel of 1680 m	03/07/2009	27/10/2010
2.9 m diameter straight tunnel start up of 100 m	13/04/2009	18/05/2009
2.9 m diameter straight tunnel of 1080 m	03/07/2009	03/05/2010
2.9 m diameter curved tunnel of 600 m	03/05/2010	25/10/2010
Project	**01/01/2009**	**27/10/2010**

TABLE 5-6 SCENARIO 1A PRODUCTIVITY FIGURES

Component	Production m/shift
3.5 m diameter straight tunnel start up of 100 m	2.15
3.5 m diameter straight tunnel of 1680 m	4.85
2.9 m diameter straight tunnel start up of 100 m	2.50
2.9 m diameter straight tunnel of 1080 m	5.00
2.9 m diameter curved tunnel of 600 m	4.76

5.03.2 Scenario 1b: Two-way tunnelling using a loading time of 0 and unloading time of 0

This scenario is the same as scenario 1a, except the loading and unloading time is set to 0. A simulation model was developed for this scenario. The total cost based on the simulation run is $15.0 million. The project is expected to start on

January 1, 2009 and finish on December 24, 2009, based on the simulation model; Figure 5-8 shows the loading and unloading as 0. Tables 5-7, 5-8, and 5-9 show detailed results for schedule, cost, and production detailed results respectively.

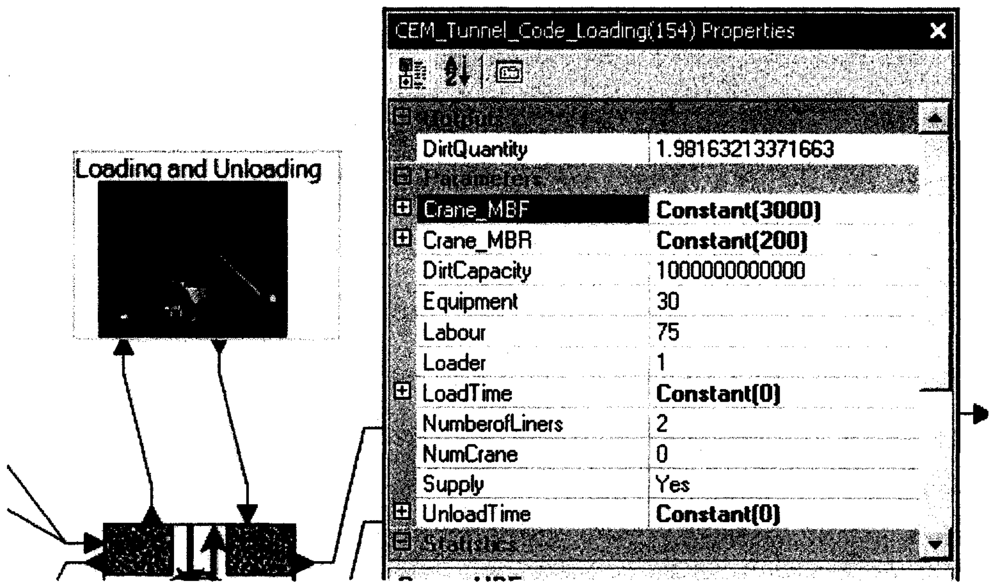


FIGURE 5-8 SCENARIO 1B: LOADING AND UNLOADING TIME IS 0

TABLE 5-7 SCENARIO 1B COST

Component	*Cost*
10 m diameter working shaft 37 m deep	$1,588,990
6 m diameter removal shaft 37 m deep for the 3.5 m tunnel	$885,418
4.5 m diameter removal shaft 20 m deep	$169,065
3.5 m diameter straight tunnel start up of 100 m	$324,438
3.5 m diameter straight tunnel of 1680 m	$1,843,844
2.9 m diameter straight tunnel start up of 100 m	$409,509
2.9 m diameter straight tunnel of 1080 m	$837,605
2.9 m diameter curved tunnel of 600 m	$522,800
Tunnel total material and indirect cost	$7,139,789

Trucking	$880,178
Crane	$409,343
Total Cost	**$15,010,979**

TABLE 5-8 SCENARIO 1B SCHEDULE

Component	*Start Date*	*Finish Date*
10 m diameter working shaft 37 m deep	01/01/2009	13/04/2009
6 m diameter removal shaft 37 m deep for the 3.5 m tunnel	01/01/2009	10/03/2009
4.5 m diameter removal shaft 20 m deep	01/01/2009	03/02/2009
3.5 m diameter straight tunnel start up of 100 m	11/05/2009	09/06/2009
3.5 m diameter straight tunnel of 1680 m	09/06/2009	18/12/2009
2.9 m diameter straight tunnel start up of 100 m	13/04/2009	11/05/2009
2.9 m diameter straight tunnel of 1080 m	09/06/2009	12/10/2009
2.9 m diameter curved tunnel of 600 m	12/10/2009	24/12/2009
Project	**01/01/2009**	**24/12/2009**

TABLE 5-9 SCENARIO 1B PRODUCTIVITY FIGURES

Component	*Production m/shift*
3.5 m diameter straight tunnel start up of 100 m	4.0
3.5 m diameter straight tunnel of 1680 m	11.4
2.9 m diameter straight tunnel start up of 100 m	3.75
2.9 m diameter straight tunnel of 1080 m	10.6
2.9 m diameter curved tunnel of 600 m	12.7

5.04 Scenario 2: Running two separate tunnels

In this scenario, the project team proposed two separate tunnels, one for each side, as shown in Figure 5-9. The major project components are:

- 6 m diameter working shaft 37 m deep for the 3.5 m tunnel
- 6 m diameter removal shaft 37 m deep for the 3.5 m tunnel
- 4.5 m diameter working shaft 20 m deep for the 2.9 m tunnel
- 4.5 m diameter removal shaft 15 m deep for the 2.9 m tunnel
- 3.5 m diameter straight tunnel start up of 100 m
- 3.5 m diameter straight tunnel of 1680 m
- 2.9 m diameter straight tunnel start up of 100 m
- 2.9 m diameter straight tunnel of 1080 m
- 2.9 m diameter curved tunnel of 600 m

Three new scenarios were presented based on material handling at the working shaft and using one crane for both tunnels.

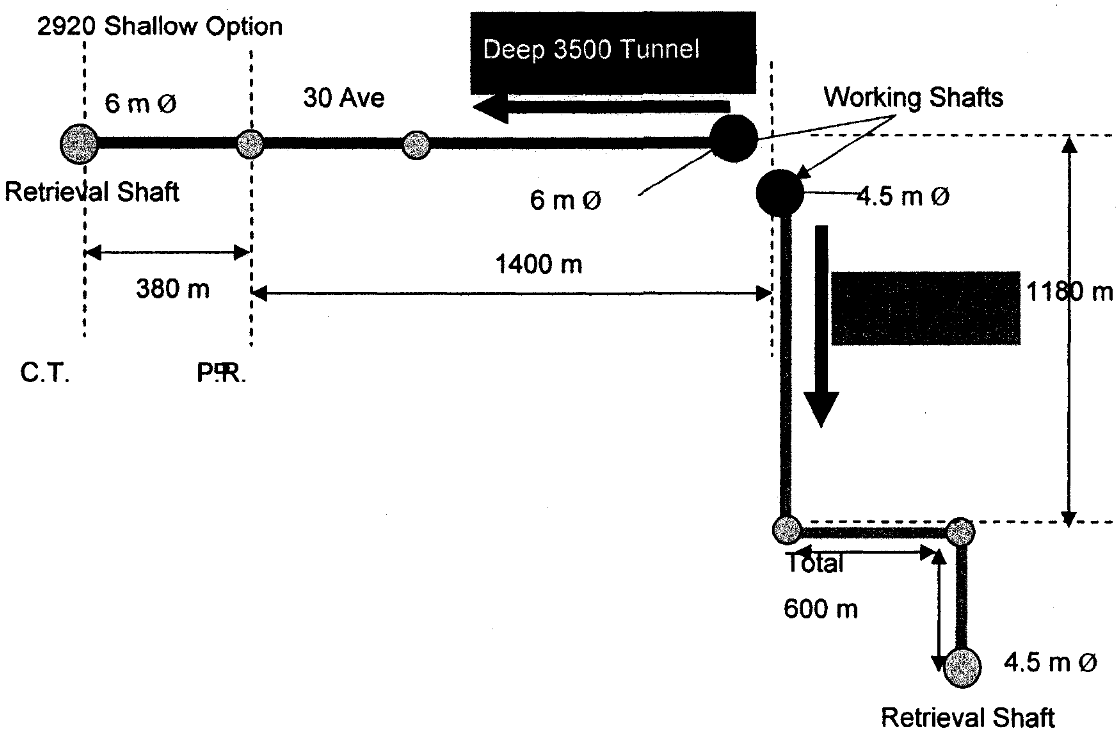


FIGURE 5-9 RUNNING TWO SEPARATE TUNNELS

5.04.1 Scenario 2a: Using two separate tunnels, with loading and unloading time.

In this scenario, the loading and unloading time for 3.5 m diameter tunnel is set at 7 min and 10 min respectively, while the loading and the unloading time for the 2.9 m diameter tunnel is 5 min. A simulation model for this scenario was developed; See Figures 5-10 to 5-13. The total cost based on the simulation run is $11.25 million. The project is expected to start on January 1, 2009 and finish on December 24, 2009, based on the simulation model; Tables 5-10, 5-11, and 5-12 show detailed schedule, cost, and production results.

