University of Alberta

AN INTEGRATED FRAMEWORK FOR TUNNEL SHAFT CONSTRUCTION AND SITE LAYOUT OPTIMIZATION

by

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ABSTRACT

A simulation-based tunneling modeling system, which was the state-of-the-art in tunneling simulation, was first developed in 2002 and has continued developing ever since. The innovative tool for decision-making has been broadly applied to tunneling projects for the bettering of construction performance. However, project engineers face the challenge of precisely evaluating and predicting tunneling behavior based on the modeling system, as shaft construction, the process significantly influencing the overall productivity of tunneling operations, was given little attention in the developed system. Moreover, the impact of well-planned construction sites during planning phases on the efficiency of tunnel construction has been recognized.

This research presents the design, development, and implementation of an integrated framework for modeling the shaft construction process and planning tunnel construction site layout in a simulation environment. A near optimum site layout is carried out through satisfying a set of identified constraints by employing genetic algorithms as the optimization engine. As another step toward the generation of a comprehensive modeling system for tunnel construction projects, the simulation tool inherits some of the existing template's features, with respect to consistency, yet enhanced with more flexibility and better extendibility. A case study from the industry was chosen to validate and illustrate the system's performance, with the comparison of performance between the original site layout and the generated one provided.

ACKNOWLEDGEMENTS

There have been a great number of truly exceptional people who contributed to my research and social life at the University of Alberta.

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LIST OF NOTATIONS AND ABBREVIATIONS

Abbreviation	Description
2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
CAD	Computer-Aided Design
GA	Genetic Algorithm
GIS	Geographic Information Systems
KB	Knowledge-Based
LS	Large Site
MS	Medium Site
NF	Number of temporary Facilities
NN	Neural Network
PF	Permanent Facility
Rnd	Random value
SPS	Special Purpose Simulation
SS	Small Site
TBM	Tunnel Boring Machine
TF	Temporary Facility
T.F.	The total fitness value for a chromosome
A_g^n	Rotating angle of facility n
C_0	Center point of Circular shaft
C_i^n	The i^{th} corner of facility n
C_i^R	The i^{th} corner of site bounding box
Cj	The j^{th} corner of the construction site polygon
d	Circular shaft diameter
d_i	Distance between a point and a line or two parallel lines
d_{ac}	Actual distance between the two facilities

d_{std}	Required distance between two facilities
$d_{\min}, d_{\max}$	Minimum and maximum distance between the reference facility and all *un-constrained* facilities
E_j	The j^{th} side of the facility
FitS	The proximity weight assigned to each a single constraint
ID	Gene's sequence number
l_n	Length of facility n
Nc	A reference value for checking facility inside site boundaries
N_G	Number of generations
N_{ch}	Number of chromosomes
N_{el}	Number of elites
Ns	Number of site edges
p	Uniform crossover contributing possibility
P_i	Possibility of chromosome i being selected for crossover
P_M	Probability of mutation
R_C	Value for seeking cut-off point
R_M	Mutation rate
Wt	Weight of the specified constraint among all other constraints
w_n	Width of facility n
x_0	X-coordinate of circular shaft center point
x_i^n	X-coordinate of the i^{th} corner of facility n
x_k	X-coordinate of the k^{th} intersection point
x_i^c	X-coordinate of the i^{th} corner of site polygon
$x_{\min}, x_{\max}$	Minimum and Maximum x-coordinates of site bounding box
y_0	Y-coordinate of circular shaft center point
y_i^n	Y-coordinate of the i^{th} corner of facility n
y_k	Y-coordinate of the k^{th} intersection point
y_i^c	Y-coordinate of the i^{th} corner of site polygon
$y_{\min}, y_{\max}$	Minimum and Maximum y-coordinates of site bounding box

CHAPTER 1: INTRODUCTION

1.1 OVERVIEW

Computer simulation has been part of the construction area in mimicking the behavior of construction activities for over a decade. Simulating in the construction domain was employed in order to assist decision makers with analyzing various construction operations and alternatives. Occasionally, simulation is integrated with other tools, such as neural network, knowledge-based system, and optimization methodologies, to extend its function so that comprehensive aspects of a problem can be represented and solved. A simulation model creating process consists of formulating the problem, establishing objectives, collecting related data, building the model, programming, and validating the system. According to AbouRizk (1990), while a real system is converted into simulation model, several assumptions are applied; some of these assumptions oversimplify the real system and do not correctly reflect the occurrence of actual events. These oversimplifications directly result in the simulation being limited to academia.

Focusing on tunnel simulation, many models have been developed in the past decade using a variety of simulating tools. Drawbacks exist with these models mainly due to the oversimplifications mentioned above. A relatively comprehensive tunneling simulation model was presented by Ruwanpura (2002), optimizing the use of tunneling equipment and predicting productivity and schedule by applying *Simphony* as the simulation tool. However, little attention was given to the shaft construction in his template, as the process was solely represented by one activity with a user-defined construction duration, such as 30 or 50 days. Feedback from the industry applying the developed template acknowledged that the shaft-modeling gap needed filling, since it significantly affects the tunneling project duration and the overall productivity.

Moreover, a proper site layout can improve the efficiency of tunnel construction operations by minimizing travel and material handling time and improving safety, as well as reduce cost. To comprehensively model a tunneling process, generating an optimum or near optimum site layout in advance is crucial. Thus, the need for the modeling site layout to augment the existing tunneling template is evident. The importance of a well-planned site layout has been recognized by many researchers and a lot of effort has been put into developing site layout models. However, none of these models focus on tunnel construction sites and most were designed for academic purposes.

The research presented in this thesis has successfully developed a shaft construction template integrated with genetic algorithms as the optimization tool for seeking a near optimum construction site layout. The template is developed using *Simphony* as the underlying simulation environment, which, as a powerful tool, supports graphical, hierarchical, modular, and integrated modeling and is thus suitable in particular for the problem at hand.

1.2 PROBLEM STATEMENTS

Having introduced the need, along with the reason, for developing a shaft construction process above, this section gives emphasis to the construction site layout. In current practice, a project engineer plans the site layout of a project at the beginning of the construction. Once the selection of temporary facilities is finished, according to the specific project, major facilities are committed to a location based on the approach site the planners have adapted to, and the rest of the facilities are located around the firstly positioned ones without questioning their locations. Often, despite many rules and considerations for laying out a site, the site planners simply use the layout of one project to fit another project. It happens so frequently that neglecting site layout planning in the early planning results in unsuitable layouts that need correction (Osman 2003). Correcting or re-planning a site layout during construction to compensate for unanticipated problems incurs costs and delays the project schedule much more than preventing it from occurring in the early phases would.

1.3 RESEARCH OBJECTIVES

The primary goal of this research is to develop a framework and a methodology for modeling the shaft construction process and planning a tunnel construction site layout. To achieve this goal, the following sub-objectives are considered.

- Identify the activities and factors influencing productivity for shaft construction.
- Develop a special purpose simulation template for shaft construction.
- Investigate the knowledge used for laying out a construction site, abstract the constraints, and formulize the representations of these constraints for the proposed site layout model.
- Expand the shaft construction template to be able to solve static site layout problems, and integrate with genetic algorithms as the layout optimization engine.
- Test and validate the shaft construction and site layout planning template's performance using an actual tunnel construction project.

1.4 RESEARCH METHODOLOGIES

To achieve the above mentioned objectives, an overall framework is proposed for modeling and optimizing shaft construction and tunnel site layout. Figure 1-1 shows the conceptual framework for the developed model.

Prior to the development of the system, many interviews were conducted with the engineers at the City of Edmonton Asset Management and Public Works Department to develop a good understanding of shaft construction activities, sequence, and methods, as well as ideas and reasons behind laying out a tunnel construction site. Literature related to theoretical models for site layout was reviewed as well to understand the problem from the perspectives of practice and theory.

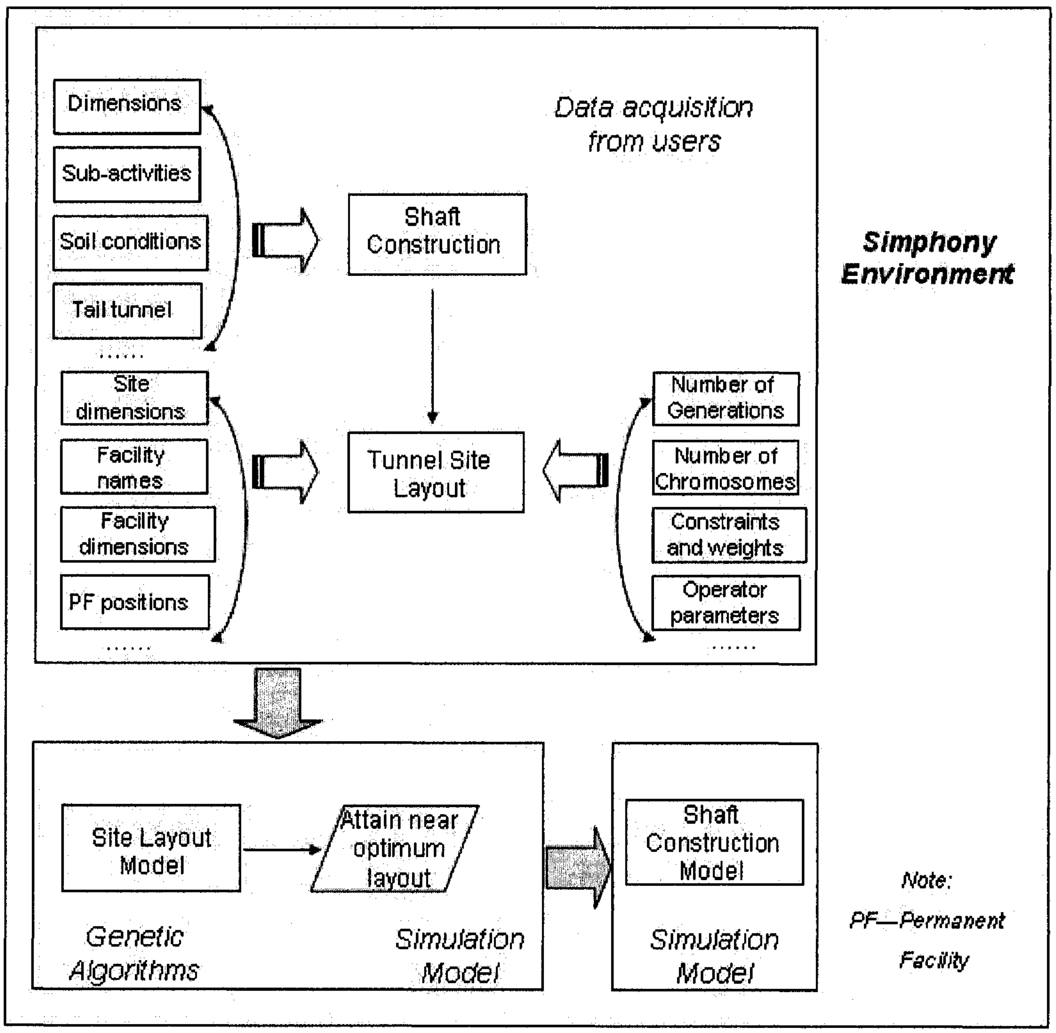


Figure 1-1 Integrated System for Site Layout and Shaft Construction

The entire system is then developed in *Simphony*, a simulation engine with details explained in Chapter 2. In the data acquisition stage, identified data items collected are classified and implemented as elements, forming the system, optimization constraints, and default values of the input parameters of the system. Furthermore, users are required to provide complete and valid information for the system; the collected information is then evaluated by the system and a warning message would be given if any of the input values is invalid or null. The programmable feature of *Simphony* was employed to enable all site-related geometrical data to be detected in the built-in orthogonal reference system. The site boundaries, tunnel centre line, and orientation arrow are coded to be created first; the optimization phase utilizing genetic algorithms is designed to be triggered afterwards. This generated site layout from simulation model thus represents a real optimum or near optimum layout in certain visual scale for the specified project, with shaft construction subsequently processed. This simulation-based modeling system is therefore designed and implemented as a platform for tunnel site layout optimization and the shaft construction process.

Simphony provides a geometric input and output interface, which facilitates users with the ability to identify the accuracy of model results. It is to be noted that instead of traditional operation research techniques, genetic algorithms are used as the optimization engine due to the nature of the problem at hand—a quite large and not perfectly smooth and unimodal search space. The objective function to be optimized for this study is based on a set of constraints, collected and abstracted from the interviews with tunnel site planners.

1.5 THESIS ORGANIZATION

This thesis consists of six chapters. Chapter 2 provides a thorough review of previous studies related to algorithms and applications of computer simulation and genetic algorithms in the construction field. Theoretical background of shaft construction process, as well as existing site layout models are two other focuses. Chapter 3 presents the shaft construction template in the *Simphony* environment, describing its methodology, design goals, structure, and modeling elements. Chapter 4 describes the proposed optimization algorithms, approaches, and functional components of the site layout planning system integrated with the developed shaft template. In chapter 5, the validation of the proposed template is performed using a tunnel construction project with a circular shaft as the case study to illustrate the developed template's functionality and usability. Chapter 6 concludes the thesis with a summary of the work along with its contributions, limitations, and recommendations for future enhancements.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

This chapter summarizes previous research and describes the background for this research. It includes four main aspects: applications of simulation in construction, underlying concepts and ideas related to the tunnel shaft, construction site layout planning, and applications of genetic algorithms in the construction domain.

Section 2.2 presents a summary of computer simulation algorithms and modeling techniques, focusing on the simulation modeling engine used in this study and construction related research conducted in recent years. Section 2.3 introduces the basic concepts and definitions of tunnel shafts, as well as historical and general excavation and support methods adopted. Section 2.4 reviews a number of approaches toward construction site layout modeling, and the merits and limitations of each. In the last section, Genetic Algorithms, the optimization approach implemented in this study, is briefly described and the applications in the field of construction are briefed as well.

2.2 APPLICATIONS OF SIMULATION IN CONSTRUCTION

Computer simulation is defined by Pristker (1986) as the process of designing a mathematical-logical model of a real world system and experimenting with the model on a computer. Simulation has proved to be a valuable analytical tool for a number of situations where no tractable mathematical model exists, including examining the interaction between flow activities, determining the idleness of productive resources, and estimating production of the system, since it provides a fast, easily-manipulated, economical way and risk-free environment to experiment with different alternatives and approaches without changing the systems themselves.

2.2.1 Simulation Methods

According to AbouRizk and Hajjar (1998), simulation systems are classified based on the underlying simulation algorithm of the developed system. Three of these algorithms are prevalent in construction.

- Static simulation algorithms describe systems mathematically where the potential effect of each alternative is ascertained by a single computation of some equation. The system does not take into account time-based variances or synergistic interactions of resources. It is useful for developing statistical distribution information about a system.

- Discrete-event simulation algorithms utilize the "next event processing" of activities based on the logical relationships between process components and the availability of resources (AbouRizk and Hajjar 1998). Discrete entities change state as events occur in the simulation; time between events in a discrete event model is seldom uniform.

- Continuous algorithms are often represented with a system of equations or mathematical models and then solved for steady state performance using differentiation, integration, or by approximation. The dependent variables of the model may change continuously over the simulated time.

Both discrete-event models and continuous models are dynamic in nature. While a static model involves a single computation of an equation, dynamic modeling, on the other hand, constantly recomputes its equations as time changes. A number of discrete-event simulation techniques have been successfully applied in modeling construction processes. This is because simulation can realistically model the probabilistic nature of operation duration by randomly sampling durations from specified probability distributions, and the discrete nature of resource flows in a process including repetitive resource flows.

Furthermore, users can simulate different construction process alternatives involving various configurations of resource selections and resource flows (Odeh 1992).