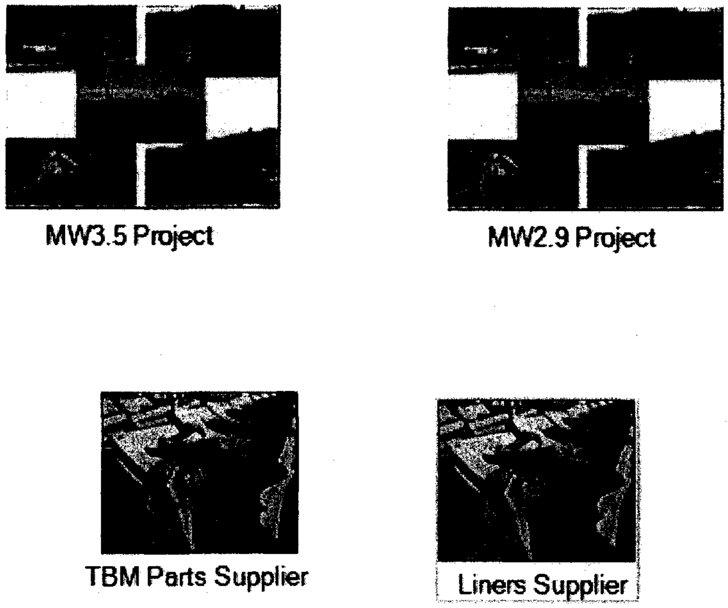


FIGURE 5-10 SCENARIO 2 SIMULATION MODEL

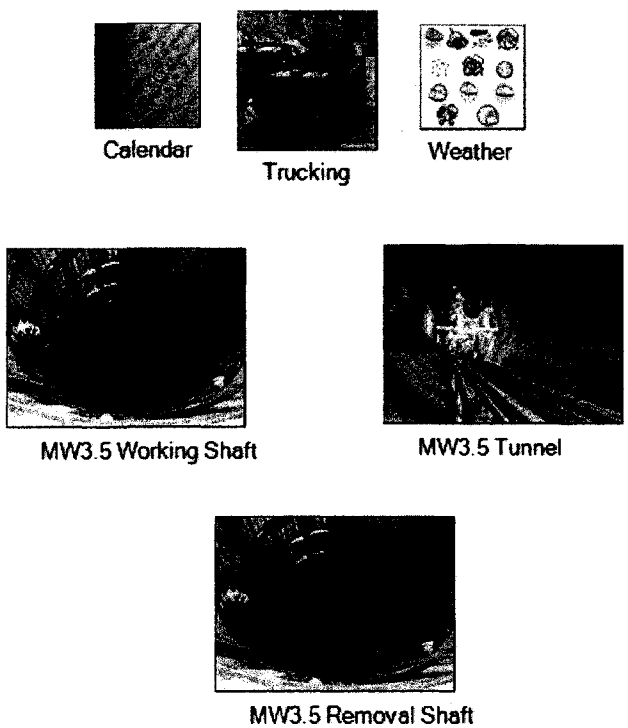


FIGURE 5-11 SCENARIO 2 3.5 M TUNNEL SIMULATION MODEL

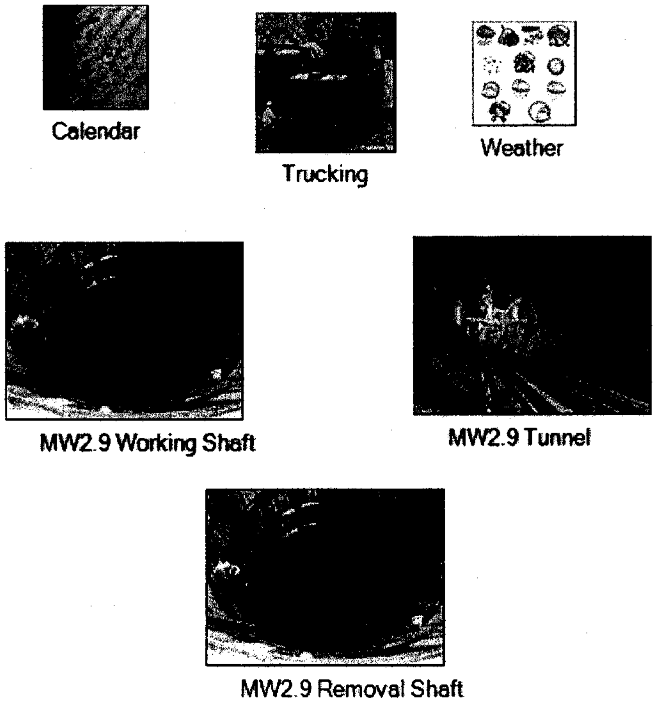


FIGURE 5-12 SCENARIO 2 2.9 M TUNNEL SIMULATION MODEL

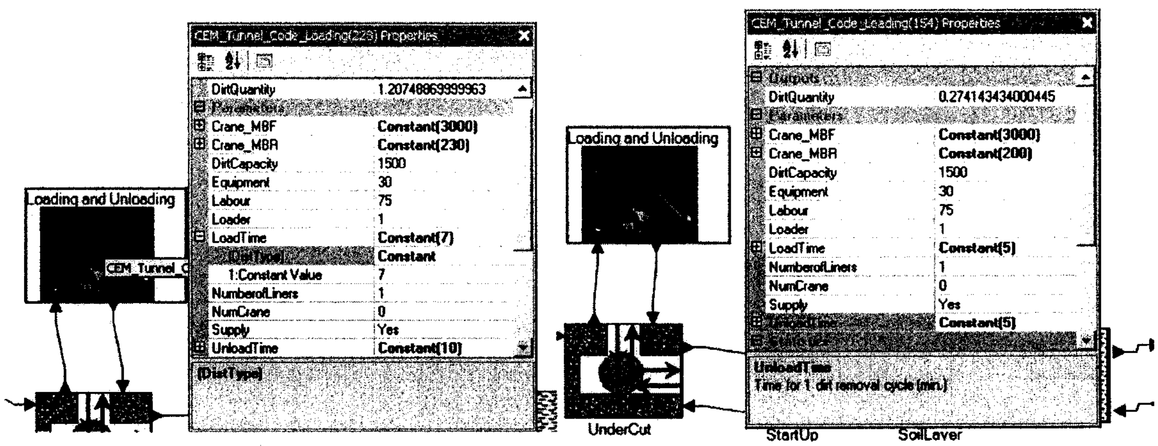


FIGURE 5-13 SCENARIO 2 TUNNEL SIMULATION MODEL LOADING AND UNLOADING TIME

TABLE 5-10 SCENARIO 2A COST

Component	*Cost*
6 m diameter working shaft 37 m deep for the 3.5 m tunnel	$1,012,782
6 m diameter removal shaft 37 m deep for the 3.5 m tunnel	$885,464
3.5 m diameter straight tunnel start up of 100 m	$478,978
3.5 m diameter straight tunnel of 1680 m	$2,671,083
3.5 m diameter tunnel total material and indirect cost	$4,141,123
3.5 m diameter tunnel trucking	$521,880
3.5 m diameter tunnel crane	$514,705
4.5 m diameter working shaft 20 m deep for the 2.9 m tunnel	$241,461
4.5 m diameter removal shaft 15 m deep for the 2.9 m tunnel	$140,777
2.9 m diameter straight tunnel start up of 100 m	$249,378
2.9 m diameter straight tunnel of 1080 m	$805,933
2.9 m diameter curved tunnel of 600 m	$519,015
2.9 m diameter tunnel total material and indirect cost	$3,071,009
2.9 m diameter tunnel trucking	$358,309
2.9 m diameter tunnel crane	$363,890
Total cost	$15,975,787

TABLE 5-11 SCENARIO 2A SCHEDULE

Component	*Start Date*	*Finish Date*
6 m diameter working shaft 37 m deep for the 3.5 m tunnel	01/01/2009	30/03/2009
6 m diameter removal shaft 37 m deep for the 3.5 m tunnel	01/01/2009	10/03/2009
3.5 m diameter straight tunnel start up of 100 m	30/03/2009	18/05/2009
3.5 m diameter straight tunnel of 1680 m	18/05/2009	10/02/2010
4.5 m diameter working shaft 20 m deep for the 2.9 m tunnel	01/01/2009	18/02/2009
4.5 m diameter removal shaft 15 m deep for the 2.9 m tunnel	01/01/2009	27/01/2009
2.9 m diameter straight tunnel start up of 100 m	18/02/2009	27/03/2009
2.9 m diameter straight tunnel of 1080 m	27/03/2009	22/07/2009
2.9 m diameter curved tunnel of 600 m	22/07/2009	05/10/2009
Project	**01/01/2009**	**10/02/2010**

TABLE 5-12 SCENARIO 2A PRODUCTIVITY FIGURES

Component	*Production m/shift*
3.5 m diameter straight tunnel start up of 100 m	2.1
3.5 m diameter straight tunnel of 1680 m	8.8
2.9 m diameter straight tunnel start up of 100 m	2.8
2.9 m diameter straight tunnel of 1080 m	13.1
2.9 m diameter curved tunnel of 600 m	12.2

5.04.2 Scenario 2b: Two separate tunnels using loading time of 0

In this scenario, the loading and unloading times were eliminated assuming they can design a material handling system in the working shaft area, since material handling takes along time that will affect production. A simulation model for this scenario was developed; see Figures 5-14 for loading time. The total cost based on the simulation run is $14.0 million. The project is expected to start on January 1, 2009 and finish on December 24, 2009 based on the simulation model. Tables 5-13, 5-14, and 5-15 show detailed schedule, cost, and production results.

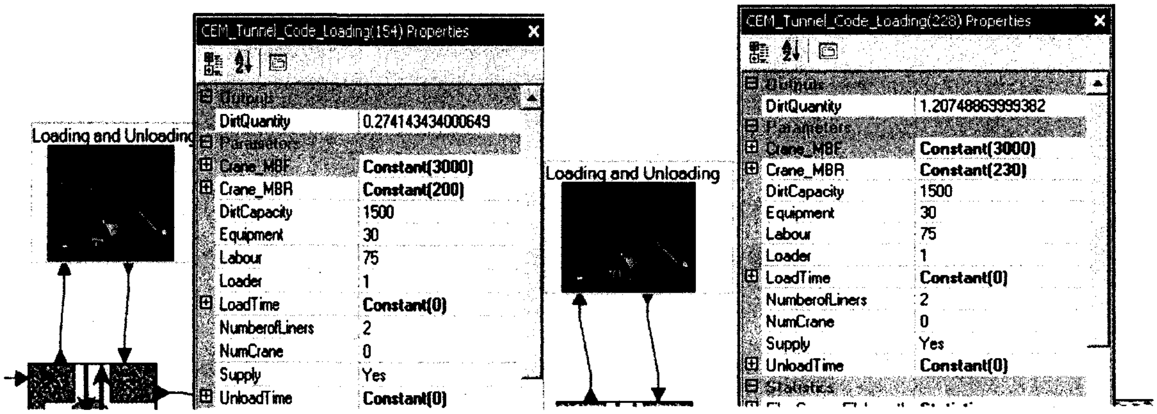


FIGURE 5-14 SCENARIO 2B LOADING AND UNLOADING TIME = 0

TABLE 5-13 SCENARIO 2B COST

Component	*Cost*
6 m diameter working shaft 37 m deep for the 3.5 m tunnel	$1,012,782
6 m diameter removal shaft 37 m deep for the 3.5 m tunnel	$885,464
3.5 m diameter straight tunnel start up of 100 m	$400,518
3.5 m diameter straight tunnel of 1680 m	$1,835,037
3.5 m diameter tunnel total material and indirect cost	$3,980,330
3.5 m diameter tunnel trucking	$521,880
3.5 m diameter tunnel crane	$365,306
4.5 m diameter working shaft 20 m deep for the 2.9 m tunnel	$241,461
4.5 m diameter removal shaft 15 m deep for the 2.9 m tunnel	$140,777
2.9 m diameter straight tunnel start up of 100 m	$245,301
2.9 m diameter straight tunnel of 1080 m	$839,236
2.9 m diameter curved tunnel of 600 m	$501,575
2.9 m diameter tunnel total material and indirect cost	$3,073,939
2.9 m diameter tunnel trucking	$358,309
2.9 m diameter tunnel crane	$366,618
Total Cost	**$14,036,609**

TABLE 5-14 SCENARIO 2B SCHEDULE

Component	***Start Date***	Finish Date
6 m diameter working shaft 37 m deep for the 3.5 m tunnel	01/01/2009	30/03/2009
6 m diameter removal shaft 37 m deep for the 3.5 m tunnel	01/01/2009	10/03/2009
3.5 m diameter straight tunnel start up of 100 m	30/03/2009	07/05/2009
3.5 m diameter straight tunnel of 1680 m	07/05/2009	11/11/2009
4.5 m diameter working shaft 20 m deep for the 2.9 m tunnel	01/01/2009	18/02/2009
4.5 m diameter removal shaft 15 m deep for the 2.9 m tunnel	01/01/2009	27/01/2009
2.9 m diameter straight tunnel start up of 100 m	18/02/2009	26/03/2009
2.9 m diameter straight tunnel of 1080 m	26/03/2009	23/07/2009
2.9 m diameter curved tunnel of 600 m	23/07/2009	05/10/2009
Project	**01/01/2009**	**11/11/2009**

TABLE 5-15 SCENARIO 2B PRODUCTIVITY FIGURES

Component	***Production m/shift***
3.5 m diameter straight tunnel start up of 100 m	3.9
3.5 m diameter straight tunnel of 1680 m	13.4
2.9 m diameter straight tunnel start up of 100 m	3.6
2.9 m diameter straight tunnel of 1080 m	13.0
2.9 m diameter curved tunnel of 600 m	12.6

5.04.3 Scenario 2c: Two separate tunnels using one crane for both

This scenario uses one crane for loading and unloading the material for both tunnels, the same for all scenarios. A simulation model was developed to help estimate the duration, cost, and productivity. The total cost based on the simulation model is $17.7 million. The start date is January 1, 2009, and the expected finish date is May 31, 2010. Figure 5-15 shows the simulation model for this scenario, and Tables 5-16, 5-17, and 5-18 present the detailed cost, schedule and productivity results.

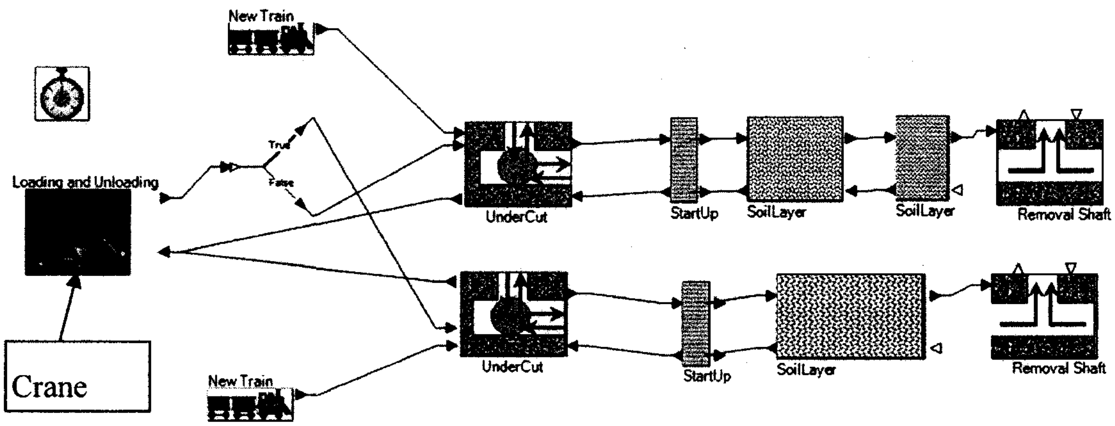


FIGURE 5-15 SCENARIO 2C SIMULATION MODEL USING ONE CRANE

TABLE 5-16 SCENARIO 2C COST

Component	*Cost*
6 m diameter working shaft 37 m deep for the 3.5 m tunnel	$1,012,782
6 m diameter removal shaft 37 m deep for the 3.5 m tunnel	$885,464
4.5 m diameter working shaft 20 m deep for the 2.9 m tunnel	$241,461
4.5 m diameter removal shaft 15 m deep for the 2.9 m tunnel	$140,777
3.5 m diameter straight tunnel start up of 100 m	$416,047
3.5 m diameter straight tunnel of 1680 m	$3,783,673
2.9 m diameter straight tunnel start up of 100 m	$189,911
2.9 m diameter straight tunnel of 1080 m	$1,206,723
2.9 m diameter curved tunnel of 600 m	$653,819
Tunnel total material and indirect cost	$7,626,628
Tunnel trucking	$879,727
Crane	$686,192
Total Cost	**$17,723,204**

TABLE 5-17 SCENARIO 2C SCHEDULE

Component	*Start Date*	*Finish Date*
6 m diameter working shaft 37 m deep for the 3.5 m tunnel	01/01/2009	30/03/2009
6 m diameter removal shaft 37 m deep for the 3.5 m tunnel	01/01/2009	10/03/2009
3.5 m diameter straight tunnel start up of 100 m	30/03/2009	07/05/2009
3.5 m diameter straight tunnel of 1680 m	07/05/2009	31/05/2010
4.5 m diameter working shaft 20 m deep for the 2.9 m tunnel	01/01/2009	18/02/2009
4.5 m diameter removal shaft 15 m deep for the 2.9 m tunnel	01/01/2009	27/01/2009
2.9 m diameter straight tunnel start up of 100 m	30/03/2009	28/04/2009
2.9 m diameter straight tunnel of 1080 m	28/04/2009	10/12/2009
2.9 m diameter curved tunnel of 600 m	10/12/2009	23/04/2010
Project	**01/01/2009**	**31/05/2010**

TABLE 5-18 SCENARIO 2C PRODUCTIVITY FIGURES

Component	*Production m/shift*
3.5 m diameter straight tunnel start up of 100 m	2.3
3.5 m diameter straight tunnel of 1680 m	6.0
2.9 m diameter straight tunnel start up of 100 m	2.5
2.9 m diameter straight tunnel of 1080 m	6.5
2.9 m diameter curved tunnel of 600 m	6.4

5.05 Results discussion and analysis

Tables 5-19 to 5-21 show the total cost, productivity values, and start and finish dates for each scenario based on simulation runs and input data obtained from the City of Edmonton Drainage Services department.

Based on Table 5-19, scenario 1a has the highest cost among all the scenarios. On the other hand, scenario 2b has the lowest cost; keep in mind that for scenario 1b and scenario 2b, an additional cost must be added to represent material handling systems at the working shaft.

Table 5-20 shows that production values are highly affected by crane use to handle materials at the working shaft. If we used one working shaft for both tunnels, it is has little effect on the 2.9 m diameter tunnel; if we use separate working shafts, it has a large effect at the 3.5 m diameter tunnel. For the last scenario, simulation results show that using one crane for two separate tunnels will improve the production compared to having both tunnels share the same working shaft, as the 2.9 m diameter tunnel has a shallower working shaft than the 3.5 m diameter Tunnel.

For the schedule results, the same should be noticed for both scenarios 1b and 2b. A larger amount of time must be added to compensate for material handling system at the working shaft. Based on the results, the fastest scenario will be 2b and slowest will be 1a.

TABLE 5-19 SCENARIOS TOTAL COST

Scenario Name	*Total Cost*
Scenario 1a	$21,416,011
Scenario 1b	$15,010,979
Scenario 2a	$15,975,787
Scenario 2b	$14,036,609
Scenario 2c	$17,723,204

TABLE 5-20 SCENARIO PRODUCTIVITY VALUES

Soil Section	*Scenario 1a (m/shift)*	*Scenario 1b (m/shift)*	*Scenario 2a (m/shift)*	*Scenario 2b (m/shift)*	*Scenario 2c (m/shift)*
3.5 m diameter straight tunnel start up of 100 m	2.15	4.0	2.1	3.9	2.3
3.5 m diameter straight tunnel of 1680 m	4.85	11.4	3.8	13.4	6.0
2.9 m diameter straight tunnel start up of 100 m	2.50	3.75	2.8	3.6	2.5
2.9 m diameter straight tunnel of 1080 m	5.00	10.6	13.1	13.0	6.5
2.9 m diameter curved tunnel of 600 m	4.76	12.7	12.2	12.6	6.4

TABLE 5-21 SCENARIO START DATE AND FINISH DATE

Scenario	*Start Date*	*Finish Date*
Scenario 1a	01/01/2009	27/10/2010
Scenario 1b	01/01/2009	24/12/2009
Scenario 2a	01/01/2009	10/02/2010
Scenario 2b	01/01/2009	11/11/2009
Scenario 2c	01/01/2009	31/05/2010

From the results above, it will be worthwhile investigating eliminating material handling at working shaft for scenario 1b, and for the 3.5 m diameter tunnel in scenario 2b, since production for the 2.9 m diameter tunnel will not be affected due to its shallow working shaft. Using one crane for both tunnels will not add any benefits since the cost saved by using one crane will be consumed by the increased duration of tunnelling activity.

Other results can be extracted from the model if desired, such as number of shifts required to finish the project, number of working days, and number of off days. Also, a detailed material delivery schedule adds the total dirt excavated from the tunnel.

This analysis was done in real time. The project manager defined these scenarios, and then we developed a simulation model for each scenario. It took us around ten minutes to develop the simulation model for each scenario, after which we ran each scenario as a separate run. Each run took around three minutes to finish. After running the models, we collected the results shown previously. The overall duration was about an hour. These results gave the project manager a good idea of how to approach this project.

5.06 Probabilistic analysis for proposed scenarios

To better understand the simulation models results we ran each scenario for number of runs, and then we calculated the mean and standard deviation for cost, duration and productivity. Tables 5-22 to 5-24 show the simulation runs results for cost, productivity and duration respectively.

TABLE 5-22 SCENARIOS TOTAL COST

Scenario Name	*Total Cost Mean*	*Total Cost StDev*
Scenario 1a	$21,492,576	$117,390
Scenario 1b	$15,175,530	$49,125
Scenario 2a	$15,829,918	$49,120
Scenario 2b	$14,091,751	$53,070
Scenario 2c	$17,687,174	$42,726

TABLE 5-23 SCENARIO PRODUCTIVITY VALUES

Soil Section	*Scenario 1a*		*Scenario 1b*		*Scenario 2a*		*Scenario 2b*		*Scenario 2c*	
	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
3.5 m diameter straight tunnel start up of 100 m	2.29	0.64	3.67	0.24	2.19	0.10	3.87	0.05	2.18	0.28
3.5 m diameter straight tunnel of 1680 m	6.05	0.12	12.85	1.27	8.78	0.15	13.48	0.14	6.01	0.17
2.9 m diameter straight tunnel start up of 100 m	2.84	0.17	4.29	0.11	2.85	0.08	3.62	0.09	2.66	0.25
2.9 m diameter straight tunnel of 1080 m	6.24	0.26	10.56	0.18	13.44	0.30	13.20	0.34	7.21	0.44
2.9 m diameter curved tunnel of 600 m	6.65	0.16	12.40	0.55	12.70	0.42	12.83	0.56	5.91	0.29

TABLE 5-24 SCENARIO DURATION

Scenario	*Mean Duration (Days)*	*Duration StDev*
Scenario 1a	400.64	3.23
Scenario 1b	251.52	4.58
Scenario 2a	276.47	2.14
Scenario 2b	210.04	0.88
Scenario 2c	357.72	1.13

The results shown in the previous tables complement the results drawn from the analysis introduced in the previous section.

5.07 Summary

In this chapter, we presented a case study using the new scenario-based planning tool we developed for tunnelling construction. During the exercise, we found the tool more flexible than the old tunnelling tool.

In the next chapter we will presents a future implementation for multi user framework for tunnelling operation and tunnelling simulation using new simulation software called CoSyE developed based on the HLA rules.

CHAPTER 6. PROPOSED FUTURE IMPLEMENTATION OF MULTI-USER FRAMEWORK FOR TUNNELLING CONSTRUCTION

Current simulation techniques lack the ability to support multiple-user decision systems in complex projects mainly because they have been designed to tackle single users and not a collaborative environment, which limits our ability to study the overall systems at hand in depth. Also, current simulation environments fail when the source of interaction is a different model. In this chapter, we will propose an implementation of a multi-user framework for tunnelling construction and tunnelling simulation models using a new simulation framework called CoSyE (AbouRizk 2006), built upon the concepts of HLA.

6.01 Framework development

To develop a comprehensive collaborative construction simulation framework, we will use the HLA concepts, and since HLA does not support hierarchy we will use Ziegler's (2000) abstraction concept to present hierarchy in our framework.

6.02 Collaborative construction simulation

Facilities are built through the collaboration of multiple stakeholders. Design engineers of varying specialties, contractors and sub-contractors, suppliers, project managers, and other stakeholders work together and overlap at various stages of the project design and construction. Different participants in the project at different times operate in different levels of the project hierarchy and with different facets of the project. They provide input, make decisions and interact with the design and the built facility. This often leads to many challenges and problems that are not reconcilable with today's technologies.

The processes required to build facilities are simulated through a myriad of abstractions and representations. Those representations evolve, change and mature from one stage of the life cycle to the next. Henderson (2002) argues that "stakeholders have their specific roles in a project, and their responsibilities change when their roles change. Based on their different roles, various stakeholders may work at different hierarchical job levels and look into operational processes at different levels of detail, i.e. at a strategic level, at a tactical level or at an operational level, both for setting up a process and during its execution."

6.03 Implementation approach

To facilitate interactions between participants in a loose network approach, we intend to build our framework to make use of the services and methods available through the HLA. The HLA supports building complex virtual environments (called federations) using distributed simulation technologies. It provides standards for building the individual components (federates) of such environments by different users while maintaining interoperability between them. The HLA standards consist of three main components: the HLA rules (IEEE 1516), the interface specifications (IEEE 1516.1), and the Object Model Template (OMT) (IEEE 1516.2). A conceptual model of the proposed research in the context of the hierarchical concepts and HLA standard is provided in Figure 6-1.