2.2.2 Simulation Tools

In general, approaches used to simulate a construction process can be categorized as: general purpose programming languages, general purpose simulation systems and special purpose simulation systems (Odeh 1992). Using the first approach results in a stand-alone model with little flexibility, being costly, time-consuming to build, and difficult to implement in the industry. General purpose simulation has been used to model construction processes (Ashley 1980), but drawbacks exist, such as the inability to easily model multiple resource requirements typical for construction operations, making the modeling task difficult. Hence, the emphasis in this section is given to the last two approaches.

Halpin (1977) popularized the use of simulation in construction research with his invention of a system named CYCLONE (CYCLic Operations Network). CYCLONE is an example of a discrete-event simulation algorithm used to analyze the movement of resource units around the site, which has led to the wide acceptance of construction-process modeling (Sawhney 1998). Despite some weaknesses, this oldest and most widely used construction simulation tool, using a set of abstract but simple constructs, became the basis for a wide range of construction simulation research efforts with the objective of enhancing the basic system functionality and development of other construction simulation systems.

The COOPS (Liu 1992) (Construction Object-Oriented Process Simulation System) simulation model is a precedence network with objects of nodes, links and attachments. It extends some modeling capabilities of CYCLONE, and at the same time inherits many of CYCLONE's modeling difficulties.

CIPROS (Odeh 1992) is a knowledge-based construction planning simulation system that makes ample use of a hierarchical object-oriented representation for resources and their properties. It integrates process-level and project-level planning by representing activities through process networks, all of which can use a common resource pool (Martinez 1998).

STROBOSCOPE (Martinez and Ioannon 1994) is a simulation programming language designed for modeling complex processes common to construction engineering. It is based on three-phase activity scanning and not process interaction.

DISCO (Huang 1994) extends the capabilities of CYCLONE by providing a graphical environment where the modeling of construction operations can be constructed in an interactive manner. The processor animates a simulation by "playing back" various statistics as they occurred during simulation.

Although CYCLONE and its successors made the modeling process relatively easy, most of the applications remain at the academic level because of their inherent limitations (Hajjar and AbouRizk 1998). In order to facilitate the use of computer simulation by industry practitioners, a simulation platform for building general and special purpose simulation models known as *Simphony* was developed under the Natural Science and Engineering Research Council (NSERC)/Alberta Construction Industry Research Chair Program in Construction Engineering and Management. It is a Microsoft Windows based computer system developed with the objective of providing a standard, consistent and intelligent environment for both the development as well as the utilization of construction special purpose simulation (SPS) tools (Hajjar and AbouRizk 1999). SPS is defined as "a computer based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the framework, creation of model specifications, and reporting are completed in a format native to the domain itself" (Hajjar and AbouRizk 1998). Developers can use *Simphony* to implement highly flexible simulation tools that support graphical, hierarchical, modular, and integrated modeling with great ease, while users have access to a single program that allows them to build simulation models in an intuitive and user-friendly manner (Hajjar and AbouRizk 1998).

Many SPS tools have been developed following *Simphony*; including the Earth Moving Template, Site Dewatering Template, Range Estimating Template, Aggregate Crushing Template, Project Scheduling Template, Tower Crane Template, and the Tunneling Template. Construction companies have demonstrated the acceptance of *Simphony* as a simulation tool for everyday decision making.

2.2.3 Tunneling Simulation Applications

Many tunnel construction operations are repetitive in nature, thus tunnel projects are especially suitable for the application of simulation. Many simulation models have been developed and widely used to predict or evaluate the tunnel construction process. CYCLONE was implemented by Touran (1988) and Tannaka (1993) to predict in advance the rate of a small diameter tunnel in soft rock and to assess the behavior of shielded tunnel boring machines respectively. Ruwanpura (2002) presented a template to optimize the use of tunneling equipment and predict productivity, cost, schedule, and resource utilization by applying *Simphony* as the simulation tool. Although much progress has been achieved from this previous research, most of the applications gave little attention to shaft construction, the duration of which could span up to three months.

2.3 TUNNEL SHAFTS

2.3.1 Introduction

For most tunnels, the sinking of a shaft for temporary working access is the first operation. Tunnel shafts can be temporary or permanent: temporary shafts serve a variety of functions including equipment and personal access and egress for tunnel muck, and are abandoned after functioning during construction; permanent shafts are used for ventilation, conveyance of liquid, pipes and cables in river crossings, drainage and pumping, temporary storage, and treatment of sewage (Megaw 1983).

Shafts serving permanent functions are sized for their ultimate purpose. If the shafts are used for construction purposes only, size may depend on the type of equipment that must use the shaft. Typical diameters are between 5m (16.4ft) and 10m (32.8ft) which can accommodate materials, a safety ladder for man access, and the largest single component of construction equipment (Jenny 1982). Temporary shafts in soft ground are mostly circular in shape (Jenny 1982). Shallow shafts through overburden are often large and rectangular in shape. In this section attention is given to the vertical instead of inclined shaft, which is mainly used.

2.3.2 Excavation and Support Methods

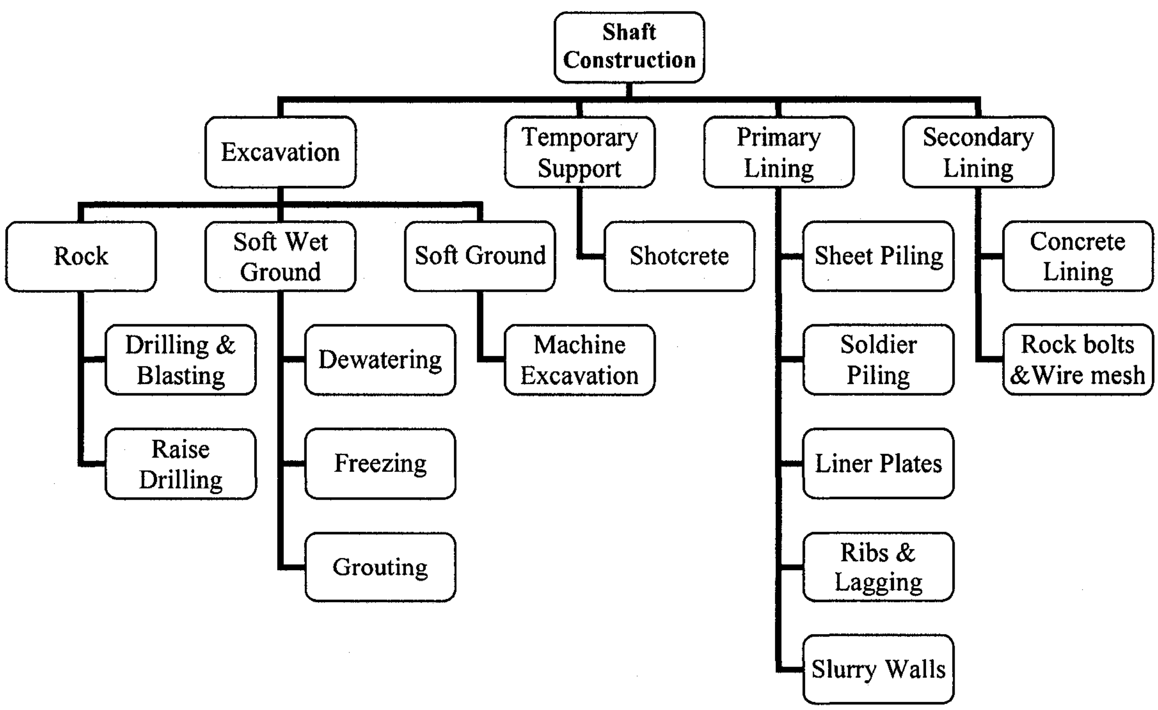


Figure 2-1 Structure of Shaft Construction Strategy

Shaft construction involves a number of interrelated operations. Major operations are excavation and primary lining, as well as lowering ground water and secondary lining if required. Figure 2-1 illustrates structure of shaft construction strategy.

Drilling and Blasting Method

Shaft excavation in rock is usually performed by the drilling and blasting method. The drill and blast process is a cyclic operation (Likhitruangsilp 2003). A series of small blast holes are drilled, which are subsequently loaded with explosives. The explosives are then detonated. After blasting, mucking is usually carried out by a crane with a clamshell bucket. Shaft blasting tends to be more difficult and more confined than tunnel blasting. This method is preferred due to the existence of plenty of skilled workers and the low capital costs of equipment.

Raising Drilling Method

Raises are excavated by downward or upward pilot bores, then reaming the hole up or down to the proper diameter. The stable ground required method is sometimes used in urban area tunnel construction to minimize surface disruption.

When difficult shaft construction conditions are predicted, ground improvements including dewatering, freezing, and grouting are often advisable. These methods are usually performed before the shaft sinking commences.

Dewatering

Excavation in soft, wet ground can be accomplished in a number of ways; the most common method is to lower the groundwater table in the working area (Jenny 1982). Dewatering can be performed by deep wells or WellPoint systems for shaft construction. Deep wells are usually cheaper than WellPoint and are used only when pervious strata is encountered; the WellPoint system is limited to 15 feet (4.57 meters) in depth when dewatering and the system must be within the area of construction. On the other hand, the dewatering operation could result in lowering the water table in adjacent areas.

Freezing

Deep groundwater usually cannot be controlled by dewatering; however, grouting or freezing can be tried. The procedure consists of sinking pipes around the area to be excavated and circulating a cold brine solution through the pipes, thereby freezing a wall of soil (Jenny 1982). Freezing is adaptable to any shape, size, or depth; on the other hand, the process requires at least two months to complete.

Grouting

Shaft grouting typically starts with drilling rows of grout holes around the shaft perimeter, grout injection is then performed in the zones from the bottom up, using packers. Freezing is more reliable, though more expensive since some areas may be left ungrouted.

Machine Excavation

Circular shafts with large diameters or rectangular shafts are excavated using backhoes and dozers, as well as cranes used for muck hoisting. Small shafts in soft ground are normally excavated by augers and bucket excavators mounted on a Kelly (the rod running through the table that tools are attached to). Up to 75m (246.06ft) in depth and 8m (26.25ft) in diameter can be achieved by this means.

In sedimentary, fractured, or blocky rock, where the ground has insufficient stand-up time to allow the construction of primary lining some distance below the face, some form of temporary ground support is required (Whittaker 1990). Temporary support is installed concurrently with the excavation. Most commonly used methods are shotcrete, rock bolts and wire mesh; steel ribs and liner plates, or steel ribs with lagging, which are known as primary lining methods.

ShotCrete

Shotcrete, or sprayed concrete, has some desirable characteristics including the ability to be applied immediately to freshly excavated rock surfaces and to have the applied thickness and mix formulation suit the variations of the ground when used as a temporary support in rock tunnels in conjunction with rock bolts and wire mesh. However, reinforcement is always applied to give it toughness and strain capacity in tension. This brittle material leads to the placement of a concrete secondary lining.

Once the shaft has been excavated, the opening generally requires some form of primary support (lining) to retain its stability. The rate of installing linings is dependant on lining type and soil nature. The selection of primary support is a major decision in tunnel projects because the cost typically ranges from 15 to 50 percent of the total tunneling cost (Golder Associates 1976).

Sheet Piling

Timber sheet piling is a traditional and inexpensive support method for shaft construction. Timbers are driven into the ground and excavation is performed concurrently, then horizontal rib sets are installed against the interior of the sheeting. This economical method is limited to soft material and a depth of only 20 feet (6.1m). If the shaft is deeper than 20 feet (6.1m), steel sheet piling can be applied. Interlocking sheet piles are driven vertically to the ground to hold back earth and prevent water. Excavation is usually not started until the driving operation is completed (refer to Figure 2-2).

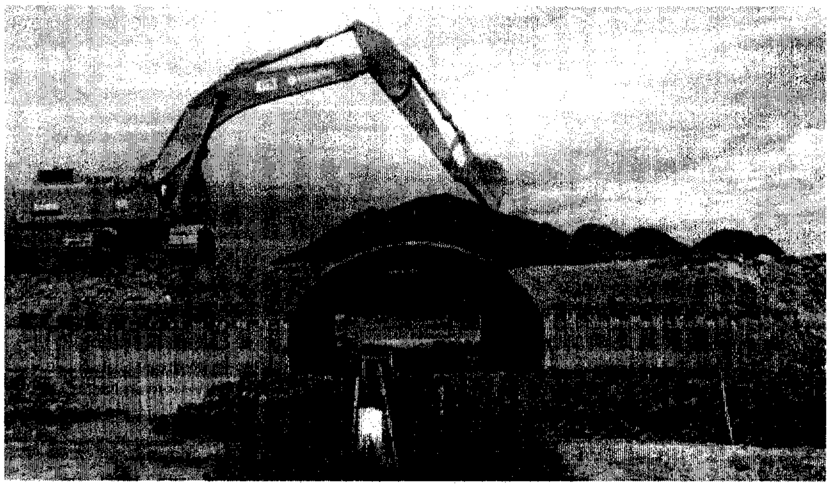


Figure 2-2 Application of Steel Sheet Piling
(www.cspi.ca/english_files/_handbook/chapter14.pdf 2005)

Soldier Pile and Lagging

Soldier pile and lagging is a common support method in urban areas. H-piles are vertical steel elements; spaced at 1.8m (5.9ft) to 3.0m (9.8ft). Horizontal timber lagging is placed against the face of the excavation and wedged between the flanges of the soldier piles. The method can be used in soils which are above the static ground water table or have been dewatered and exhibit sufficient arching potential to permit lagging (Macnab 2002). Soldier piles can be driven, or drilled and concreted. The piling method is selected on the basis of the soil conditions and vibration requirements. Drilled and concreted soldier piling will be detailed in Section 3.2.2.

Liner Plates

The liner plate method starts with precisely erecting the first ring on the ground and placing a collar around it, followed by excavation and plates being added progressively to the required depth of the shaft. The space between plates and soil is promptly backfilled when excessive soil is removed. This method is especially suitable for small shafts.

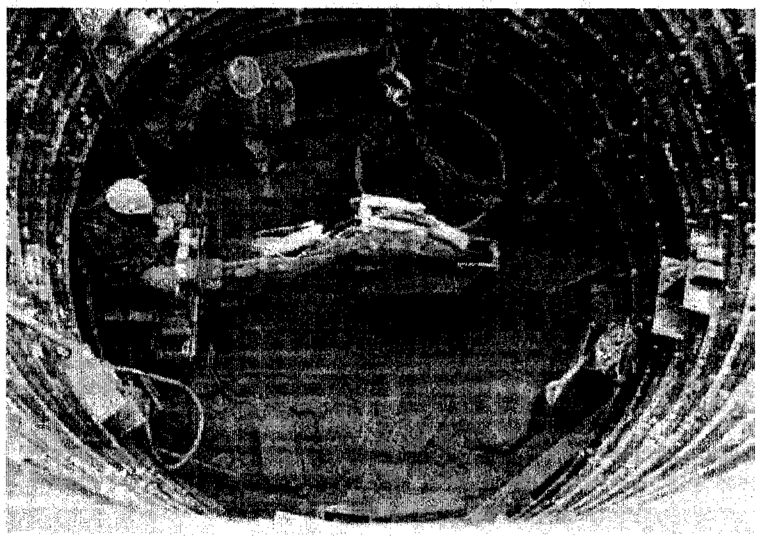


Figure 2-3 Liner Plate Shaft Construction
(www.cspi.ca/english_files/_handbook/chapter11.pdf 2005)

Ribs and Lagging

The horizontal ribs and vertical lagging method is somewhat similar to that of the liner plates (Jenny 1982). Excavations to a distance equal to the length of the lagging (usually 6ft (1.83m) to 8ft (2.44m) timber) are required for this method. Curved ring segments made of structural steel are bolted together and held in place by tie rods and spacers. The vertical lagging is subsequently placed (see Figure 2-4). Timber ribs and steel lagging are used occasionally. This method is applicable in cohesive soils due to the self-supporting interval required.

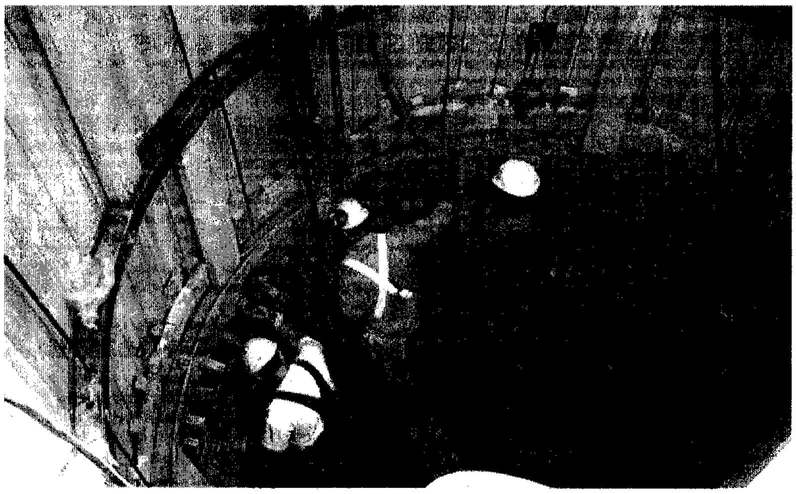


Figure 2-4 Ribs and Lagging Shaft Construction (City of Edmonton 2005)

Slurry Walls

This is an alternative to sheet piling in relatively shallow shafts through soft ground, particularly granular soils (Megaw 1983). Narrow trenches are excavated where the shaft is to be located, supported by the use of bentonite suspensions; concrete is then placed with the aid of a tremie pipe and displaces the slurry already in the trench. The shaft can then be excavated with reinforced steel in the trench if desirable.

Secondary Linings are required if the shafts are permanent in nature. Erosion and corrosion protection for the primary lining and further waterproofing may also be required, all of which are provided by secondary linings (Whittaker 1990). The shafts are usually concrete lined.

Concrete Segments

Concrete linings, derived from cast iron linings, can be divided into pre-cast segmental lining and cast in situ lining. An advantage of pre-cast segmental lining over in situ is that in wet and difficult ground each segment can be set in place with minimal excavation and the whole ring will immediately develop its full strength in resisting compression as soon as all its segments are in place (Megaw 1983). For the ground where soils can temporarily self-support, in situ concrete is probably the most widely employed lining for deep shafts on account of its substantial advantages in being easily adaptable to varied conditions and avoiding the problems regarding the manufacture, delivery, and storage of segments (see Figure 2-5).

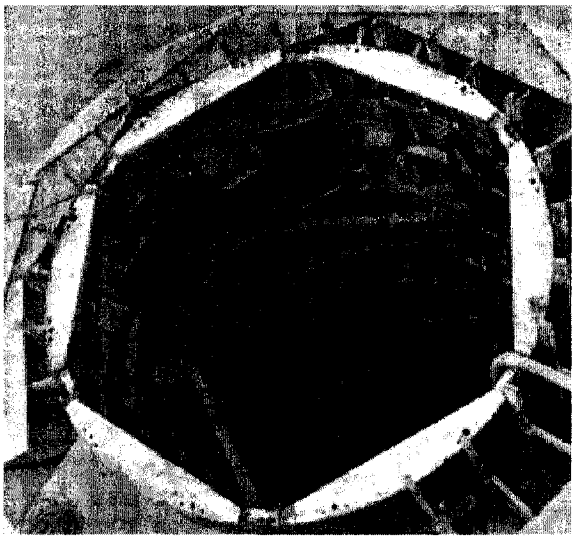


Figure 2-5 Forms for Concrete Shaft Lining (Mayo 1968)

Rock Bolts and Wire Mesh

Rock bolts are used to secure locally loosened blocks of rock, or in a systematic way, at predetermined spacing, to restrain loosening and plastic deformation in the arch of a tunnel, alone or in conjunction with shotcrete in both forms (Mason 1982). The main function is to use its inherent strength (arch concept) to make a rock mass support itself. The length and pattern of the rock bolts vary according to the quality of the rock mass. Wire mesh reinforcement is used to slow down the formation of failure and have it repaired without catastrophic consequences. However, the installation of wire mesh becomes an extremely time-consuming operation.

2.3.3 Undercut and Tail Tunnel

Another important feature of shaft construction is the provision of a tail tunnel at the termination shaft to accommodate the launch. The area and length of a tail tunnel are mainly influenced by the equipment required for constructing the tunnel. Excavation of the tail tunnel usually starts with a small opening in the shaft from where a short timbered heading is driven. During construction, great care needs to be taken since the ground is already disturbed by sinking the shaft.

An undercut is an enlargement area at the bottom of the shaft connecting the tunnel face and the main tunnel, which is used for staging material handling and dirt removal operations. For a two-way tunnel, certain portion of the undercut function as the tail tunnel to accommodate equipment.

2.4 MODELS AND METHODS FOR CONSTRUCTION SITE LAYOUT

Construction site layout and the benefits from laying out a site well, defined by Tommelein (1989), are

"Identifying the facilities that are temporarily needed to support construction operation on a project but that do not form a part of the finished structure; determining the size and shape of these facilities; positioning them within the boundaries of the available on-site or remote areas."

"The so-called temporary facilities usually remain on site for a period ranging from a few days to several months or even years, a time period that ranges from the duration of a construction activity to the duration of a major phase of the entire construction period."

"A well-organized site facilitates inventory control, cuts travel times, reduces noise and dust, prevents obstructions and interferences, increases safety and security, and improves site access."

As well, she summarized the principles, considerations, and criteria affecting a site layout, shown as Figure 2-6.

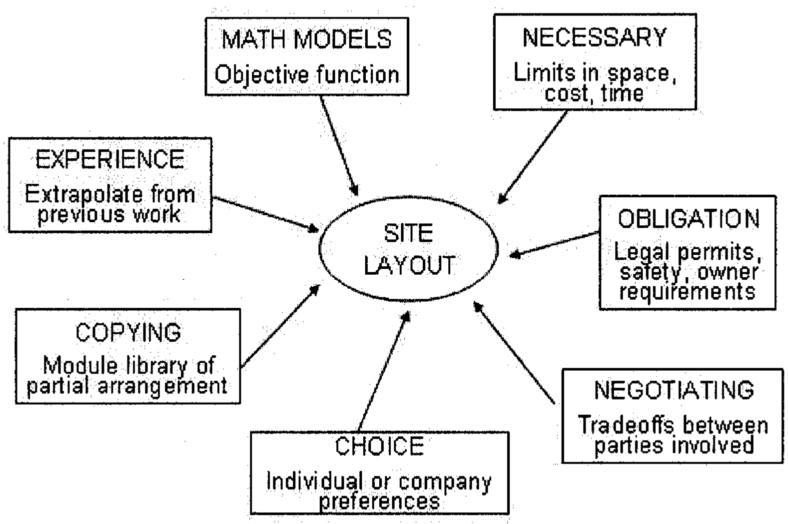


Figure 2-6 Principles, Considerations, and Criteria that Affect Site Layout (Tommelein 1989)

Efficiently using site space to accommodate resources throughout a construction project is fundamental to the success of any project undertaking, thus the issue has attracted many researchers' attention and various site layout models have been developed using different methodologies and assumptions. Based on the performance, Tommelein (1989) classified site layout models into two categories: physical models and computational models. In this section, a review of several types of models assisting with the layout of construction sites will be provided.

2.4.1 Physical Models

Physical models represent properties of the entity to be represented in such a way that the entity and its representation have the same visual appearance; that is, to a human viewer they look alike (Tommelein 1989). The most commonly used physical models are engineering drawings, templates, previously designed sites, two-dimensional scale models (2D), and three-dimensional (3D) scale models (see Figure 2-7). Templates and facilities on computer drawings are easy to be moved around to achieve a satisfying layout, and they were widely adopted by site planners in a certain period. The emergence of 3D models updated the physical models' history by scaling all spatial relations between the modeled parts of the reference. However, high cost and difficulty in maintenance and updating prevent physical 3D models from being commonly used in practice (Sadeghpour 2004). These physical models, in general, helped site planners with exploring different layout generations, however, neither do they provide any guidance towards which generation to select, nor are evaluation scales or standards purveyed to site planners with learning and comparing.

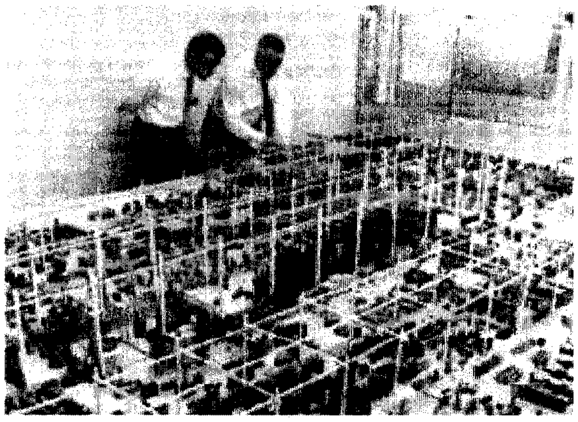


Figure 2-7 Three-Dimensional Iconic Model (Francis 1974)

2.4.2 Computational Models

Computational models, defined by Tommelein (1989), are methods applied to the input of a problem in order to generate a solution; the models have no physical appearance besides that of the code implementing them. Several ways of categorizing computer models have been adopted by researchers. Francis (1974) classified layout models as applying construction algorithms and improvement algorithms according to the way the final layout is generated. Construction algorithms consist of the successive selection and placing of one object at a time until a layout design is achieved. Improvement algorithms, on the other hand, start with creating an initial complete layout, modifying the layout to generate an alternate one, evaluating both layouts and identifying the best solution accordingly.

Depending on the factors the models consider, computational models can be classified as *facility to layout assignment* and *facility to location assignment*. The *facility to location assignment* neglects the dimensions of the facilities and all facilities are assumed to be able to fit in all locations. To apply this method, sufficient site space is necessary to allow the facilities being abstracted to points comparing with the site size. As such, the method is especially suitable for a single facility. The assumption has been adopted by many researches when they identified construction site layout problems. Yeh (1995) assigned n resources to n available positions in order to minimize the operation and setup cost. He formulated the problem as a discrete combinatorial optimization problem and a neural network was applied to generate a site layout alternative. Li and Love (1998) introduced a genetic algorithm system finding an appropriate arrangement for placing a set of predetermined facilities into a set of predetermined spaces on site, under the assumption that each place is capable of accommodating the largest one among the facilities and the number of places is equal to or greater than the number of predetermined facilities. Tam, Tong, and Chan (2001) developed a genetic algorithm model to optimize tower crane and supply locations, the major facilities for high-rise building construction; with the crane, supply, and demand items each represented as points. Although the model offered some superiority over the traditional approaches, the authors admitted that they oversimplified the site space allocation and the positions of tower cranes and neglected the interdependent and space competition relationships between site facilities. Similarly, Cheung and Tong (2002) proposed a model using genetic algorithms to search for a solution with a minimum total cost for a pre-determined daily output after assuming that the geometric layout of available locations was predetermined and fixed that and each of the predetermined layouts was considered capable of accommodating the largest one among the facilities. The common assumption for these models is weakened by the fact that there are usually substantial differences in size among most construction site facilities (Osman 2003).

In contrast, the method of *facility to site assignment* assigns a set of predefined facilities to any available space on site. The *facility to site* problems, also recognized as *facility to layout* problems, are occasionally considered as a special class of *facility location* problems, since the *facility to layout* problem consists of the determination of the facilities location as well as a determination of the size and the configuration of the facilities (Francis 1974). The method proposed in this study tackles the positioning of temporary facilities on a tunneling construction site as a *facility to layout* problem, and according to the way the final layout is generated, improvement algorithms are applied.

Computational layout models, in general, derive from mathematical optimization techniques and succeed in laying out a limited number of facilities; the models were gradually replaced by heuristic models due to the limitation and complexity when applied. Heuristic approaches have been used to solve the larger size problems of site layout; the method distinguishes the good from the better solution, but does not guarantee that the best solution will ever be obtained (Tommelein 1989). Later, some optimization techniques based on artificial intelligence (AI) were applied to solve site layout problems and continue to be of high interest today. The main notion in AI systems is their ability to deal with missing, inexact, and poorly defined problems (Sadeghpour 2004). A review of the models widely used for dealing with layout problems based on an AI system or conventional systems is presented in the following text.

2.4.2.1 Knowledge Based (KB) Models

Construction site layout problems often require considering an immense amount of incomplete, imprecise and vague information distributed across many variables. In this regard, knowledge-based approaches appear quite promising. Knowledge-based systems apply theoretical information and practical domain-specific knowledge from human experts to solve layout problems. A knowledge-based system is normally constituted of two parts, represented in a declarative fashion specifying the problem-solving process and a knowledge processor manipulating the knowledge and applying it in the appropriate circumstances. Consequently, a knowledge–based expert system is free to apply that knowledge (Hamiani 1987). Those in favor of this approach believe that the knowledge of experts combined with computer power would augment human decision-making and outperform the computer implementation of general heuristic principles (Zouein 1995).

One of the earliest applications of knowledge-based systems in solving site layout problems is CONSITE (Hamiani 1987). A structure of the system is shown in Figure 2-8. The prototype system was implemented in a knowledge engineering environment and uses knowledge representation, which is a mix of frames, production rules, object-oriented programming, and a plan-generate-and test strategy to construct the layout. The system starts by identifying the facility to be entered, ordering the list of layout objects beforehand based on the priorities experts would give to the facilities; then it generates possible positions for the selected facility, identifies location constraints and tests the feasibility of the generated locations. The final positions of the facility are accordingly selected. Convex polygons were used to represent site and temporary facilities. CONSITE has the advantage of being able to locate facilities under multiple constraints;

however, no detailed explanation was provided on how final positions were selected and no different levels of importance were adopted to evaluate the constraints.

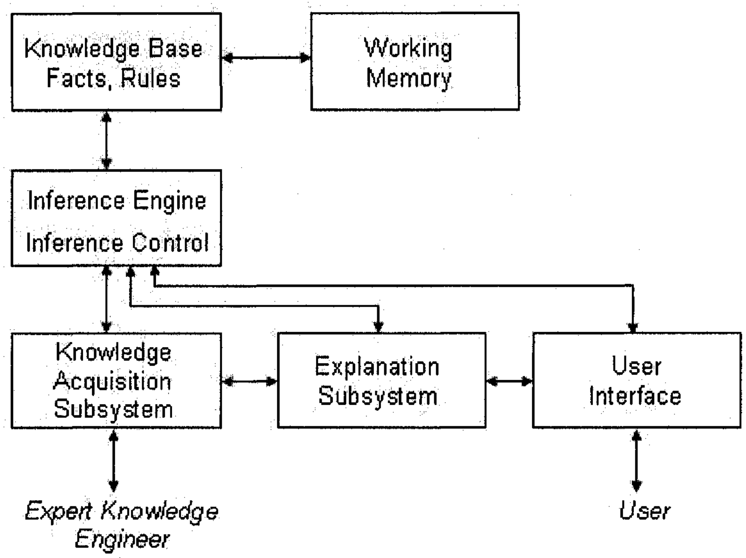


Figure 2-8 Architecture of Knowledge-Based Expert System (Hamiani 1987)

SightPlan (Tommelein 1989) is another application of a knowledge-based system in solving construction site layout problems. It follows constructively assembling arrangements by positioning one facility at a time. By applying independent and domain-specific knowledge sources, SightPlan solves a problem cooperatively through storing and exchanging solution elements on a global data structure. It uses procedural constraint processing to achieve the solution. Nevertheless, as a typical application of heuristic algorithms, SightPlan lacks a mechanism that would allow for "backtrack" in execution cycles and thus may result in failure in finding the layout solution when it does exist.