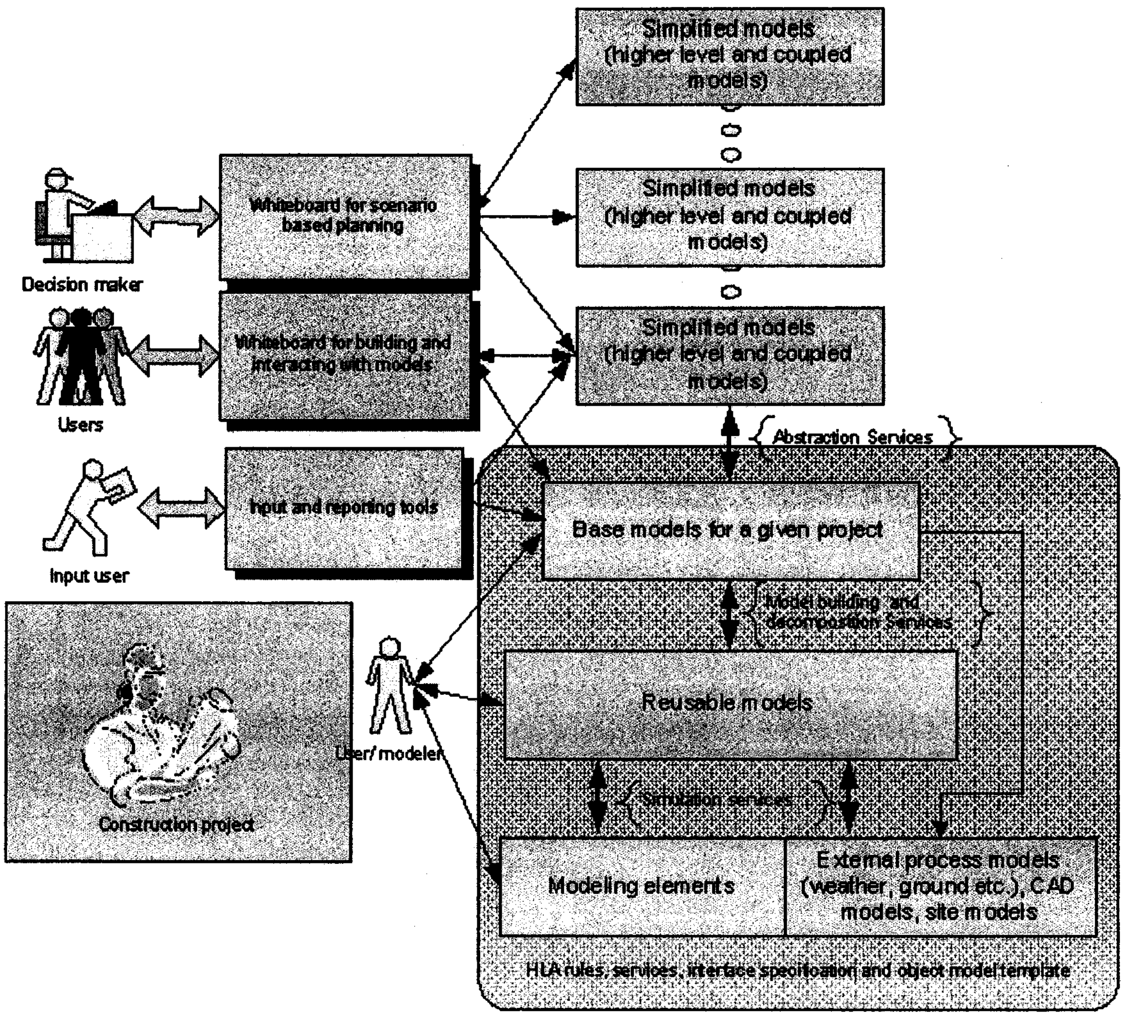


FIGURE 6-1 CONCEPTUAL REPRESENTATION OF THE COLLABORATIVE FRAMEWORK (ABOURIZK 2006)

6.04 Framework overview

The framework we are presenting in this chapter is composed of a number of components to help in understanding and simulating construction project, especially tunnelling. This framework will help researchers to develop a multi-user based model for any construction project. Figure 6-2 shows the tunnelling construction framework.

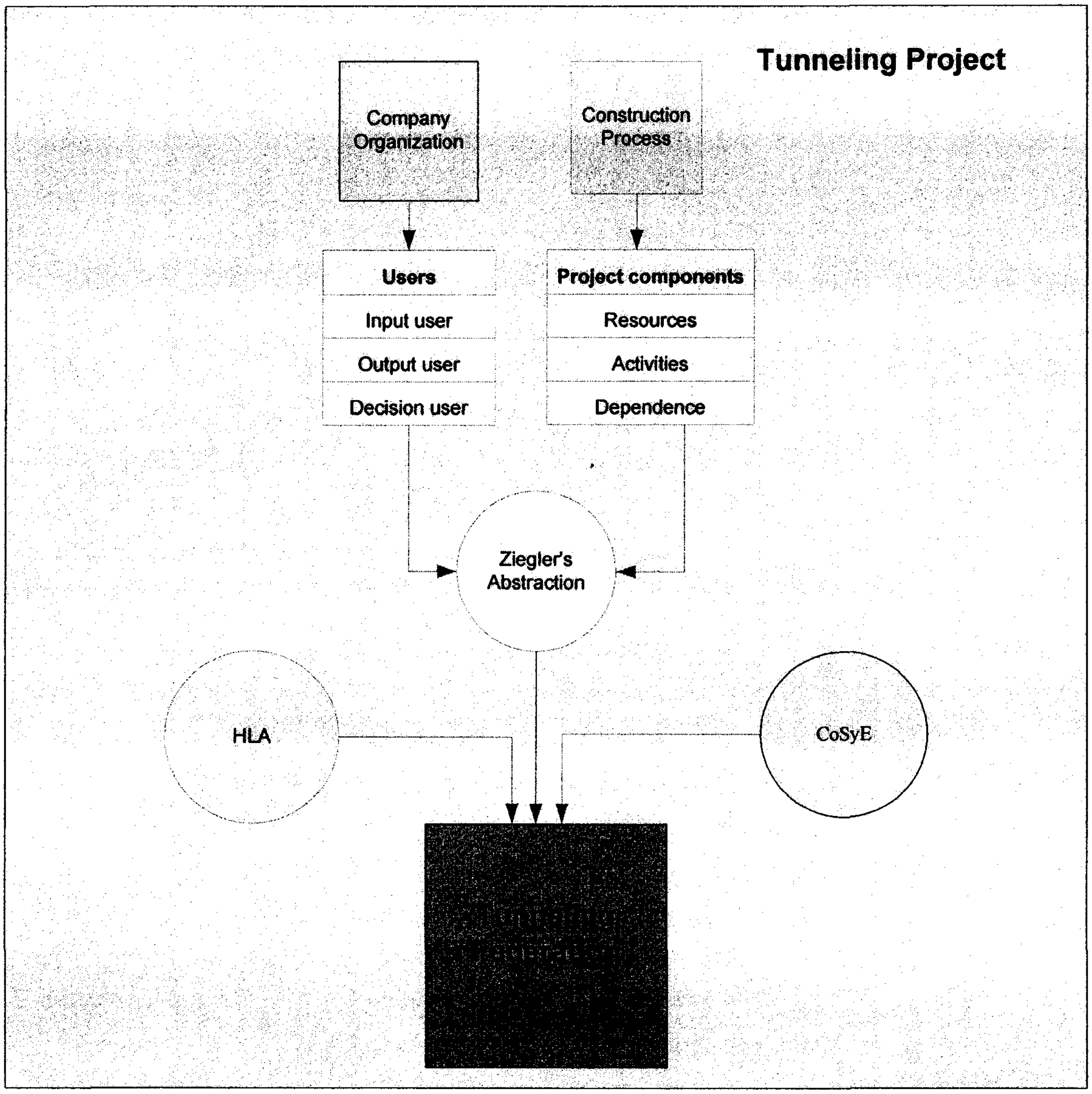


FIGURE 6-2 MULTI-USER FRAMEWORK FOR TUNNELLING CONSTRUCTION

Even though our focus will be on tunnelling projects, this framework can be generalized for any construction project. In the following, we will describe each of the framework components.

6.05 Framework components

The framework we are presenting consists of a number of components that will integrate together. This integration will facilitate the development of a multi-user simulation-based model for tunnelling operations.

These components will help to develop a better understanding of the construction process under consideration, in our case tunnelling; also, they will help define the company hierarchy. A CoSyE simulation environment based on HLA concepts is another component of this framework that will be used to develop the simulation models. Meanwhile, Ziegler's abstraction concept will be used to represent the hierarchy in the simulation model, as HLA doesn't support hierarchy.

The detailed description of the framework components is presented in the following sections.

6.05.1 Process study

To be able to understand the complexity of the construction process, the construction process under consideration should be studied and documented closely. To achieve this, a number of site visits should be scheduled.

In our case, the focus was on tunnelling operations. To understand more about the process, we visited a number of sites in Edmonton, Canada over the course of our research. During these visits, we recorded the process activates and their durations. Process descriptions can be found in Chapter 3.

From this component, a number of issues should be highlighted, such as: resources, processes, activities, materials, outcome, upper management input, weather effects, and material delivery impact. The idea behind this is to define the information exchanged between the site and the company, and also other parties involved in the project such as consultant, designer, etc.

6.05.2 Company organization

This component will present us with the different users involved in the project and their levels of involvement. That will help us to define our system users: the input user will input data to the system and update project status; the output user will receive outputs based on the input data from the input user, analyze them, and make recommendations based on that. Lastly, the decision-making user, which is the highest user level, will set the actions and strategies. See Figure 6-3.

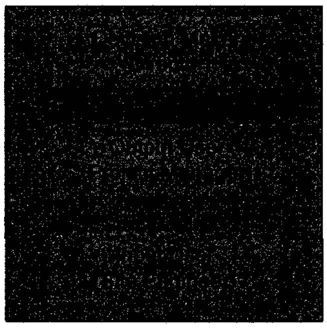


FIGURE 6-3 USER TYPES

6.05.3 Ziegler's abstraction

To represents hierarchy in the framework, we used Ziegler's (2000) abstraction concept, in which the higher the user level, the higher the abstraction and the fewer details required. Figure 6-4 represents the mapping between the company and simulation.

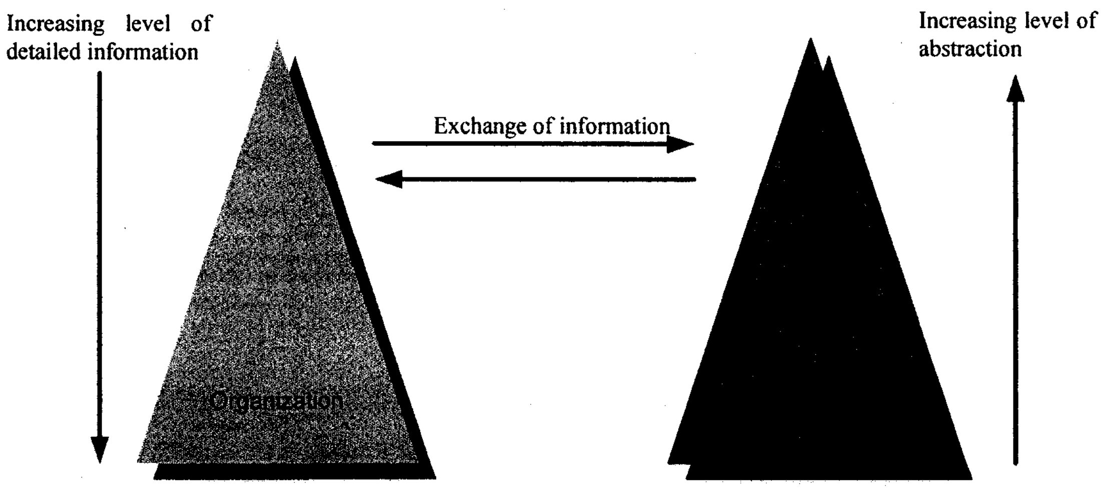


FIGURE 6-4 COMPANY VS. SIMULATION MAPPING

6.05.4 High Level Architecture

Current simulation techniques do not allow users to combine a number of computer simulation models into a larger simulation. The user is forced to recreate the overall simulation model, which adds additional time and cost to the whole process. HLA, a standards created by the Department of Defense (DoD), which will allow users to combine these simulation models.