A graphical and interactive decision support tool named MovePlan for creating dynamic layouts spanning the project construction was developed following SightPlan (Tommelein and Zouein 1992, Tommelein and Zouein 1993). In a MovePlan model, the activity schedule is augmented along with resources required to perform activities and dimensions of the resources. The augmented schedule then drives the dynamic layout process by moving facilities, materials and equipment on site. Users are asked to change the schedule when there is not enough space on site.

The space conflict problem of MovePlan was alleviated by MoveSchedule (Zouein 1995), an extension of MovePlan. The system uses time-space tradeoff strategies that modify the schedule to vary the demand for space at a given time through heuristics algorithms. MoveSchedule solved a constrained dynamic layout problem with the objective of minimizing resource transportation and relocation costs. Instead of assuming a constant space need for all the resources on site through the project construction like MovePlan, in MoveSchedule the consumption rate of resources was modeled. The system is especially efficient for large projects.

Although applied a lot, the procedure of knowledge-based systems proved difficult to be structured. Hamiani (1987) recognized the difficulty of knowledge acquisition as the bottleneck of knowledge-based system development. Mawdesley and Al-jibouri (2002) summarized the drawbacks of applying knowledge-based models to solve site layout problems:

- They rely on the generation of a knowledge base that will allow choice between various geographical layouts. This has proved difficult to produce for real projects.
- The integration of the scheduling procedures with the geographical aspects to generate the site layout has proved difficult.

2.4.2.2 GIS Based Models

According to Jeljeli and Russell (1993), the geographic information system (GIS) has the ability of collecting spatial and non-spatial data from different sources, then storing, analyzing, and presenting the data systematically. Hence, Cheng and O'Connor (1994) developed a system called ArcSite comprised of GIS, a knowledge-based system, and database management systems to identify suitable areas to locate temporary facilities on the construction site. The system was developed to achieve these four objectives:

- Obtain the knowledge and procedures that project managers use in laying out the temporary facilities.
- Model experts' knowledge and experience of site planning and express it in a systematic form.
- Define the dominant variables and develop an evaluation method to identify the suitable location for the temporary facility.
- Develop a GIS-based site layout system to replace manual methods.

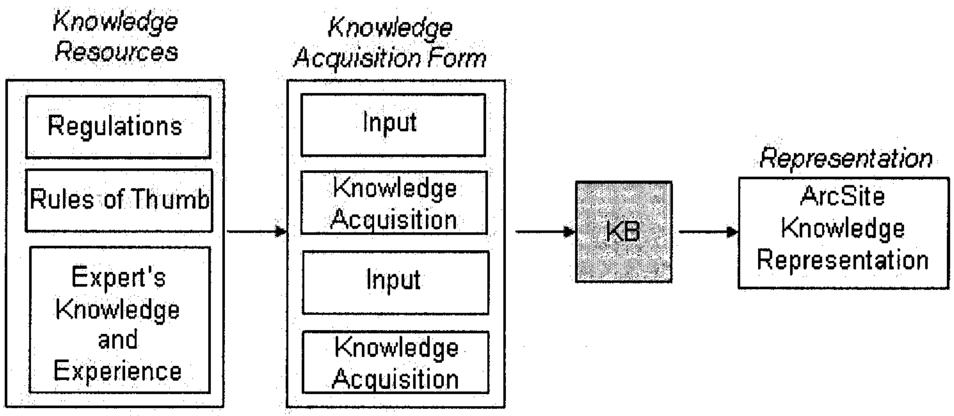


Figure 2-9 Procedures of Knowledge Acquisition and Representation (Cheng and O'Connor 1994)

The heuristic approach was used to help in the modeling of the process of human decision-making and to identify the spatial relationships between the different data layers that represent site geographies. The system starts with knowledge acquisition and representation (refer to Figure 2-9), which is acquiring, interpreting, and translating experts' knowledge into a systematic form. Then, after assessing the needs of the user (design, pre-construction planning, and during construction), the requirements are translated into system functions. A hierarchy of the sub-modules of the temporary facility layout design function can be seen from Figure 2-10. To determine the optimal site, Proximity Index, the sum of the product of the distance and relationship rating between facilities was used to rank the identified potential sites. Constraints defined in ArcSite are distance, adjacency, position, accessibility, and the space required for each facility. The similar heuristic approach was later on used in developing a system named MaterialPlan to identify optimal areas for locating construction materials.

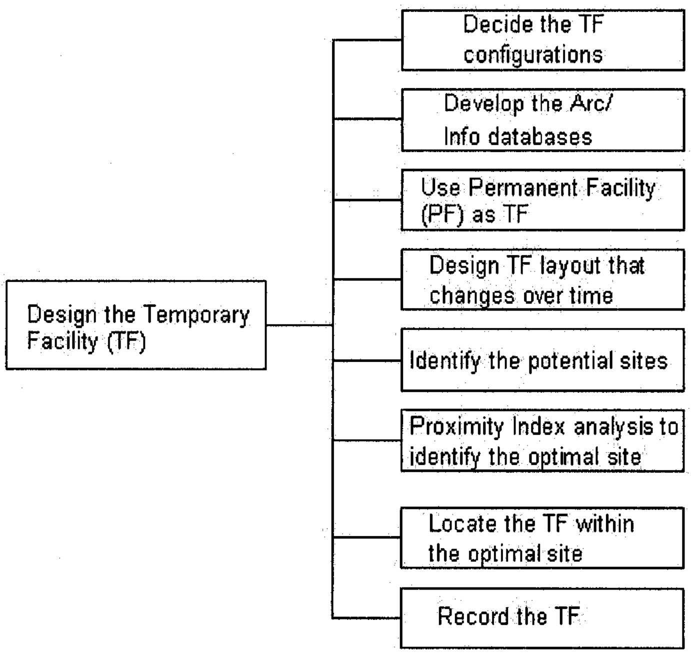


Figure 2-10 Temporary Facility Layout Design Functions
(Cheng and O'Connor 1994)

2.4.2.3 Computer-Aided Design Based Models

Mahoney and Tatum (1994) reported the potential benefits of using Computer-Aided Design (CAD) on construction site operations, as adopting the system allowed for the easy, quick, and accurate visualization of construction operations and the interaction between permanent facilities and temporary facilities on site. This feature leads to many attempts to employ CAD on site layout problems. Sadeghpour (2004) developed a CAD-based model for site layout planning aiming at searching the optimum geometrical layout according to the users' requirements. The system supports user-system interaction to utilize the users' experience and knowledge by providing a set of objects, including site objects (permanent facilities), construction objects (temporary facilities), and constraint objects for users to select from. A set of relations between facilities, such as "close to", "far from", "visible from", "west of", etc. were created as options for users from which to choose. However, no quantitative relation was added; traffic routes on the construction site were neglected; the orientation of each facility was limited to 0/90 degree. A comprehensive site layout model should always avoid these over-simplifications in respect of feasibility. Osman (2003) introduced an approach of utilizing Genetic Algorithms (GA) within the CAD environment to optimize the location of temporary facilities on site. The system's novelty lies in its utilization of CAD capabilities as the input/output media as most construction companies have their project drawings in a CAD format. GA was employed to perform the optimization process using the objective function of minimizing the total transportation costs between site facilities, which was admitted by the author that should not have been the only goal a site layout strived to achieve. As well, 4D (integrating 3D with schedule) has been adopted by researchers (McKinney and Fisher 1997, Ma and Shen 2005) in recent years to visualize and trace the construction process thus carrying out efficient locations of the facilities.

2.4.2.4 Genetic Algorithms Based Models

Genetic algorithms (GA) are a class of stochastic search algorithms based on the mechanics of natural evolution and biogenetics. While randomized, GA is still a structured search and parallel evaluation of nodes in the search space. An implementation of GA begins with randomly initializing a group of points (chromosomes), followed by evaluating the structures and allocating reproductive opportunities in a way that the chromosomes representing a better solution are more likely to reproduce and undergo a sequence of operations such as crossover and mutation—along the lines of "survival of the fittest" in Darwin's evolution theory. The iterative process of selecting and combining good chromosomes continues for a number of generations until a solution is found. Due to the characteristics of not using gradient information, GA is highly applicable to problems with non-differentiable functions, as well as functions with multiple local optima (Whitley 1993).

GA was applied on *facility to location* problems in the early attempts from the researchers (Li and Love 1998, Hamamoto, Yih and Salvendy 1999). The first model developed applying GA to *facility to layout* problems was probably EvoSite (Hegazy T. and Elbeltagi 1999). EvoSite exhibits much flexibility in representing the shape of facilities and site boundary by utilizing a simple but effective spreadsheet representation of site geometry. The area of a grid unit is the greatest common divisor of all facility areas. However, as shown in equation 2-1, the model considers the total travel distance as the only objective function.

$$Min:\{\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} d_{ij}R_{ij}\} \qquad \text{(Equation 2-1)}$$

Where: n is number of fixed and temporary facilities; d_{ij} is distance between facility i and j; R_{ij} is desired proximity weight value between facilities i and j.

Moreover, by applying GA, Zouein and Harmanani (2002) developed a model solving site layout problems with unequal-size and constrained facilities. In the model, GA was tested on a variety of layout problems in the cases of: loosely versus tightly constrained layouts with equal levels of interaction between facilities; loosely versus tightly packed layouts with variable levels of interaction between facilities, and loosely versus tightly constrained layouts. The author concluded that GA performed better in loosely constrained problems with small facilities-to-site area ratio even with large number of facilities. Yet some limitations of the model are: the objective function used was again to minimize total transportation cost (refer to equation 2-1); constraints on relative positions between facilities are minimum and maximum distance, orientation and non-overlap only; facilities can be positioned in $\mathbf{0^0}$ or $\mathbf{90^0}$ orientation only.

$$Min:\{\sum \sum_{j<i}(w_{ij} \times d_{ij})\} \qquad \text{(Equation 2-2)}$$

Where: w_{ij} is the affinity weight between objects i and j that could be used to represent the flow or the unit transportation cost between I and j; d_{ij} is the rectilinear distance separating objects i and j.

Mawdesley and Al-jibouri (2002) presented another model applying GA to construction site layout problems with the adopted objective function shown as equation 2-2.

Min: {f(material transport cost+ facilities setup cost+ facilities removal cost+ work site personnel visit cost+ others)} (Equation 2-3)

In the model, a site is divided into small grids, within which the cost can be assumed to be uniform. Based on the site cost distribution information, a least cost route can be established and used as a criterion for the facility configuration. For certain areas not suitable for positioning some facilities, the setup cost is assigned to be arbitrarily high. The model is more comprehensive and generic compared to the previous ones, however, it is to be noted that over-simplifications such as limiting facilities and site area to be rectangular in shape, their sides to be parallel with each other and the coordinate system axes still exist.

Aside from the models mentioned above, efforts to solve site layout problems used some other techniques as well over the last few decades. Operation research techniques were applied on some early-computerized systems such as CRAFT (Armour and Buffa, 1963) and CORELAP (Lee and Moore, 1967). The methods divide the site into cells assigned to facilities and thus have limitations when dealing with complex facilities and a site with many facilities. Yeh (1995) proposed a layout model employing a hybrid type of neural network, named annealed neural networks, to overcome the drawback of traditional neural networks in getting easily trapped in the local optimum by integrating simulated annealing to allow random changes. Defects of the model were discussed in the previous section. Tam (2002) developed a nonstructural fuzzy decision support system (NSFDSS) that integrates both experts' judgment and computer decision modeling, making it suitable for the appraisal of complicated construction problems. The system allows assessments based on pair wise comparisons of alternatives. However, this pair wise comparison approach is inherently unwieldy in analyzing problems with a large number of alternatives and requires frequent and expensive backtracking.

2.5 GENETIC ALGORITHMS IN CONSTRUCTION

Although no studies of applying combined GA and simulation in construction site layout, especially in tunnel site layout, have been reported, GA has been successfully applied to numerous areas in construction engineering and management searching problems in the recent decade on account of it being generic in nature and the fact that little information is needed about the problem domain. Some examples follow.

Chan (1996) presented a resource scheduler using GA with the methodology not depending on any set of heuristic rules. Zheng (2003) proposed a multi-objective approach for optimizing twin resources simultaneously based on GA. Hegazy and Kassab (2003) introduced an approach for resource management and optimization in construction projects using a combination of flow chart-based simulation and GA. Senouci (2004) developed an augmented Lagrangian genetic algorithm model for resource scheduling. Instead of focusing on duration minimization only, the model considers all precedence relationships, multiple crew strategies, total project cost minimization, and time-cost trade-off. Resource leveling and resource-constrained scheduling are performed simultaneously.

Other than resource scheduling, GA systems have been applied to solve schedule and cost optimization problems as well. Feng and Liu (1997) introduced an algorithm based on the principles of GA for construction time-cost trade-off optimization; similarly, by employing GA and the fuzzy set theory, Leu and Chen (2001) developed a construction time-cost trade-off model under uncertainty. A model on a spreadsheet for scheduling and cost optimization of non-serial repetitive projects was developed by Hegazy and Wassef (2001) through utilizing GA to determine the optimum combination of construction methods, number of crews, and interruptions for each repetitive activity. In 2002, Que proposed an approach that made time-cost optimization using GA viable for practical application by integrating a project management system into the GA system, allowing realistic evaluations to be made during optimization through the scheduling functionality of the project management system. Using GA to determine the optimum set of construction methods and the optimum routing order among sites, Hegazy and Elhakeem (2004) presented a distributed scheduling model for scheduling, resource planning, and cost optimization of large construction and/or maintenance programs that involve multiple distributed sites.

As such, construction cost estimating and control using GA has attracted the attention of many researchers. Hegazy and Petzold (2003) developed a model for carrying out dynamic project monitoring and control by means of the overall optimization of the project intermediate schedules based on genetic algorithms. Kim and Yoon (2004) applied a neural network model incorporating genetic algorithms to estimate construction costs. In the model developed, GA performed backstage to help find the optimal architecture and parameters of the back-propagation algorithm, improving the accuracy of cost estimation and verifying the performance and validity of optimizing the size and parameters of the neural network.

Many advantages of GA over traditional optimization methods lead to these successful implementations in construction domain mentioned above. A detailed introduction of GA, along with a comparison of GA and other optimization methods, is given in Chapter 4.

2.6 CONCLUSIONS

In this chapter, definitions, key issues, modeling tools, and applications of computer simulation were reviewed. Basic concepts and some commonly used construction methods of shafts were introduced. After this, approaches toward solving construction site layout problems were explored and a literature survey of the state-of-the-art in construction site layout was conducted. At the end, certain literature in applying genetic algorithms in other construction areas was summarized.

According to the literature reviewed, most previous research in construction site layout was found over-simplifying site layout representations. These models were implemented with a fixed number of temporary and permanent facilities, as well as limited site shapes and orientations. Some of them even neglected including traffic routes on the site. Thus, they failed to represent all or most of the factors that needed considering in designing a site layout (Sadeghpour 2004). Consequently, the limitation renders the models impractical to layout planners and confines the models to the research level.

Anther shortcoming found of the existing models is that many of them make their efforts to minimize travel cost. Admittedly, this should be a substantial factor considered when planning a large construction site layout; however, some other goals, such as decreasing site congestions and providing for a safe working environment, are not negligible in comprehensively modeling a site layout. Hence, the models are useful only as far as distance is concerned.

To fill the missing gap in shaft construction modeling, and to address the cited shortcomings of the existing site layout models, this research has the objective of developing an effective tunnel construction template. This template is developed as a general modeling framework for simulating shaft construction as well as the laying out of tunnel construction sites.

CHAPTER 3: MODELING TUNNEL SHAFT CONSTRUCTION PROCESS

3.1 INTRODUCTION

The proposed initiative of using special purpose simulation (SPS) to model the shaft construction process was put forward by the existence of a tunneling template. While shaft construction was considered one single activity, with duration as an input parameter, by the tunneling template developed by NSERC/Alberta Construction Industry Research Program in Construction Engineering and Management, the development of the shaft construction process was in high demand.

The template was developed collaboratively with the City of Edmonton Asset Management and Public Works Department under the NSERC/Alberta Construction Industry Research Program in Construction Engineering and Management. The shaft construction work performed by the City of Edmonton was studied before creating this SPS template.

Shafts are mentioned as working shafts and retrieval shafts in terms of function. The former serves as equipment and personnel access and egress for tunnel muck, while the latter functions to retrieve the Tunnel Boring Machine (TBM). The City of Edmonton presently sinks four sizes of circular shaft with diameters of 14ft8in (4.47m), 12ft (3.66m), 10ft (3.05m) and 8ft (2.44m). The equipment utilized for excavation and muck handling is typically augers, crane, clamshell or bucket excavators, or backhoes. Construction of rectangular shafts is achieved by driving piles around shaft perimeters, and using steel walers for lateral support. An excavation crew is deployed depending on the size of the main tunnel.

This chapter outlines the development of the proposed shaft template. Section 3.2 and Section 3.3 explain in detail the shaft and tail tunnel construction processes, respectively. Section 3.4 presents the design goals and modeling system structure. Section 3.5 reviews the elements that constitute the simulation template and their attributes and parameters.

3.2 SHAFT CONSTRUCTION PROCESS

3.2.1 Construction of Circular Shaft

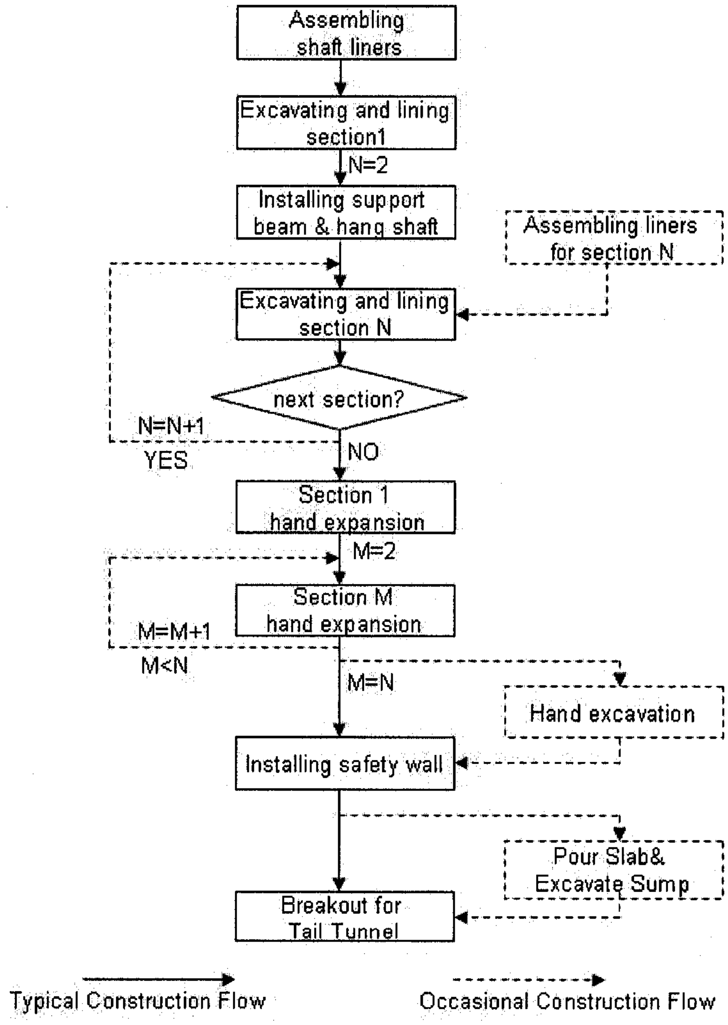


Figure 3-1 Circular Shaft Construction Process

The process of circular shaft construction commences with assembling shaft liners for different excavation sections. Other typical activities consist of machine drilling, installing shaft liners, hand excavating, installing the safety wall, etc. Typical and occasional construction process flows are illustrated in Figure 3-1.

The major shaft support system utilizes the ribs-and-lagging segments. The ribs-and-lagging method has a record of high performance in a variety of ground conditions. Curved steel ring segments are bolted together, with side-by-side timber wedging circumferentially between rings. Ribs-and-lagging segments, shown in Figure 3-2, are pre-fabricated before excavation, a process which is known as "assembling liner". Assembling liner happens a while before the corresponding shaft section is excavated, behaving as a parallel activity of excavating the previous shaft section.

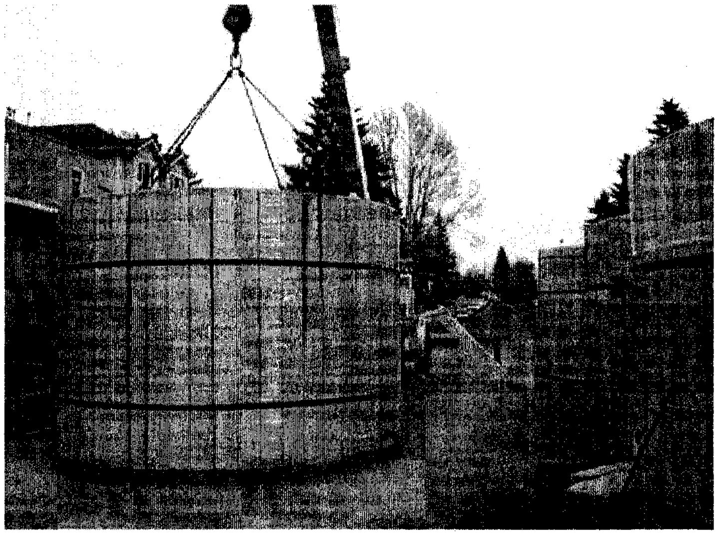


Figure 3-2 Pre-Fabricated Rib-and-Lagging (City of Edmonton 2005)

Hand excavation is used extensively in enlarging the manhole drilled by the flight auger, whilst in the depth that machine is unable to excavate due to geology limitations or due to the limitation caused by the excavating tools currently equipped. Hand expansion process progresses outwards until the shaft end diameter is achieved.

The base slab is poured to resist uplift by its own weight and by anchorage into the lining of the shaft, and it is normally made watertight by grouting. The shaft base may also have to accommodate various items of the construction plant. In water-bearing ground the provision of a sump and pumps is almost invariably essential for the construction stage (Megaw 1983). A sump, along with pumps, is employed to remove the water entering the shaft after the seal is placed or from accumulating in the low spots during construction, a process which is known as unwatering. Sometimes a sump serves for dumping dirt as well.

3.2.2 Construction of Rectangular Shaft

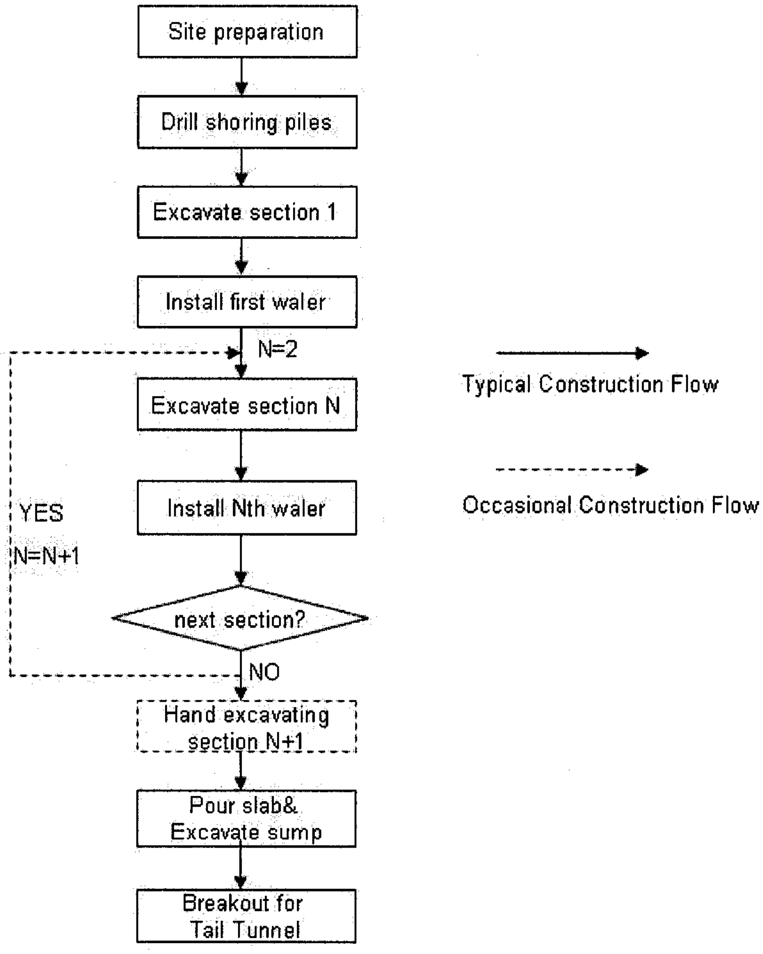


Figure 3-3 Rectangular Shaft Construction Process

Construction of rectangular shafts normally commences with soldier piling along the perimeter of the shaft. A hole of adequate diameter (usually around 1m) is drilled by a flight auger to permit the introduction of a wide steel flange section with sufficient extra space to allow any variations in the drilled hole. Whereafter, a wide steel flange section is introduced vertically into the drilled hole. The drilled hole is backfilled with structural concrete after the steel section has been installed. This process is repeated until the required number of shoring piles are completed. Piles with concrete reinforcement are only installed between each pair of adjacent soldier piles.

Figure 3-4 Rectangular Shaft (City of Edmonton 2005)

Excavation then starts and continues until a depth of five to six meters is achieved. Walers, wide flange steel beams which are attached horizontally to the wall, together with corner braces which are made of steel column sections, are subsequently employed as lateral support of the excavated section. Walers are attached directly to the wall, with the gap between themselves and the wall filled with wooden or steel wedges. Corner braces are then attached directly to the waler. Figure 3-5 illustrates the structure mentioned above.

Hand excavation is employed in the layer between the tip of the piles and required bottom of the shaft. Construction methods and the functions of the slab and sump are identical with that of a circular shaft.

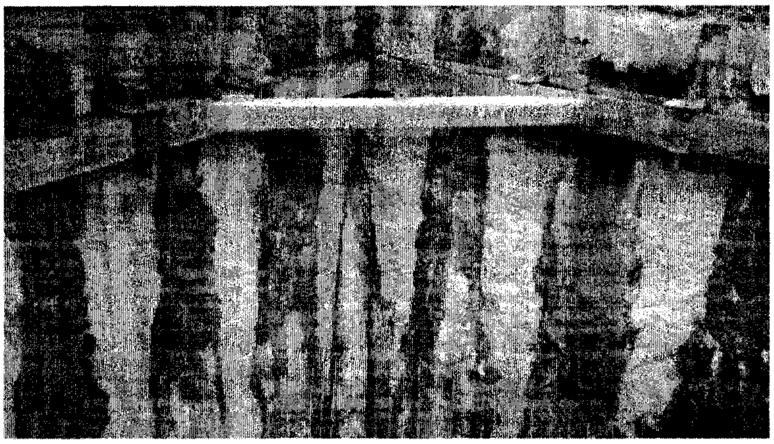


Figure 3-5 Corner Brace with Brace Mounted Against Waler (Macnab 2002)

3.3 TAIL TUNNEL AND UNDERCUT CONSTRUCTION PROCESS

Figure 3-6 Construction of Tail Tunnel (City of Edmonton 2005)

The construction of a tail tunnel (Figure 3-6) starts with a small opening in the shaft from which a short timbered heading is driven. Table 3-1 explains the sequence of the typical construction operations shown in Figure 3-7. The cycle is repeated until the required length is achieved. Excavation and rib-installation of the top sections always happen before the corresponding bottom sections are excavated. The rib spacing can be 1.0m (3.28ft), 1.22m (4ft), or 1.5 m (4.92ft).

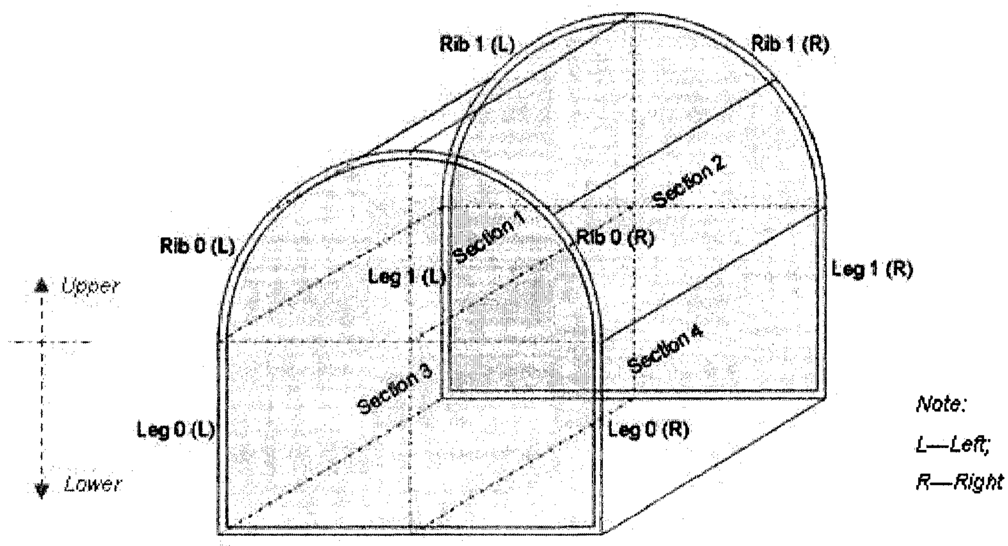


Figure 3-7 Tail Tunnel / Undercut Section

Table 3-1 Sequence of Tail Tunnel Construction Activities

Operation	Sequence	Operation	Sequence
Install rib 0 (L)	1	Install rib for leg 0 (L)	9
Excavate section 1 (U.L.)	2	Excavate section 3 (L.L.)	10
Install rib 1 (L)	3	Install rib for leg 1 (L)	11
Install lagging for section 1	4	Install lagging for section 3	12
Install rib 0 (R)	5	Install rib for leg 0 (R)	13
Excavate section 2 (U.R.)	6	Excavate section 4 (L.R.)	14
Install rib 1 (R)	7	Install rib for leg 1 (R)	15
Install lagging for section 2	8	Install lagging for section 4	16

Note: U.L.—Upper Left; L.L.—Lower Left; U.R.—Upper Right; L.R.—Lower Right; L—Left; R—Right

Dirt from the excavation is normally hoisted using clamshells (shallow shafts) or cranes (medium to deep shafts). A gantry hoist or derrick hoist is used occasionally for deep shafts. The construction processes for the undercut and tail tunnel are identical.

3.4 PROPOSED SHAFT SIMULATION TEMPLATE

A tunneling model capable of capturing the complexity of excavating, lining, dirt removing, their interactions and the uncertainties in a tunneling project would be of great value to engineers and planners. Based on the currently available simulation platforms and the comprehension to the area studied, the proposed shaft modeling system would extend the existing Tunneling template's capabilities to address the unique requirements of modeling the whole tunneling process.

As a supplement of the Tunneling template, some of the original template's features are inherited, aiming for consistency.

- *Project Planning:* As a computer simulation tool, it enables the planners to specify the methods and sequence of the construction operations, define the resources required for the operations, and analyze the production of the system before commencing construction.

- *Bottlenecks Detection:* Some problems that may happen in a typical construction project could be discovered by the simulation model. Detection of these problems helps the planners and engineers decide on corrective measures before commencing construction.