In HLA terminology, the simulation model is called a federation, and each component included in simulation model is called a federate.

Each federation needs a Run Time Interface (RTI), which is a supporting software used to control the data flow between federates, and a Federation Object Model (FOM), which has the common object model for the data exchanged between federates in a federation (Kuhl et al. 1999).

6.05.5 Construction Synthetic Environment (CoSyE)

CoSyE (AbouRizk 2006) a simulation environment based on the HLA rules, consists of three major components:

- CoSyE RTI Server, a .NET implementation of IEEE standards 1516-2000. Currently, the CoSyE RTI server has implemented 50% of the standards and provides services, such as federation, declaration, object, ownership, and time management.
- Object Modelling Template (OMT) editor, used to define objects and their attributes. It defines the structure of Federation Object Model (FOM) for the federation. FOM for a single federation defines the communication language through which federates included in the federation speak with each other, including the name of things and occurrences. It includes the internal in a single federate.
- CoSyE Framework, an application programming framework that allows developers to create federates, handle details of communication with the RTI, integrate with code generated by the

OMT editor, and use many of the visual programming features supported by Visual Studio. In addition, the framework supports both discrete-event and time-stepped federates.

6.06 Tunnelling federation

The synthetic environment we are planning to develop for tunnelling simulation will mirror the real company hierarchy, in which each user will have a different level of detail required to represent his level in the company hierarchy. Figure 6-5 illustrates the mapping between the company hierarchy and the tunnelling federation we intend to build. To overcome HLA's lack of support for hierarchy, we used abstraction to represent the hierarchy in the context of a higher level user, represented by a higher level of abstraction and fewer details.

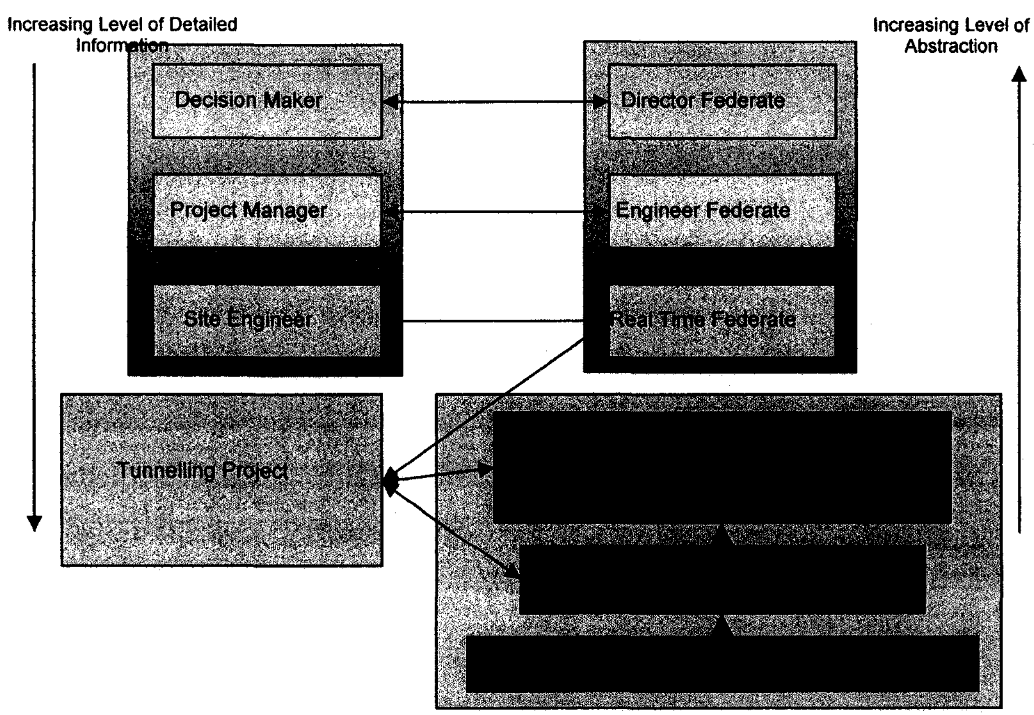


FIGURE 6-5 TUNNELLING FEDERATION VS. COMPANY HIERARCHY

The following list shows the number of federates that will be included in our federation:

1. Excavation Federate: Responsible for excavation of the tunnel segments, loading of the dirt onto the train, performing lining operations, and installing the tracks
2. Geotech Federate: Carries the ground profile and produces the penetration rate for the TBM
3. Statistics Federate: Used to collect statistics for the operation, such as production rate, resource usage, and project duration
4. Breakdown Federates: Predicts the breakdown of different machinery, estimates the duration of the breakdown, and the time required to fix it
5. Viewer Federate: 3-D animation of the entire operation
6. Shift Federate: Manages shifts properties such as the duration of the shift, the lunch break, etc
7. Real time Federate: Responsible for real time update data from the site
8. Shaft Construction Federate: Used to simulate shaft excavation for tunnelling. The shaft can be working shaft, removal shaft, or emergency shaft.
9. Material Delivery Federate: This federate is responsible for simulating material delivery to the project. This material can be lining, mechanical parts, electrical parts, etc.
10. Earth Moving Federate: Used to simulate the removal of the excavated dirt form site to dumping area
11. Weather Federate: Used to predict the weather parameters during the simulation period for a site location

12. Engineer Federate: Responsible for producing reports for the project manager, such as updates to the schedule, and cost estimates

13. Director Federate: Used for high-level users to help them to run selected scenarios and come up with the best approach to achieve their goals

6.07 Tunnel construction federation using CoSyE

In this section, we will present the tunnelling federation. This federation consists of seven federates and is used to calculate the tunnelling excavation prosecution part of the whole process. It also shows the start and finishing dates for the soil segment excavation. We will also discuss the FOM for this federation.

6.07.1 Tunnelling federation FOM

The first step in developing any federation is to create the FOM. The FOM includes three components: data types, interactions (we don't have any interaction in this federation), and object classes. To develop FOM using CoSyE, the user can use OMT editor (see Figure 6-6)

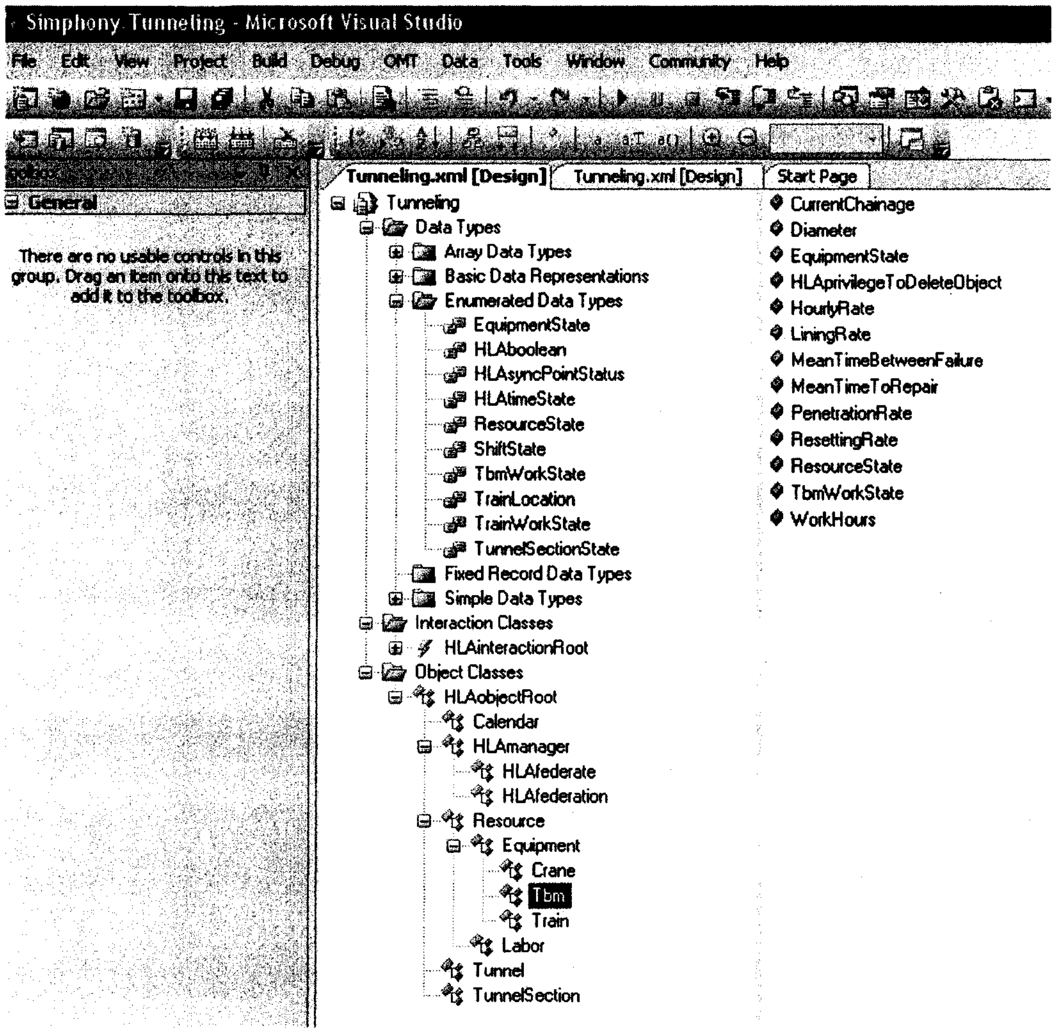


FIGURE 6-6 COSYE OMT EDITOR

6.07.1.1 Data Types

We use data type to define our object classes by attribute data type such as integer, double, etc. CoSyE has five different data types available: array data type, basic data representations, enumerated data type, fixed record data type, and simple data type. Users can define custom data type within those data type groups except the basic data type.

For tunnelling federation, we created seven custom enumerated data types. These data types are:

- EquipmentState: This data type defines the state of any resource marked as equipment. The value of this data type can be either 'Down' or 'Functional'.
- ResourceState: This type is used for any resource, both workers and equipment. This data type can have the values of 'Busy' or 'Idle'.
- ShiftState: This data type is used to define the crew state and the time of the shift. This type can have the values of 'Starting', meaning the shift just started; 'Ending', meaning the shift finished; 'Coffee', meaning the crew is on coffee break; 'Lunch', meaning the crew is on lunch break; 'Working', meaning the crew is active; and 'Off' meaning the day is a non-working day such as Sunday.
- TBMWorkState: Used to define the TBM working state during the operation, which can have three states: 'Excavating', meaning the TBM is excavating a soil section; 'Lining', meaning the TBM is installing liners or rib and lagging; and 'Resetting'.
- TrainLocation: This data type is used to describe the train location during simulation. The train used to haul the excavated dirt to shaft and material from shaft to TBM can have three possible locations: 'Undercut', meaning the train is in the shaft waiting to dump dirt or waiting for second train to arrive from the tunnel face; 'Tunnel', meaning the train is traveling from or to the tunnel face; and 'TunnelFace', meaning the train is at the TBM.
- TrainWorkState: Used to describe the working state of the train, which can be 'Dumping', 'Hauling', 'Returning', and 'Loading'.
- TunnelSectionState: In our model, the tunnel is divided into sections. Each section has it is own state, which can be: 'Complete', meaning the section has been excavated and lined; 'Excavating', meaning the TBM is excavating the section; 'Lining', meaning the TBM is lining the section; 'Resetting', meaning the TBM is resetting to start the

next section; and 'Unstarted', meaning the TBM hasn't reached the section yet.