- *Scenarios Comparison:* Simulation allows users to predict productions and compare the productions of different scenarios, and thus make informed decisions before they embark on the project.

Several enhanced features are:

- *Extendibility:* The proposed template can be easily extended to accommodate more policies, more disciplines, more strategies, and more advanced outputs in simulation blocks.
- *Compatibility:* The proposed simulation setting is compatible with other developed simulation templates for construction processes and other applications. This will be detailed in Chapter 4.

3.5 SIMPHONY SHAFT MODELING ELEMENTS AND FUNCTIONS

The template for Shaft construction was implemented in *Simphony* (AbouRizk and Hajjar 1999). Various shaft construction equipment, labor disciplines, and material handing systems were studied systematically to extract the modeling elements for the template. The proposed SPS template for shaft construction comprises eleven modeling elements, with the graphical representations demonstrated in Figure 3-8. A review of the eleven elements' characteristics along with their functions is presented in this section.

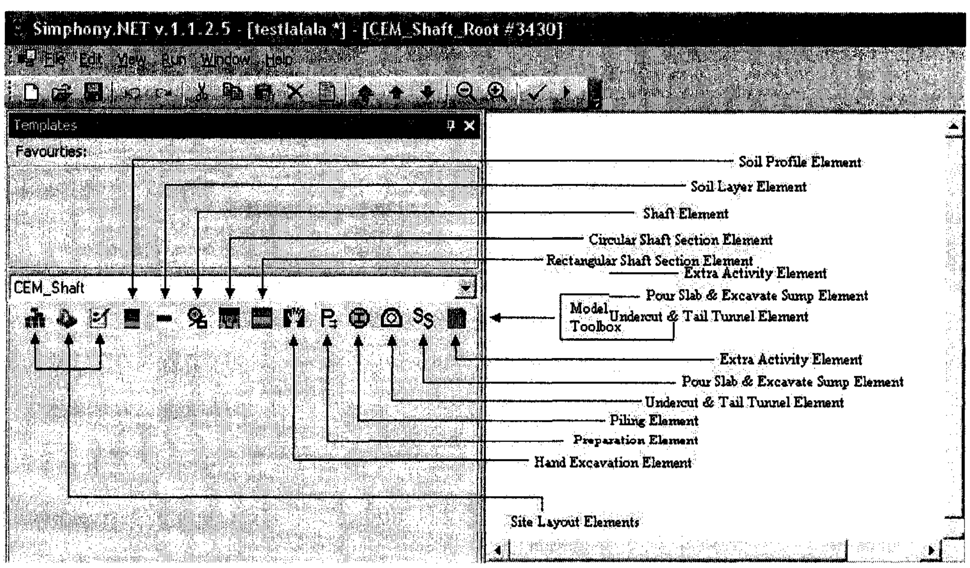


Figure 3-8 Shaft Template Elements

3.5.1 Shaft Element

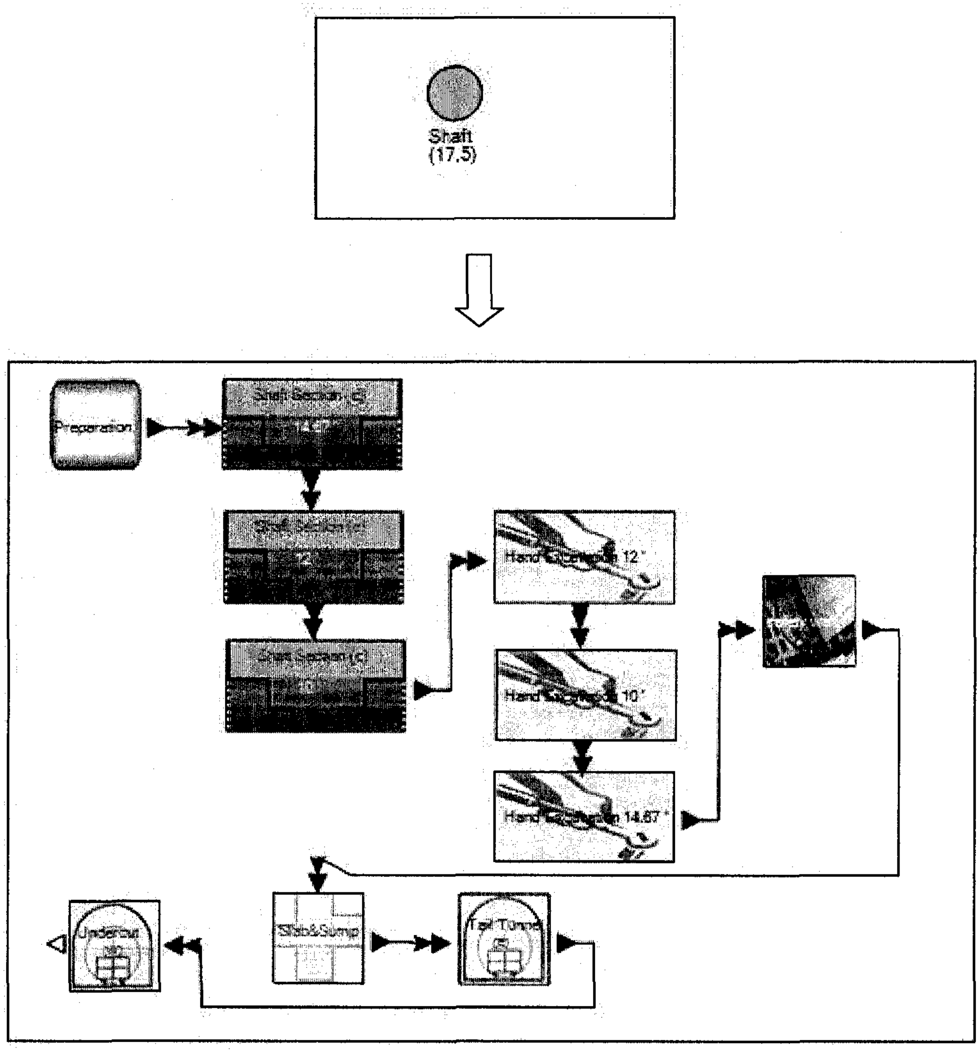


Figure 3-9 Circular Shaft Element and Layout of its Child Window

This element is a parent element designed to encompass all other elements that are shaft-construction-related in the template (see Figure 3-9 and 3-10). Six inputs, three outputs, and one statistic are included in the element.

- *Description* is a parameter letting users define a name for the specific type or name of the shaft represented by the "Shaft" element.

- *Shaft Depth* is another user-defined parameter referring to the depth of the shaft.
- *Shaft Length (m)* exists or vanishes together with *"Shaft Width"*.

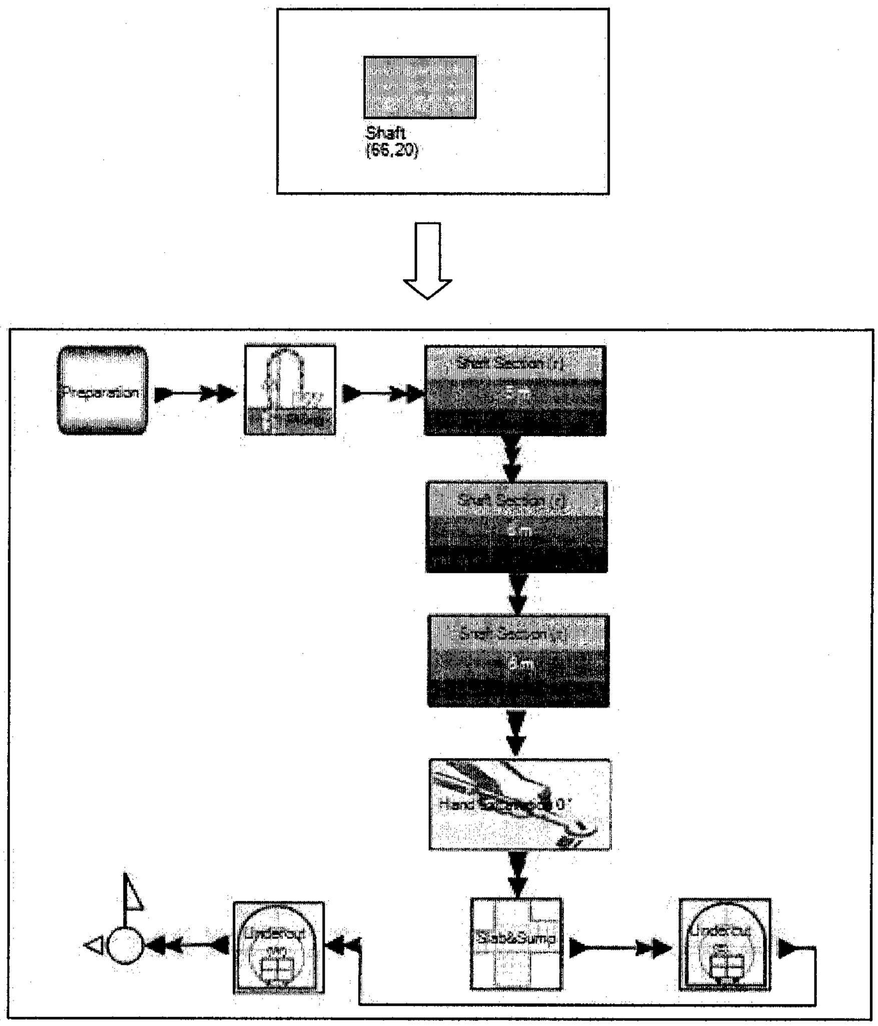


Figure 3-10 Rectangular Shaft Element and Layout of its Child Window

- *Shaft End Diameter (feet)* represents the end diameter of the shaft. It is created for circular shafts only.
- *Shaft Width (m)* represents width of rectangular shaft, corresponding to *"Shaft Length"*.
- *Rotating Angle* refers to the angle formed by the horizontal direction and the long edge of the rectangular shaft.

- *Shaft Shape* is to allow users to choose the shape of the shaft from the options of "Circular" and "Rectangular". If the choice is of shape "Circular", *"Shaft End Diameter"* with a default value appears as its specific parameter, and all child elements to be created are limited to common-use or circular shaft use only. On the other hand, by choosing "Rectangular", the parameters of "*Rotating Angle*", *"Shaft Length"*, and "*Shaft Width"* with default values are automatically added or deleted, and a parameter of *"Shaft End Diameter"* is automatically deleted or added. Consequently, users are allowed to create child elements developed for common-use or for rectangular shaft only. As well, the element appearance is updated in connection with the shape selected. A method of "ob.attribute.count" is used to ensure that the three attributes mentioned above are not added repeatedly under any circumstance.
- *Shift Length (hours/shift)* is to allow users to assign a crew's working hours per shift.
- *Number of Shifts per day* is to allow users to assign the daily number of shifts for the project.
- *X-Coordinate and Y-Coordinate* are two parameters that represent the position of the shaft. These two parameters, along with are to be explained in detail in Chapter 4.

The output of the "Shaft" element is:

- *Dirt Amount from Construction* exhibits the amount of dirt accumulated by excavating the shaft, sump, undercut, and/or tail tunnel. Based on the soil information users provide, the system calculates the muck removed from each operation and accumulates the total. This facilitates decision making in the area required for spoil pile, which will be discussed in detail in the following chapter.

The statistics of this element are:

- *Shaft Construction Duration* is to have a statistics record of the construction duration of the project, including that for shaft, sump, undercut, and/or tail tunnel.

One thing users have to notice is that if the elements have already been added in the child window, the attribute *"Shaft Shape"* cannot be altered any more.

3.5.2 Soil Profile Element

This element (see Figure 3-11) was designed to function as the soil information source for the whole model. All elements representing shaft construction operations read penetration rate and soil swell factor from this element and its child elements. The element is to be created in the same level as the "Shaft" element; and existence of more than one "ShaftProfile" is not allowed in the same model. When the number of test holes on site is more than one, users would have to select the one closest to the shaft and input the soil information. The default diameter for the borehole is 2 ft (0.61m).

- *Number of layers* is the only input parameter contained by this element. The actual layer information is manipulated by changing the parameters of the "SoilLayer" elements that are automatically added as children of the "ShaftProfile" element.

Two outputs, "X-Coordinate" and "Y-Coordinate" refer to the position of the test hole. A detailed explanation will be presented in Chapter 4.

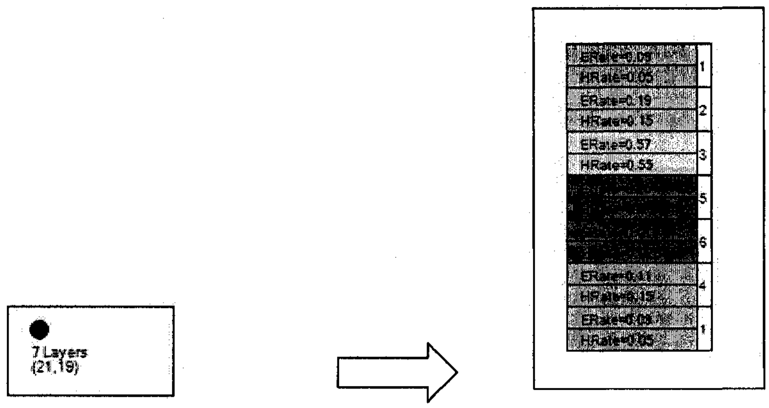
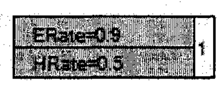


Figure 3-11 Soil Profile Element and Layout of its Child Window

3.5.3 Soil Layer Element



Several "Soil Layer" elements are created automatically in the child window of the "Shaft Profile" element. The number of creations equals the layer value assigned by the users for its parent element. Users are not requested to add or delete any of them. Five input parameters are comprised of the following items:

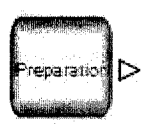
- *Soil Type* is designed to allow users to choose a number representing type of the soil layer from a list with default numbers from one to six. Different layers with the same soil type are supposed to have identical excavation rates and swell factors as input.
- *Layer Thickness (m)* can be used by users to specify the thickness of each soil layer. A sum value of no less than shaft depth from all "Soil Layer" elements is required; otherwise a warning window will appear.
- *Excavation Rate (Machine)* is a parameter referring to the productivity of the excavation and support installation when augers are used for excavation during shaft construction. Users are given an opportunity to indicate the value based on

their personal experience. "*Excavation Rate (Machine)*" can be defined as a statistical distribution or as a formula by users. If distribution is adopted, users can define the parameter as either constant or any of these distribution types: uniform, triangular, normal, exponential, or beta.

- *Excavation Rate (Hand)* refers to the productivity of hand expansion or excavation and support installation. Similar to "*Excavation Rate (Machine)*", the parameter is designed to let users indicate the rate. Again either a statistical distribution or a formula can be adopted as the input value for this parameter.
- *Sequence of the Layer* refers to the sequence of the specified layer from the ground level down to the bottom layer of the test hole. Default values are given to each of the "Soil Layer" elements when created. Users are not encouraged to modify the default value; however, if needed, no two layers with identical value are allowed. Whenever any element in the model introduces soil information, it obeys the "sequence of the layer".
- *Swell Factor* refers to the soil swell factor of the specified layer.

The color of the element corresponds to the parameter *"Soil Type"* (see Figure 3-11). All parameters except *"Soil Type"* and "*Sequence of the Layer*" have a default value of zero. Even after created, the elements are also automatically added and deleted in connection with the parameter *"Number of Layers"* of the "Soil Layer" element.