6.07.1.2 Object Classes

Under this, the user will define the common object model that will be used to transfer data between federates in the federation; all these classes are derived from HLAObjectRoot. Each object class has a number of attributes that will be updated during simulation. An object class can be a child of another object class; in this case, the child class will inherit the parent's attributes. In our federation, we have nine object classes:

- Calendar Class: This class has four attributes: InitialDateTime, which represents the starting date of our simulation; ShiftsElapsed, showing how many shifts we used; ShiftState shows different shift states with ShiftState data type; and WorkingDaysElapsed, which shows the number of working days since we started working.
- Resources Class: This object class represents the parent class for all resources included in the simulation. The class has two attributes: HourlyRate, the resources' hourly pay, and ResourceState, which uses the data type marked as ResourceState.
- Equipment Class: This class is a child class of the Resources class, so it will carry those attributes in addition to: EquipmentState, which has the data type of EquipmentState; MeanTimeBetweenFailure, the time for the next breakdown; MeanTimeForRepair, the time to repair the breakdown; and WorkHours, which is the total working hours.
- Crane Class: This class is a child of the Equipment class, which means it will carry the same attributes; there are no additional attribute for Crane.
- TBM Class: The same as the Crane class, but with a number of extra attributes: CurrentChainage, which shows the location of the TBM; Diameter, which represents the TBM diameter; LiningRate, the time

for the TBM to finish lining one section; PenetrationRate, the time the TBM needs to finish excavating one section; ResettingRate, the time needed to reset the TBM for the next section; and TBMWorkingState, which uses the data type TBMWorkingState.

- Train Class: This class is the same as Crane, with extra attributes: Capacity is the volume of dirt the train can haul in one trip; CurrentLoad is the volume of dirt the train carries; Location represents the train location and uses the Location data type; NumberofMuckCars is the number of dirt cars in the train; Speed is the train speed when travelling; and TrainWorkingState, which represents the train working state based on the TrainWorkState data type.

- Labour Class: A child of Resource class; it has the same attributes as Resources.

- Tunnel Class: This class represents the tunnel soil sections we are trying to excavate. It has eight attributes which are: Diameter, the tunnel's diameter; InitialSectionChainage, representing the location of the first soil section—usually 0 during the planning phase of the tunnel and greater than 0 during construction; LastSectionChainage, the location of the last section; Length, the tunnel's length; Name, which represents the project name; PriorPenetrationRate is the initial penetration rate; PriorStandardDeviation, used to update the penetration rate; and SectionLength, the length of each tunnel section.

- TunnelSection Class: This class has five attributes: Chainage, the tunnel section location; Diameter is the tunnel section's diameter; Length, the tunnel section length; SoilType is the tunnel section soil type; and State, which uses the TunnelSectionState as a data type.

6.07.2 Tunnelling federates

This federation consists of seven federates. These federates are: Removal Federate, Excavation Federate, Viewer Federate, Breakdown Federate, Shift Federate, Geotech Federate, and Statistic Federate (see Figure 6-7).

Geotech Federate is used to create tunnel sections and keep track of the total length finished to date; it also defines the TBM penetration rate. **Excavation Federate** is used to simulate the actual TBM excavation process. In this process, the TBM excavates one tunnel section at time. The train will be used to carry the dirt excavated by the TBM, and then the TBM will install tunnel liners. **Removal Federate** models dirt handling at the working shaft. Once the loaded train arrives, the dirt will be dumped and lining material will be loaded to the train; meanwhile, the second train will travel to the TBM to excavate the next section. **Shift Federate** simulates the shift control of the crew by defining if it is time for a break or to start or end the shift. Based on the calculated date this federate also finds out if it is a working day or a holiday. **Breakdown Federate** handles equipment breakdown and repairs based on the mean time between breakdowns and the mean time to repair, respectively. **Statistic Federate** is a listing federate that collects observations during simulation, such as cumulative production and TBM state during excavation. **Viewer Federate** shows the tunnel in 3-D during construction.

During execution of the simulation, federates will be responsible for creating object instances of the object classes we defined in the FOM. Also, federates can publish and subscribe to an object instance attribute; for example, a federate can subscribe to the diameter of tunnel section, or it can publish the tunnel section diameter. Some federates can publish and subscribe, publish only, or subscribe only.

A federate will be interested in publishing an attribute if it updates its value; for example, Excavation Federate updates the TrainState. A federate will be interested in subscribing to an object class instance attribute if it triggers an action; for example, Excavation Federate will subscribe to TBMState because if the TBMState is 'Down', no excavation can be done until the TBMState changes to 'Functional'.

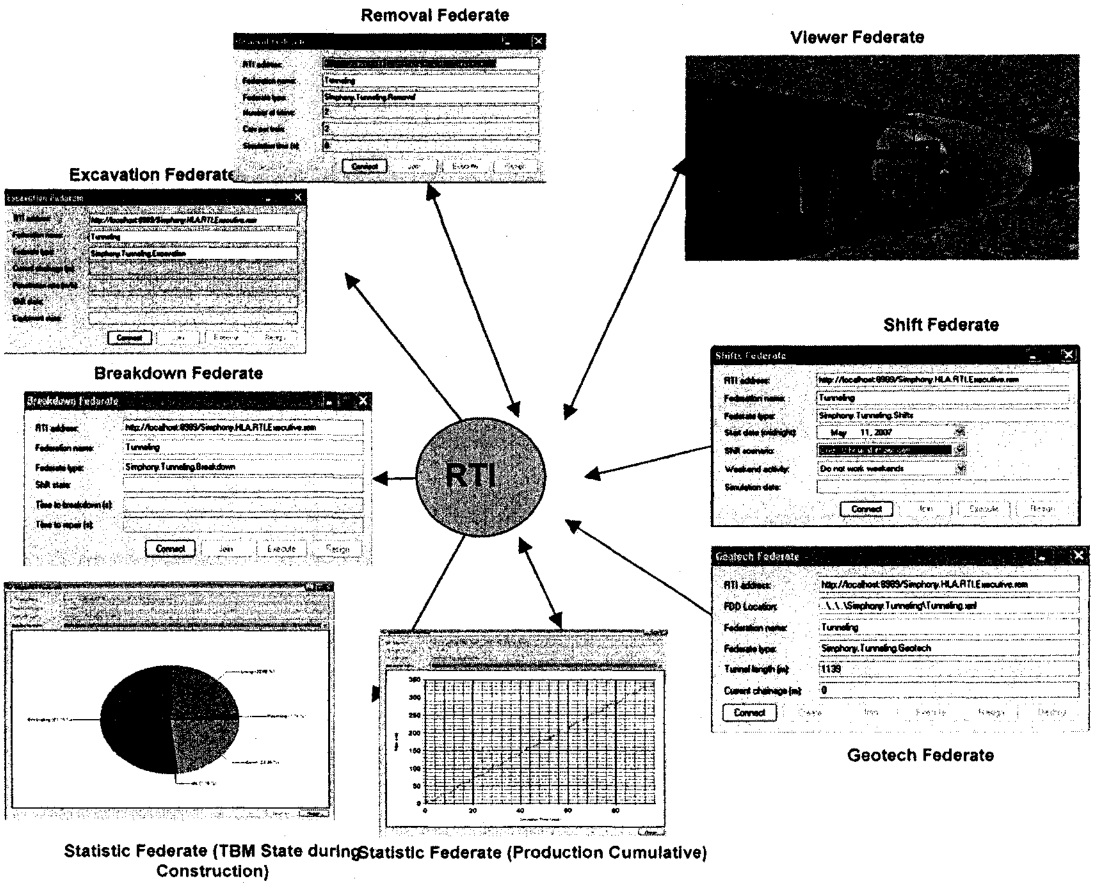


FIGURE 6-7 TUNNELLING FEDERATION

This federation can be compared to the tunnel template discussed in Chapter 4. It models the soil excavation and calculates productivity and schedule. This federation supports one way tunnelling only and dose not model start up of the excavation.

6.08 Summary

In this chapter, we presented a proposed future implementation for multi-users in tunnelling operations. Over the span of the analysis, it has become clear to us that Simphony.NET, like any current construction simulation environment, lacks the capability to tackle multi-user multi-layer problems such as the one we presented. In this project, every time a change is requested, someone has to go back, modify the simulation model, and rerun it The project team cannot use the simulation environment at the same time, which costs us a lot of time and effort to finish the job. After finishing the simulation models, a number of issues arise. This program is efficient during pre-construction estimating, but once construction is underway, a number of users will be involved in the simulation because of the dynamic nature of tunnelling operations. Each user has different interests in the simulation. For example, senior managers will be interested in end results per day, while site engineers will be interested in low-level detailed information so that they can make a decision based on this data. Simphony.NET follows the current simulation environment scheme, in which all the simulation environments were meant to tackle processes and operations rather than integrate projects with multi-user environments. Also, Simphony.NET lacks the ability to interact with users during the simulation run, which limits the real time input to the simulation. Considering the previous limitations, a new method of simulation needs to be developed to further support specific requirements. To address these issues, we presented a tunnelling simulation using CoSyE.

CHAPTER 7. CONCLUSIONS AND CONTRIBUTIONS

7.01 Research summary

In this thesis, we presented the development and successful implementation of a scenario-based planning framework and a tool for tunnelling projects. This tool was built based on simulation models in Simphony.NET. It will enable the project team to evaluate all proposed scenarios in real time manner and accelerate the selection of the best scenario during project planning phase. Scenario-based planning is a powerful approach for project planning, as it helps stakeholders to define the most efficient way to finish a project and to achieve the maximum value from the project.

This tool was built based on FIATECH's scenario-based planning vision and the variables proposed therein. The tool includes a number of FIATECH variables, such as cost, schedule, productivity, material, and resources. In this thesis, we were able to demonstrate the power of scenario-based planning in construction through the MWDB case study. We were able to automate the scenario-based planning for tunnelling projects by developing a Simphony.NET simulation tunnelling tool.

Simphony.NET is a powerful simulation tool that can be used to simulate any construction operation, especially repetitive operation type projects. In this research, we developed three SPS templates that can be used collaboratively or separately: tunnelling template, shaft construction template, and support template.

We discussed the need for scenario-based planning pre-construction workshops for all construction projects. During the workshop, the project team will define a number of scenarios, and using a simulation modelling tool, the project team can experiment with all of them in a timely manner to come up with the best scenario. We pointed to the value the project team will gain from implementing scenario-based planning for construction projects; at the end of the exercise, the project team will have a better understanding about the project they are trying to build. Also, it will help them to identify many of the risk factors that may be present in the project, and it will help them to eliminate many problems that may occur during construction by creating mitigation strategies.

We presented a future implementation of a multi-user framework for tunnelling operations. This framework is built on a CoSyE base, which in turn is built upon the concepts of the HLA. We were also successful at building a tunnelling federation for tunnel excavation.

7.02 Research contributions

By achieving the research objectives, we have contributed effectively to academic research as well as practical construction industry applications, especially tunnelling construction. These contributions can be described as follows:

- Introduced a specialized scenario-based planning process for tunnelling projects prior to construction. This process will be separated from other processes such as value engineering and constructability reviews.
- Shows the flexibility and effectiveness of simulation in project planning.
- The scenario-based planning process we presented will help the project team to evaluate and select the best scenario for constructing the project in a well-organized, structured, and easy-to-use set up. This process can be used for any construction project; it helps reduce the cost and time required to select the best scenario.
- The tool we developed to evaluate tunnelling construction projects will allow the researcher to develop other tools for other projects using a similar procedure.
- The proposed multi-user framework for tunnelling projects will open the door to apply HLA concepts in construction simulation.

7.03 Recommendations for future research

During the research into developing and implementing the scenario-based planning simulation tool, a number of items were noted as a recommendation for future research.

- Many tools have been used over the years for producing scenario-based planning, and simulation was found to be the most efficient tool of all. Current simulation environments are powerful if the problem is a single-user type problem; these environments help model real life and experiment with it to find the best solution. The simulation environments currently available fail when the problem requires input from a number of users at the same time because the simulation environments were built to tackle one-dimensional user problems and not ones that are collaborative in nature.
- The FIATECH Roadmap has a complete vision to help the project achieve their purpose in a timely, automated, and effective manner. A new simulation environment is needed to help achieve the vision of the FIATECH Roadmap. This environment should be able to support the collaborative nature of the problem. HLA-based simulation environments should be able to overcome the shortages accrued using the current simulation environments.

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APPENDIX A: APPROACHES TO ENHANCE PROJECT PLANNING IN TUNNEL PROJECTS

In this appendix, an approach to enhance scenario-based planning in tunnelling projects will be presented. This approach uses Bayesian updating techniques to update the penetration rate in real time based on data collected from project site.

Introduction

Uncertainty is an inherent part of project management. It is critical for managing large high-risk projects, but can also directly affect the bottom line of relatively routine projects. In construction, engineering uncertainty and the concomitant risks lurk everywhere: uncertain durations, uncertain cost, sudden weather changes, equipment breakdown, human resource problems, unexpected changes in project scope, and so on.

The most common casualty of uncertainty is the project schedule. Changes in the durations of specific tasks have a ripple effect on the start times of all consecutive tasks down the activity chain. Although a certain amount of contingency time is normally built in to the schedule of all projects, changes in the schedule have to be managed in a timely fashion in order to ensure the relatively smooth flow of labour and materials. This makes forecasting task execution time an essential ingredient of successful project management.

An important general observation about evolutionary processes, and construction projects in particular, is that the level of overall uncertainty normally decreases as time advances. This is due both to the decrease of the remaining project length and to the increase of the amount of available information about the project. As a result, an approach that suitably adapts the project variables to the arrival of new information could be very helpful in the adequate management of uncertainty. In this paper we employ the Bayesian method (see for example Gelman (2004), Lancaster (2004)) as an online tool for data analysis and forecast.

The Bayesian approach is a branch of the theory of random processes where the uncertain process quantities are considered random variables (r.v.) characterized by probability density functions (pdf). The approach uses the probabilistic framework to make statistical inferences about the ensemble averages of the random variables. An essential characteristic of Bayesian inference is the consistent method for updating the expected value of the r.v. in view of new evidence. Such updating can be done sequentially as the new evidence arrives and is very useful in building adaptive online monitoring and control systems.

In this appendix, we present an application to enhance project planning using the Bayesian approach to a system for monitoring the productivity in a tunnelling project and the forecasting of the progress in said project, called Construction Synthetic Environment (CoSyE). CoSyE is a discrete-event simulation system that gives the project planner the ability to produce effective project schedules and cost estimates. It allows for the simulation of all production operations with varying degrees of detail as well as modelling uncertain quantities as random draws from specified distributions.

The key element in the project is the tunnel boring machine (TBM), which drills tunnels of circular cross section. The production efficiency of the TBM is characterized by its penetration rate, defined as the distance drilled per unit of time. Knowledge of the historical penetration rate allows for the forecasting of the future position of the TBM and the ability to estimate its effect on the project schedule. The forecasting accuracy, admittedly, involves a high degree of uncertainty, being affected by changes in the soil type, variations of the water content, the degree of wear on the cutting edge, etc. Incorporation of new information as it arrives using the Bayesian method decreases uncertainty and provides a foundation for better management of project schedules.

Uncertainty modelling

Bayesian approach

The Bayesian approach has a long history of successful applications in enormously diverse disciplines (see for example Congdon (2007)). The theory is built upon a single universally accepted mathematical proposition, Bayes' theorem, which asserts that the conditional probability that event A occurs given that the event B has already occurred is given by

$$P(A \mid B) = \frac{P(B \mid A)P(A)}{P(B)}. \qquad (1)$$

For a pair of random variables X and Y with marginal probability densities $p(x)$, and $p(y)$ and conditional densities $p(x \mid y)$, and $p(y \mid x)$ the theorem is written as $p(x \mid y) = \frac{p(y \mid x)p(x)}{p(y)}$. (2)

Usually y is interpreted as the observed 'data' and often is written as y^{obs}, while x plays the role of the vector of the parameters of the model, and is denoted by θ. The normalization constant in the denominator in, the marginal distribution of the data, does not depend on θ and is, usually, ignored, which leads to the following form of the Bayes' theorem:

$$\pi(\theta \mid y^{obs}) \propto p(y^{obs} \mid \theta)\pi(\theta). \qquad (3)$$

This is a mathematical expression of the proportionality of the posterior distribution $\pi(\theta \mid y^{obs})$ to the product of prior $\pi(\theta)$ distribution and the likelihood $p(y^{obs} \mid \theta)$, i.e. $Posterior\ pdf \propto Likelihood\ function \times Prior\ pdf$. Written in this form, Bayes' theorem provides a recipe for statistical inference. Here the uncertainty about the unknown parameters θ before making the observations y^{obs} is captured by the prior distribution $\pi(\theta)$. The information contained in the observations is incorporated in the model by applying Bayes' theorem and results in the modification of the parameter uncertainty, modeled by the posterior distribution $\pi(\theta \mid y^{obs})$.

The prediction of unknown observables in the Bayesian framework is in terms of marginal distributions of data

$$\pi(y)=\int p(y\mid\theta)\pi(\theta)d\theta. \qquad (4)$$

This is called prior predictive distribution because it does not involve previous observations of the r.v. and only takes into account the uncertainty about the values of the parameters θ and the conditional uncertainty about the data y when θ are known. If the observations of a time-ordered random variable Y up to the moment t are $y_t^{obs}=(y_0,y_1,\cdots,y_t)$, then the value of a future observation y_{t+1} can be found from the posterior predictive distribution:

$$\pi\left(y_{t+1}\mid y_t^{obs}\right)=\int p\left(y_{t+1}\mid y_t^{obs},\theta\right)\pi\left(\theta\mid y_t^{obs}\right)d\theta. \quad (5)$$

Traditionally, the Bayesian relied on symbolically tractable integrals by using conjugate priors. By definition, a class of prior distributions is a natural conjugate to a class of likelihood functions if the result from their multiplication posterior is a distribution of the same class as the prior. Popular examples are the pairs Normal-Normal, Poisson-Gamma, and Normal-Gamma, among others. Although the catalogue of conjugate distributions is quite large, often, real life data is best modeled by combinations of distributions that are not conjugated. Fortunately, the increased power of computers made viable the alternative solution of numerical integration by the Monte Carlo method.

MCMC method

Integration is a key mathematical operation in the Bayesian approach. It is used to obtain the normalization constant in 3, to calculate marginal distributions as in 4and 5, and to find the expected values of quantities of interest as $E_p[g(X)]=\int g(x)p(x)dx$, where g is some function of the r.v. X, which has a known pdf p.

The general idea of the Monte Carlo approach is to draw samples $\{x^{(i)}\}_{i=1}^{N}$ of size N from a target distribution $p(x)$ and calculate the mean of the integrand over the sampled points, i.e. $\bar{g}_N = \frac{1}{N}\sum_{i=1}^{N} g(x^{(i)})$. For i.i.d. samples by the law of large numbers $\bar{g}_N \to E_p[g(X)]$ as $N \to \infty$.

Critical factors for the accuracy of the Monte Carlo approach are the quality of the random number generator, and the sampling algorithm of the target distribution p. The most popular algorithms are importance sampling, rejection sampling, inversion, and Markov Chain Monte Carlo (MCMC); see for example Andrieu (2003). The last algorithm is particularly powerful and has already been implemented in various statistical packages.

The MCMC strategy uses a Markov-chain stochastic process with a stationary distribution that converges toward the required target distribution. The generated samples $\{x^{(t)}\}$ are identically, but not independently, distributed. The draws are sequential and each one depends on the previous value drawn with a distribution $x^{(t)} \sim p(x \mid x^{(t-1)})$ for $t = 1, 2, \cdots$ determined by the transition kernel p. Thus, at each step of the simulation we possess an approximation of the target distribution which is better than the approximation at the previous step.

There are various ways of constructing a Markov chain whose stationary distribution is the required target distribution. The most popular method is through the use of the Metropolis-Hastings (MH) algorithm, which starts from some crude starting distribution and proceeds to drawing candidate points x^* from a proposal distribution $x^* \sim p(x^* \mid x^{(t-1)})$. The candidate point is then accepted with acceptance probability

$$\alpha(x^*, x^{(t-1)}) = \min\left\{1, \frac{p(x^*)p(x^{(t-1)} \mid x^*)}{p(x^{(t-1)})p(x^* \mid x^{(t-1)})}\right\},$$

and rejected otherwise, i.e. retains its last value $x^{(t-1)}$. See Gelman (2004) for more details.

For practical problems involving complicated distributions, the sampling algorithm of choice is the Gibbs sampler, which uses the full conditional distributions $p(x_j \mid x_1, \cdots, x_{j-1}, x_{j+1}, \cdots, x_n)$ at step j of iteration t. The Gibbs sampling is interpreted as a special case of Metropolis-Hastings with acceptance probability $\alpha(x^{*}, x^{(t-1)}) = 1$. This interpretation allows the embedding of MH steps in the Gibbs algorithm when dealing with non-standard distributions. Otherwise, when the full conditional distributions belong to some standard distribution class (Normal, Beta, etc.) the samples are drawn directly.

Data

The data is a subset of the information collected from the excavation of the tunnelling project SW3 executed in the city of Edmonton, Alberta, Canada using a tunnel boring machine. The project involves about 3.5 km of sanitary sewer tunnels. It started in February 2006 and is expected to finish in December 2007. The tunnelling operations are constantly monitored, and data about the production progress are collected and all interruptions are recorded.

The tunnelling operation comprises a set of activities, each one associated with a specific characteristic time. The activities sets are partitioned in cycles corresponding to the completion of one segment of the tunnel. The segment length is fixed to one meter corresponding to the length of the concrete cement liners used to cover the tunnel walls. Each cycle starts with unloading the liner blocks from the train. Usually two trains are used during the tunnel excavation, travelling back and forth in opposite directions between the entrance shaft and the face of the tunnel.

The empty train is used to collect the dirt from the excavation. After an excavation the length of one segment, the train travels back to the shaft while the TBM starts installing the liner blocks.

The loaded train dumps the dirt into a sump pocket, while the first train, already loaded with liner blocks starts traveling towards the face of the tunnel. The crane will hoist the dirt from the sump pocket to the surface, where it is stockpiled. After dumping the dirt, the crane lowers down the liner blocks for the next segment of the tunnel. This completes one cycle of tunnel operations.

There are two sources of information about the daily production of the TBM. One is a surveying system called TACS, which gives the total duration for the installation of one segment. The other is the set of daily reports of the measurement of the total daily production in meters, including project delays and interruptions. The latter also contains information about the number of work-shifts per day (normally one or two), and the length of the shifts (normally ten or eight hours). The information from the daily reports is essential for a more accurate estimation of the actual proportion of production times recorded by the TACS.

After the synthesis of the information from these two sources, the obviously erroneous records are marked as missing (NA). All records with time durations shorter than the mean support time, or longer than one day if there is no corresponding information in the daily report, are ignored. This is done algorithmically by the data cleaning module of the CoSyE.

The available data for the period between September 14, 2006 and March 5, 2007 was used for building and testing the model. There are 545 time records in the TACS database and 134 corresponding daily productivity reports. The records were divided in two: a training set with a length of 460, and a test set of the remaining 85 records. The density distribution for the time duration over the full period between September 14, 2006 and March 5, 2007 is shown in Figure A1.

Simulation framework

The CoSyE simulation environment is a .NET implementation of the HLA (High Level Architecture) standard (Kuhl et al. 1999). The HLA architecture supports creation of complex virtual environments, called federations, using distributed simulation technologies. It provides a standard for combining individual components (federates) of such an environment built by different people and maintaining the interoperability between them.