3.5.4 Preparation Element



The "Preparation" element is developed as a child of the "Shaft" element only. This element serves as the start of any shaft models: it creates entities and has them transferred out. Due to the fact that site preparation or assembling liners are necessary for any real project, “Preparation” was set to be a functional element, and a model without this element is incomplete. Two input parameters are:

- *Time of first Creating* refers to the time at which the entity is created in the simulation model. It is a user defined parameter and can be any non-negative number or formula.
- *Duration for site preparation* is the time interval required for the preparation work. Users can set this time to a constant or a random distribution.

3.5.5 Circular Shaft Section Element

This element is designed specially to simulate the circular shaft section patterns. It is a functional element that is required by all circular shaft models. During modeling, more than one element is created, each of which stand for operations such as excavating and lining for one section shown in Figure 3-12. The “Circular Shaft Section” elements, in company with the “Hand Excavation” elements, are the main components of a circular shaft model. Four input parameters as followed are contained by this element.

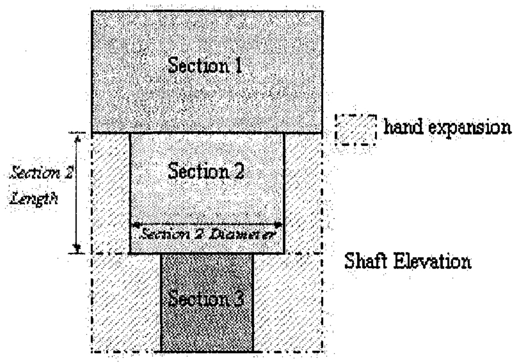


Figure 3-12 Circular Shaft Sections

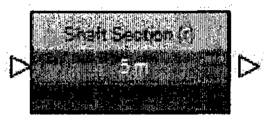
- *Section Length* is a parameter letting users to determine the length of each circular shaft section represented by the "Circular Shaft Section" element. Refer to Figure 3-12 for an illustration.
- *Section Diameter* is a parameter letting users determine the diameter of each shaft section represented by the element. Refer to Figure 3-12 for an illustration.
- *Duration for assembling liner* is a user-defined parameter. Mostly the liners are prepared before the shaft excavation commences, represented by the "Preparation" element; however, on some occasions, liners for different shaft sections are assembled right before the excavation of the corresponding section starts. In this case, users are requested to determine the duration as a constant value or in any other statistical distribution format mentioned previously.
- *Duration for installing beam & hang shaft* refers to the time interval for installing the beam and hang shaft. In real projects this operation usually only happens between finishing with the first section and starting with the second, accordingly the first "Circular Shaft Section" element is created with a default value of 1 and all other subsequent elements are assigned a default value of zero for this parameter. Users are allowed to change the value if they so desire.

Some hidden attributes were added so as to link with the "Soil Layer" elements and to induct the penetration rate and swell factor for different soil conditions from them. Any "soil layer" that has been fully or partially finished "excavating and lining" is correspondingly marked. Each of the "Circular Shaft Section" elements created employs the soil information from the first unfinished layer (based on the *"Sequence"* of "Soil Layer" elements), and continues to the succedent layer or passes the entity to the next element if desired.

"Dirt Amount for the section" is the only output from this element. According to the dimensions of the section and swell factor introduced for the soil condition in the section, the system calculates the muck removed from each operation and adds itself up.

The statistic "*Section Cycle Time*" is designed to enable the user to gain the duration range required for constructing the specific section represented by this element.

3.5.6 Rectangular Shaft Section Element



This element is created specially to help with the simulating of the rectangular shaft. The structure and function of this element are analogous to the "Circular Shaft Section" element: it is required for all rectangular shaft models; each of the elements created in a model represents operations, including excavating and installing walers for one section (see Figure 3-13); the penetration rate for various soil conditions are linked with the "Soil Layer" elements. When calculating, the element starts itself employing swell factor and productivity from the right soil layer.

Two input parameters are:

- *Section Length* refers to the length of each circular shaft section represented by the element. An illustration can be seen from Figure 3-13.
- *Duration for installing waler* refers to the time interval required to install the waler for the corresponding rectangular shaft section represented by the element. The value can be either constant or any other distribution mentioned in the preceding sections.

The output and the statistics of the element again are "Dirt Amount Excavated" and "Section Cycle Time", respectively, to enable users to collect the amount of muck produced as well as timely information.

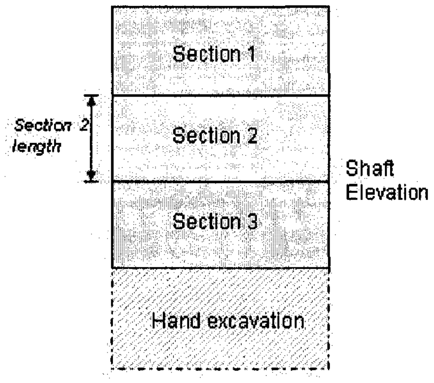
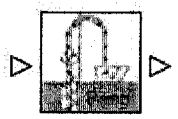


Figure 3-13 Rectangular Shaft Sections

3.5.7 Piling Element



Since piling is required for all rectangular shafts, this element is a mandate when a rectangular shaft model is created. Therefore, "On Check Integrity" was added in this element to ensure the sum "section length" of all "rectangular shaft section" elements is equal to the "shaft depth" parameter for the "Shaft" element.

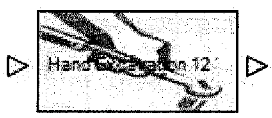
This element has four input parameters:

- *Number of Piles* has an initial value calculated using a formula related to *"pile diameter"* and parameters of the element's parent element—"Shaft"—according to the historical information collected. Users are allowed to modify the value to any positive integer as needed.
- *Pile diameter* is to let users input the diameter of the piles for the project. The value can be a number or a formula.

- *Productivity (piles/8hrs)* refers to the estimated piling speed in piles per eight hours according to historical data and the users' personal experience. It can be a constant value or in the format of any other distribution.
- *Swell Factor* corresponds to the average swell factor in the piling area, which is along the perimeter of the rectangular shaft. Either a number or a formula is accepted as the value for this parameter.

Two outputs for this element are *"Dirt Amount from piling"* and *"Duration (days)"*, the explanation of which can be referred to the "Circular Shaft Section" element.

3.5.8 Hand Excavation Element



This element represents a common member for shaft construction. It may represent hand expanding certain circular shaft section excavated by machines to the shaft end dimension, excavating and lining circular shaft wherever machines are limited by the geology or depth, or excavating and installing walers for a rectangular shaft. The same as the "Circular Shaft Section" element and the "Rectangular Shaft Section" element, the entity starts working from the first fully or partially un-excavated soil layer. For a circular shaft, this element initiates a search for the corresponding "Circular Shaft Section" element by comparing the value of *"Section Diameter"* for both elements to get the operation duration from it; then, when calculating the dirt amount it deducts the volume of the dirt removed by the "Circular Shaft Section" from the element's output (layer in dark portion in Figure 3-14). For rectangular shaft and circular shaft sections excavated completely by hand, the element calculates the duration and dirt amount from the operations represented by this element itself. The dimension of the circular shaft is obtained from the "Hand Excavation" element while the dimension of the rectangular shaft is attained from its parent element. An illustration of the operating process can be seen in Figure 3-14.

Two input parameters are included in the "Hand Excavation" element. *"Section Length"* refers to the length of the shaft section represented by this element; the value is supposed to equal that of the corresponding "Circular Shaft Section" element or "Rectangular Shaft Section" element. Another input parameter is *"Section Diameter"*. A default value of zero was added; hence users are not required to pay any attention to this parameter when creating a rectangular shaft model. The only output is *"duration"* referring to the time required for the operation of the section represented by the element.

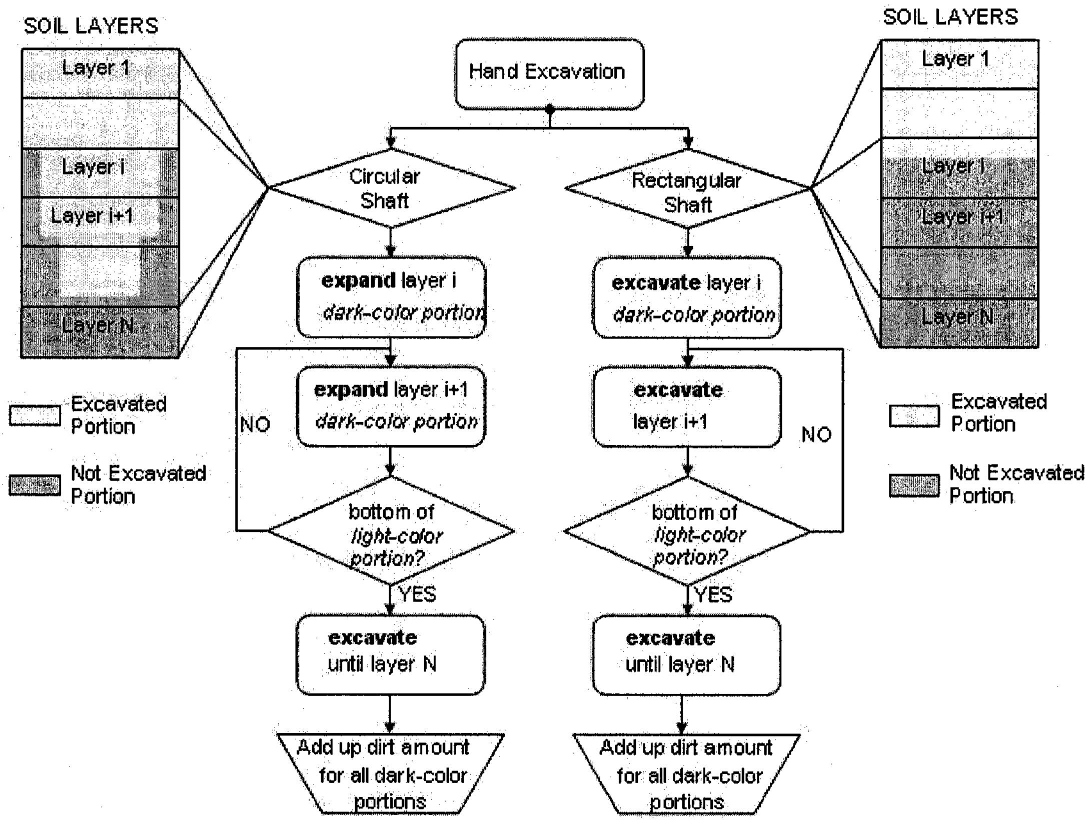
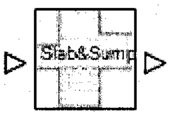


Figure 3-14 Hand Excavation Process

3.5.9 Slab & Sump Element

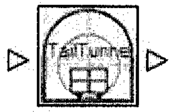


This element was designed to simulate the process of excavating sump and pouring slab. It has five parameters including *"Depth of the sump"*, *"Diameter of the sump"*, *"Duration for pouring slab"*, *"Duration for excavating sump"*, and *"Swell factor"*. All these parameters assist the system in calculating the "Dirt Amount from excavating sump" and "Duration", the two outputs of the element.

3.5.10 Extra Activity Element

This element is created to represent any construction activity that is not covered by the other elements, for instance, constructing a safety wall. The delay time can be directly specified as a sample from any distribution. Two parameters are included, one of which is "Description", a user-defined parameter representing the name of the activity; the other parameter is "Delay Duration", referring to the period of time after which the entity will be transferred out from the element.

3.5.11 Tail Tunnel Element



This element again can only be created as a child of the "Shaft" element. It was developed for simulating either the tail tunnel or the undercut.

One or more "Tail Tunnel" elements can be created in a simulation model to represent the tail tunnel/undercut construction process in different directions, corresponding to the parameter *"Direction"*. Tail tunnel/Undercut construction normally commences with a two-day-breakout, followed by step-by-step openings along with ribs and lagging as the primary support. A detailed explanation is given in Section 3.3 and Figure 3-6. Similar to the circular shaft, a tail tunnel/undercut may contain more than one section with different dimensions. Three groups of section parameters with default values were added as input parameters for this element. The summation of a sections' length should be equal to the parameter *"Total tail tunnel length"*, checked by "On Check Integrity". The duration for excavating the tail tunnel/undercut and lining is calculated backstage. The dirt amount is calculated and exposed as an output. A summary of input and output parameters is as follows:

Input: *Duration for break out; Rib Space; Advance Rate; Swell Factor; Direction; Total Tail Tunnel/Undercut Length; Leg height & O.D. & Section Length*

Output: *Dirt Amount from constructing tail tunnel*

3.6 CONCLUSION

The design and development of the template has been presented for the analysis of shaft construction projects, and is being integrated with the existing Tunneling template to provide users a complete, functional and more flexible simulation tool for tunnel construction. The template is of great benefit to the people willing to experiment with different sophisticated options in order to achieve an optimal choice; further, it assists users to model several scenarios without changing the developer's code or the base of the tool, and it does not need to be integrated with any other templates to model a shaft construction process. Successful applications for project planning for a circular shaft project and a rectangular shaft will be presented in Chapter 5.

CHAPTER 4: OPTIMIZING TUNNEL CONSTRUCTION SITE LAYOUT USING GENETIC ALGORITHMS INTEGRATED WITH THE PROPOSED SIMULATION TEMPLATE

4.1 INTRODUCTION

Construction site layout is often a preplanning task, following substantial completion of design drawings, after civil works, which include the clearing and grading of the site, or excavating and installing foundations for the project, have already commenced, but before construction of the project gets too far along (Tommelein 1989). Tunnel construction site layout, commonly recognized by project managers, is fundamental to any successful tunneling project undertaken. Despite its importance, currently the task of planning tunnel site layout is mostly accomplished by site planners based on their experience, common sense and adaptation of past layouts—a trial and error process. As stated by Mawdesley (2002), the nature of site layout problems means that no well-defined method can guarantee a solution; at best, guidelines point out the issues that field managers must consider while laying out their project sites. Although various efforts have been made to support construction site planning from different perspectives, no single tool has gained acceptance by the tunnel construction industry on account of their assumptions and over-simplifications of the problems. In an attempt to improve the existing solutions, and to create a tool aimied at tunnel construction site layout, this research presents a framework for tunneling site layout modeling.

This chapter begins with presenting the theoretical background behind genetic algorithms, the method adopted as the function optimizer in this study. The reason behind using genetic algorithms, a comparison of traditional optimization methods and genetic algorithms, and some basic concepts of genetic algorithms will be included. The chapter then describes the specific problems existing on the tunnel construction site, the objectives to be met in this study, and the overview of the proposed system structure as a whole. The representation of logical and geometrical constraints that tunnel construction site facilities are subjected to is then explained. The chapter concludes with detailing the tunneling site layout planning tool.

4.2 THEORETICAL BACKGROUND

4.2.1 Introduction

Genetic Algorithms (GA) was invented by Holland in the 1960s, and was developed by Holland and his students and colleagues at the University of Michigan in the 1960s and 1970s (Goldberg 1989). As mentioned previously, GA is a numerical optimization algorithm inspired by both natural selection and natural genetics. In natural evolution, each species seeks beneficial adaptations in an ever-changing environment. As species evolve, the new attributes are encoded in the chromosomes of individuals. The main driving force behind evolutionary development is the combination, swap, and occasional mutation of chromosomal material during breeding. Similarly, GA simulates the survival of the fittest among individuals over sequential generations for solving a problem.