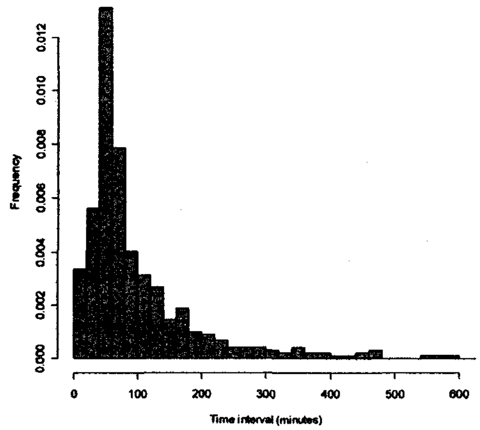

FIGURE A1 DENSITY DISTRIBUTION OF THE TIME DURATIONS

The CoSyE architecture is presented in Figure A2. Its core components are a Run Time Infrastructure (RTI) Server, an Object Model Template (OMT) editor, the system framework, and the modelling federates. The modelling federates can either be integral parts of the CoSyE system, or external software packages adding specific functionality.

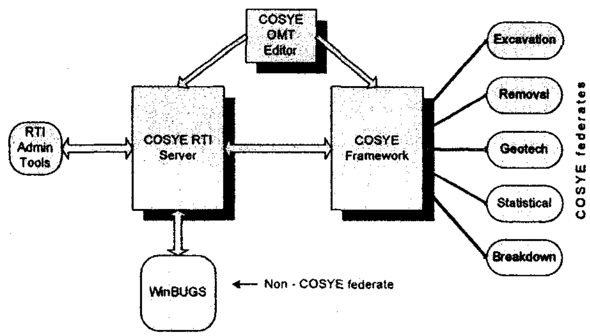

FIGURE A2. COSYE ARCHITECTURE WITH THE MODELLING FEDERATES COMPRISING THE TUNNEL BORING SIMULATION

The simulation model of the tunnel boring operations is comprised of several federates. The Excavation federate simulates the operations at the face of the tunnel, which include both the excavation and the installation of the liners. The Geotechnical federate simulates the creation of tunnel sections using the data for the penetration rate. All operations involved in the removal of the excavated dirt from the tunnel, including the motion of the trains and the crane operations, are handled by the Removal federate. Equipment breakdowns are modeled as interruptions of the normal operation flow by the Breakdown federate. The Statistical federate collects relevant information from the model federates and produces summary reports, such as total duration to finish the tunnel, production per shift, equipment utilization, etc.

The foundation of the software architecture, the HLA, was designed specifically with the purpose of integrating diverse computer simulation systems. We employed this functionality to implement the penetration rate model using a separate simulation system, called WinBUGS (Spiegelhalter 1996).

Model

The focus of the model is the uncertainty in the durations of the various production activities and their effect on the production rate of the TBM. From this point of view, all operations can be divided in two groups: production operations and supporting activities. The corresponding times spent in those operations are called production time and support time. The production time t_p is found as the difference between the total time needed to complete a section of the tunnel of length Δx (usually 1 m), minus the support time t_s spent in supporting activities. Once the production time is known, the production rate is easily calculated as the $r_p = \Delta x / \Delta t_p$ in cm/min.

Support time

The support time has several components divided into two groups, depending on the degree of the uncertainty in their estimates. All support time is measured in minutes.

The first group consists of operations with relatively low variation in the estimation of the time it takes for completion. One such component is a constant that includes the time spent in shift start-up (15 min) and shut-down (15 min) as well as the 60 min lunch time, in total $t_c = 90 min$. Another component is the time it takes the train to travel the distance d between the entrance shaft and the current position of the TBM. It is calculated from the known average train velocity $V = 5km/h$, as $t_{tr} = d/V$ and increases linearly with time.

The second group is comprised of operations with a relatively high degree of uncertainty in their time duration. Their parameters are modeled as r.v. with empirical distributions determined on the basis of historical data collected during tunnelling and the experience of personnel at the City of Edmonton (Ruwanpura et al. 1999). Two of these components are modeled by the generalized beta distribution defined as follows:

$$Beta(x;a,b,\alpha,\beta) = \frac{(x-a)^{\alpha-1}(b-x)^{\beta-1}}{B(\alpha,\beta)(b-a)^{\alpha+\beta-1}}. \qquad (6)$$

For values of x in the interval between the location parameter, a, and the scale parameter, b, i.e. for $x \in (a,b)$, and for positive shape parameters, $\alpha > 0$, and $\beta > 0$. The beta function, $B(\alpha,\beta)$, is a part of the normalization constant and is typically expressed via the gamma function as $B(\alpha,\beta) = \Gamma(\alpha)\Gamma(\beta)/\Gamma(\alpha+\beta)$.

One such high uncertainty component is the lining time, which is the time it takes to place the cement liners around the newly excavated section of the tunnel. It is modeled by a generalized beta distribution with parameters t_{lin} □ $Beta(15,25,2,5)$ graphically presented in Figure 3A(a). The time it takes to load the train is represented by symmetric generalized beta distribution $t_{load} \sim Beta(3,7,2,2)$, graphically presented in (b). The time for unloading the train is approximately four times longer, i.e. it is $4t_{load}$, so the overall contribution of the loading and unloading operations to the total support time is $5t_{load}$. The resetting time is given by the uniform distribution $t_{res} = Unif(2,4)$ and presented for completeness in (c).

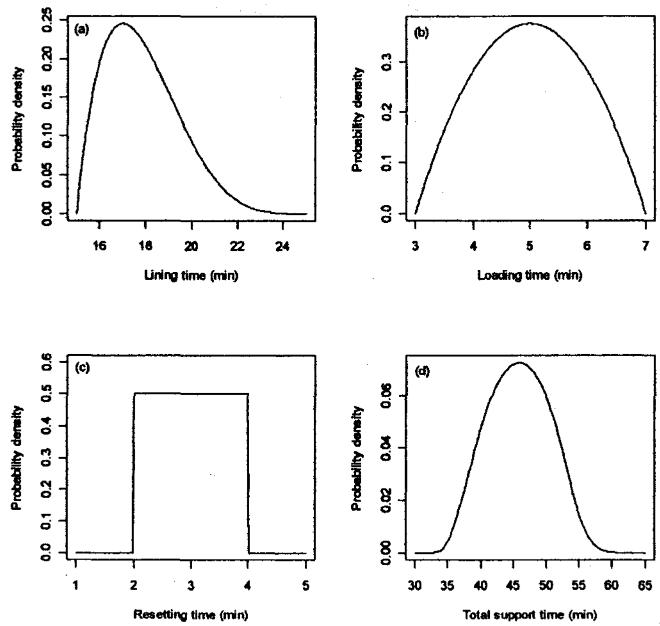

FIGURE A3 DENSITY DISTRIBUTIONS OF THE VARIOUS COMPONENTS OF THE SUPPORT TIME; (A) LINING TIME, (B) LOADING TIME, (C) RESETTING TIME, AND (D) THE VARIABLE COMPONENT OF THE TOTAL SUPPORT TIME.

The total support time t_s is the sum of all time intervals of the operations not directly involved in excavation

$$t_s = t_c + 2t_{tr} + t_{lin} + 5t_{load} + t_{res} \,. \qquad (7)$$

Bearing in mind that the last three terms are independent random variables, this expression has to be interpreted as a convolution of the corresponding probability density functions. The resulting pdf for these three components of the total support time is graphically illustrated in (d).

Penetration rate

The penetration rate r_t at time t was calculated for fixed distance increments $\Delta x = 1m$ as the ratio of the distance and production time. The latter was obtained by subtracting the support time from the observed total work-shift times recorded in the daily reports.

The data was modeled as an autoregressive process of the third order, AR(3), within the Bayesian approach as:

$$\mu_t = \beta_0 + \beta_1 r_{t-1} + \beta_2 r_{t-2} + \beta_3 r_{t-3} + \varepsilon_t, \qquad (8)$$

with normally distributed penetration rates

$$r_t \sim Normal(\mu_t, \sigma^2), \qquad (9)$$

with mean μ_t, and variance σ^2. The order of the autoregressive process was suggested by the results from initial experiments with the models of different orders. The regression coefficients β_k were also assumed to be normally distributed

$$\beta_k \sim Normal(\mu_k, \sigma_k^2), \quad k = 0, \cdots, 3, \qquad (10)$$

with mean μ_k, and variance σ_k^2 fitted to the data.

The choice of this particular model was influenced by several factors. First, it was influenced by the need to incorporate and monitor the uncertainty of the inputs to the model. The second influencing factor was the requirement for adaptive updating of the model parameters. Thirdly, given the changing underground conditions and in particular the variation of the soil type, we wanted a model that on the one side reflects the historical values, but on the other, puts a higher weight on the more recent values. Autoregressive models of the type given by adequately reflect the effect of the previous observations within the error margin ε_t. In addition, the Bayesian formulation allows the model parameters to be interpreted as random variables and the accuracy of the fit to be indirectly controlled.

The forecast of the average penetration rate for the next day was implemented as a two-step process. In the first step, all available data prior to the starting date was used to obtain the posterior distributions of the coefficients β_k of the autoregressive process, starting with non-informative priors:

$$\begin{aligned} &\beta_k \sim Normal(0,10^{-4}), \quad k = 0:3, \\ &\sigma^{-2} \sim Gamma(0.1,10^{-3}). \end{aligned} \qquad (11)$$

Afterwards, the posterior predictive distribution was found by sequential application of the Bayesian formula and informative priors for the parameters obtained from the previous iteration.

The mean values of the posterior coefficients of the model along with the corresponding standard deviations and 95% confidence intervals (CI) are shown in Table A1.

TABLE A1 POSTERIOR VALUES FOR THE AUTOREGRESSIVE MODEL AND THE CORRESPONDING STANDARD DEVIATIONS AND 5% CONFIDENCE INTERVALS

Node	*Mean*	*Std. dev.*	95% CI	
β_0	3.7820	0.5761	2.7100	4.9960
β_1	0.1392	0.0700	0.0036	0.2744
β_2	-0.0278	0.0742	-0.1878	0.1133
β_3	0.1155	0.0628	-0.0057	0.2364

Sequential application of the model to the out of sample data yields a standard error of 17%. Although the absolute value of the prediction error is significant, we consider this a promising result because of the high degree of uncertainty in the input values. Also, the large percentage of data records that were marked as missing or erroneous, 58% of the time durations in the test sample, after combining with the information from the daily reports must be noted.

Discussion

The Bayesian method provides a powerful approach to decreasing uncertainty in project timelines and incorporating the impact of new information as it arrives. We applied this method for the online calculation of the penetration rate of a TBM within a distributed software framework that combines different sources of data from the field with discrete-event simulations. Still, the simulation can be improved in certain directions. For example, different operations have a different impact on the production rate. We expect that explicit separation of these effects would not only improve the accuracy of the forecast, but would also allow users to model the mean times of the duration of the effects, such as changes in the soil type, and the rate of wear on the cutting edge of the TBM. This would also allow for the implementation of a better algorithm for filtering out the outliers in the data from the field. Finally, we are planning on developing a stochastic model for the unplanned interruptions and breakdowns that also have a significant impact on the project timelines. The model will include simulation of both the mean time of failure and the mean time to repair.

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APPENDIX B: GLOSSARY

TBM: Tunnel boring machine used for tunnel excavation

Spider Mole: TBM built by the City of Edmonton and used for tunnel excavation

Scenario (Company): A possible future based on a number of possible occurrences in the future; it should also be linked to historical events. The results are usually used for developing a company's strategic plan.

Scenario (Project): A story used to describe how we will build our project and achieve all goals been set for this project. The story should be possible and somehow linked to historical events.

Federate: A notation used by the U.S. Department of Defense to describe a simulation model, which is a part of a distributed simulation model

Federation: A notation used by the U.S. Department of Defense to describe the overall distributed simulation model, which is composed of number of federates

Template: A collection of simulation modelling elements, which will be used to create simulation models

Run Time Infrastructure: Software used to control the development of federations and federates and allow communication among these federates

Construction federates: A federate simulating construction activities such as tunnel or shaft excavation.

Supporting federate: A federate simulating an action that will be used by a construction federate, such as the weather federate