Fundamental to any GA structure is the *encoding* mechanism for representing a candidate solution of the problem to be solved; such a representation is referred to as a *chromosome*; elements of a chromosome are independent variables for the problem named *genes*; and a set of chromosomes constitutes a *generation. Encoding* schemes provide a way of translating problem-specific knowledge directly into the GA framework; as it plays a key role in determining GA's performances. The GA processes generations of chromosomes, successively replacing one generation with another. The generation size depends on the nature of the problem, typically consisting of hundreds of chromosomes. A *fitness function* is normally required to assign a score *(fitness)* to each chromosome in the current generation to evaluate how well the chromosome solves the problem at hand (Mitchell 1997). A basic version of a GA works as shown in Figure 4-1.

```
Choose an initial population of chromosomes;
while termination condition not satisfied do
    repeat
        if crossover condition satisfied then
        {select parent chromosomes;
        choose crossover parameters;
        perform crossover};
        if mutation condition satisfied then
        {select chromosome(s) for mutation;
        {choose mutation points;
        perform mutation};
        evaluate fitness of offspring
    until sufficient offspring created;
    select new population;
endwhile
```

Figure 4-1 A Genetic Algorithm Template (Reeves 2002)

4.2.2 GA versus Traditional Optimization Methods

Many optimization methods have been developed relying on using information about the gradient of the function to guide the direction of the search. These methods perform well on functions with only one peak (unimodal), and always fail when encountering discontinuous functions. An instance is hill-climbing. Simulated-annealing, as a modified version of hill-climbing, accepts a small amount of negative moves. However, it deals with one candidate solution at a time, which results in no information saved from previous moves to guide the selection of new moves. By working from a population of well-adapted diversity instead of a single point, genetic algorithms can easily overcome the shortcomings mentioned above. GA as a robust search method is stochastic, flexible, incorporates parallel-search procedures, and requires little information, with these features making it capable of tackling large complex problems, especially the search spaces with many local optima where other methods have experienced difficulties.

Goldberg (1989) presented four ways in which GA surpasses normal optimization and search methods:

1. *GA works with a coding of the parameter set, not the parameters themselves.*
2. *GA searches from a population of points, not a single point.*
3. *GA uses objective function information, not derivatives or other auxiliary knowledge.*
4. *GA uses probabilistic transition rules, not deterministic rules.*

Although highly applicable, GA is not guaranteed to be the best optimization tool for all applications. Al-Tabtabai and Alex (1998) suggest that the use of GA in optimization is appropriate when the space to be searched is large, or when it is known not to be perfectly smooth and unimodal, or when it is not well understood, or if the fitness function is noisy, or if the task does not require that a global optimum be found. A GA's performance is more dependent on details such as the method for encoding candidate solutions, the operators, the parameter settings, and the particular criterion for success (Mitchell 1999).

4.2.3 GA Operators

Rather than starting from a single point within the search space, the GA is initialized by the random generation of chromosomes, which cover the entire range of possible solutions (the search space). A typical algorithm then uses three types of operators: selection, crossover, and mutation, to direct the population over a series of time steps or generations towards a convergence at the global optimum (Coley 1999).

4.2.3.1 Selection Operator

This operator selects chromosomes in the population for reproduction. The higher the fitness (i.e., how well they solve the problem at hand) of the chromosomes, the more likely those chromosomes will be selected to reproduce. The rest will perish. Many approaches can be used as the selection operator, including roulette wheel selection, ranking selection, tournament selection and truncation selection. The most commonly known method is roulette-wheel selection, also known as fitness-proportional, which uses a probability distribution in which the selection probability of a given string is directly proportional to its fitness (Reeves 2002). The steps required for applying this algorithm are summarized by Coley (1999) below:

1. *Sum the fitness of all the population members; call the sum* f_{sum}.
2. *Choose a random number* R_s, *between 0 and* f_{sum}.
3. *Add together the fitness of the population members (one at a time) stopping immediately when the sum is greater than* R_s. *The last individual added is the selected individual and a copy is passed to the next generation.*

4.2.3.2 Elitism Operator

Associated with the selection step is the optional *elitism* strategy, in which the best chromosomes (as determined from their fitness evaluations) are preserved for the next generation without a crossover or mutation operator being applied. This operator ensures the best chromosomes (termed "elite") at each generation against being thrown away and has been found significantly to improve searching performance if applied. It should be noted that the elitist chromosomes in the original population are also eligible for performing selection, crossover and mutation operators.

4.2.3.3 Crossover Operator

The so-called crossover operator recombines the selected parent chromosomes. This operator chooses a random locus (point) and swaps the genes before and after that locus between the two parent chromosomes in order to create offspring: two new chromosomes. The basic form of the operator is the random selection of one locus (termed "one-point crossover") or two loci (termed "two-point crossover") within the chromosome before swapping genes (see Figure 4-2). Uniform crossover is an operator deciding (with probability *p*) which parent will contribute each of the gene values in the offspring chromosomes. Unlike one-point and two-point crossovers, this form allows the parent chromosomes to be mixed at the gene level rather than the segment level. It is common in recent GA applications to use either two-point crossover or uniform crossover with *p* equal to 0.7 to 0.8 (Mitchell 1999). Crossover is generally accepted as the basis of GA as it provides a method whereby information for differing solutions can be melded to allow the exploration of new areas of the search space. While crossover simply intermixes the existing population to create new chromosomes, the next operator introduces new genes into the population (Jones 2003).

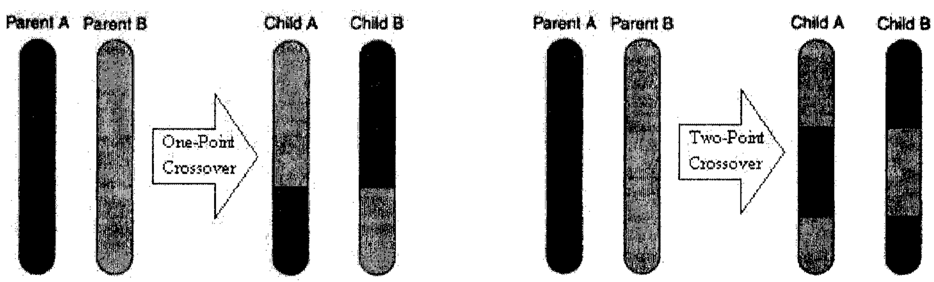


Figure 4-2 One-Point and Two-Point Crossover (Jones 2003)

4.2.3.4 Mutation Operator

This operator is designed to prevent the population from converging and stagnating at any local optima and to expand the solution space through providing the opportunity to "shake-up" the population. Without mutation, the population would rapidly become uniform under the conjoined effect of selection and crossover operators (Coley 1999). Mutation methods normally include flip bit, random, and minimum-maximum. To implement the operator, some of the genes in a chromosome (or more than one chromosome, depending upon the rate of application) are randomly changed, with a probability equal to a given mutation rate (see Figure 4-3). Similar to the natural world in which mutations, such as an error during replication, are caused very occasionally, it has been suggested by many researchers that this operator be used only sparingly; however, as mentioned by Mitchell (1999), it should not be a choice between crossover and mutation but rather it is the balance between crossover, mutation, and selection that is important. The correct balance also depends on the details of fitness functioning in the encoding.

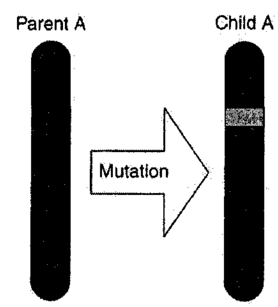


Figure 4-3 Mutating a Single Chromosome (Jones 2003)

4.3 PROBLEM ANALYSIS AND DESIGN GOALS

Site layout planning, in general, involves identifying the type and number of temporary facilities, sizing the temporary facilities, and locating them (Hamiani 1987). Many considerations, principles, and criteria must be complied with during the process of planning a site layout. For a tunnel construction layout, some sort of common set of rules existing on genetic construction sites must be obeyed besides tunnel construction-specific factors. Examples of these types of rules include that the traffic path must be of minimum width for trucks to drive over; materials are to be positioned to avoid double handling and unnecessary movements; and the administration office should be away from noise and free from disruptions. As well, legal rules and regulations are to be considered for safety reasons. As such, the size of the facilities can be affected by construction type, contract type, project size, and project location (Hamiani 1987). These factors prescribe a direction for arranging a site layout rather than outlining precise instructions.

According to Tommelein (1993), when a construction project is of a particular type of which many instances have been built, then its design concepts lend themselves to generalization. In the case of tunnel construction projects, the shaft mostly appears as the only permanent facility on site, and all temporary facilities are sized and positioned around the shaft based on shaft configuration and tunnel size. At this stage, definitions of the permanent facility and dedicated area can be given: *a permanent facility* is defined as a site facility that has fixed position while maintaining a close relationship with temporary facilities (Hegazy and Elbeltagi, 1999), which in this study correspond to shaft; *dedicated areas* refer to the site place occupied by trees, existing buildings, and other areas marked unavailable or unsafe where no temporary facilities are allowed to be positioned. A list of temporary facilities with recommended dimensions adopted on the tunnel site is summarized in Table 4-1 from the interview with the engineers at the City of Edmonton. An important feature of tunnel construction is the employment of moles, including both totally enclosed moles and spider-type moles (open-face moles). As can be seen in Table 4-1, the type of mole used provides a particular set of rules to estimate the needs for temporary facilities; as such, project size plays a key role on the selection of facilities. The type of hoisting equipment utilized certainly has to be taken into account as well. Appendix I contains the descriptions of the temporary facilities' functions in detail.

Table 4-1 Temporary Facilities and Recommended Dimensions

Type	Facility Name	Comments	Recommended Dimensions
Obstacles	Dedicated Area	Including trees, existing buildings, unsafe areas	User-defined
Hoisting Equipments	Derrick Hoist	Deep shafts; large-open work sites	Refer to Appendix II.
	Gantry Hoist	Medium-sized work sites	
	Crane	Limited work sites	User-defined
Hoisting-related Equipments	Draw Works	Together with hoist	Refer to Appendix II.
	Spoil Muck Bin		6.0m W x 9.0m L
	Spoil Pile	Always-needed	
Electrical Equipments	Electric Compressor Building	Always-needed	2.5m W x 5.5m L
	Construction Boxes	Large projects; usually two or three	0.6m W x 0.6m L
	Potable Power Supply (Genset)	Small projects	2.0m W x 4.5m L
	Power Trailer	Spider Mole	2.5m W x 6.7m L
	Switch Gear	Totally enclosed Mole	1.5m W x 3.0m L
	Cable Lay Down Area		4.5m W x 12.0m L
	Mole Transformers		User-defined
Miscellaneous Site Equipments	Crew Trailer	Refer to Section 4.4	3.0m W x 16.0 m L
	Field Office		3.0m W x 16.0 m L (LS) 2.5m W x 7.3m L (SS)
	Washroom Trailer	Long-term project	3.6m W x 6.0m L
	Portable Privy	Small Project	1.0m W * 1.2m L
	Site Parking		Project-size-dependent
	Tool cribs	Usually two	2.0m W x 3.0m L
	Propane Tank	LS and MS	User-defined
	Ventilation System	Always-needed	1.2m W x 4.3m L (with combined utilities)
	Area for off loading materials from tractor trailers		Sufficient
	Area for Storage and Heating of Concrete Segments	Totally Enclosed Moles	Sufficient
	Area allocated for Tracks, Rail ties, timbers, miscellaneous Supplies		4.0m W x 10.0m L (LS) 4.0m W x 8.0M (MS) 4.0m W x 6.0m L (SS)

Note: L—length; W—width; LS—large site; MS—medium size site; SS—small site

Regarding the site layout for tunnel construction, the study for this thesis aims to develop a template that would model closely the steps a site planner takes while laying out temporary facilities on a tunnel construction site on the platform provided by *Simphony*. Due to the diverse nature of the temporary facilities for different projects, users are given the opportunity to select required facilities from a pull-down list and to size each of them. The template is then carried out under a set of hard constraints, which have to be satisfied and soft constraints of which it is preferable that they be satisfied. These constraints will be presented in the following section in detail. The evaluation is a set of fitness functions scaling how well the generated layouts meets the constraints. While integrating with the shaft construction template, the search for the optimum or near optimum location for each temporary facility utilizing GA is accomplished before the commencement of shaft construction and after the shaft position is decided, in accordance with the sequence of constructing a shaft in the real life. In an effort to improve user recognition and enhance visualization, the graphical representation of the optimum layout achieved is shown in the modeling window in *Simphony* once the system finishes running, complete with the names, dimensions, positions, and orientations of all facilities exported as a Microsoft excel file.

4.4 LOGICAL AND GEOMETRICAL CONSTRAINTS

The constraints for site layout, defined by Hamiani (1987), are desired qualities of the layout due to relationships between facilities and the work area or relationships between the facilities themselves. Prior to the operation of placing facilities, all potential constraints have to be detected, and locations of all facilities on site are subject to constraints. In this study, the objective function is essentially an equation expressing how well the constraints are fulfilled. By means of satisfying the underlying constraints, the process of seeking near optimum locations for temporary facilities is carried out. A list summarizing the domain-specific constraints for this study is shown in Appendix II.

4.4.1 Spatial Representation

It is essential that both the available space on site and the site objects themselves are represented accurately to yield a feasible layout solution. Although choosing any representation scheme implies some loss of information in translation, it is not always desirable to represent shapes in full detail, thus spatial abstraction is appropriate (Tommelein 1989).

The presented study models any user-defined polygon site using an orthogonal two-dimensional reference system. Any space that is neither a dedicated area nor occupied by a permanent facility is detected as an available space for allocating temporary facilities. The site polygon is further composed of a set of sides (site boundaries), each of which is defined by two end points, represented by x- and y-coordinates as input parameters. Each side can thus be identified by the corresponding equation derived from equation 4-1. Figure 4-4 shows the graphical representation of a tunnel construction site.

$$y = a_i x + b_i \qquad \text{(Equation 4-1)}$$

Where: i has a maximum value of the number of polygon edges.

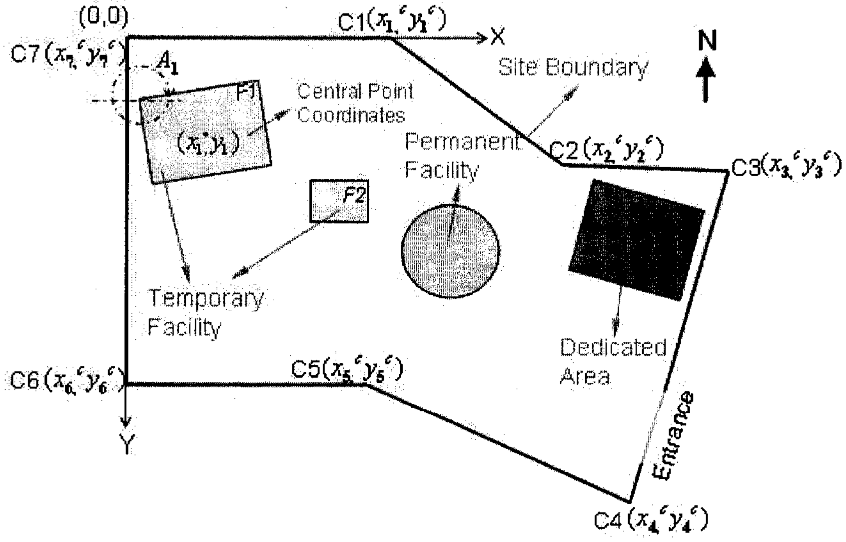


Figure 4-4 Graphical Representation of a Tunnel Construction Site

In addition to the site's representation, facilities are represented by similar schema. From the interview with tunnel site planners, most temporary facilities (listed in Table 4-1) are in essence rectangular in shape. Hence, for simplicity all temporary facilities are abstracted and represented by rectangles, which are further represented by their central points, appropriate orientations varying from $\mathbf{0^0}$ to $\mathbf{360^0}$, and user-defined dimensions in the study (refer to Figure 4-4). Dedicated areas are assigned with the same type of representation, except that all location-related information is user-defined. A circular shaft is represented by the diameter and center point coordinates while a rectangular shaft has an identical type of representation as in the dedicated areas. According to Jones (1997) and Sadeghpour (2004), spatial relationships among facilities can be categorized as topological, proximal, and directorial. Topological relationships are orientation-independent and can be further classified as *equivalence, partial equivalence* (overlap, cross), *containment* (inside), and *adjacency* (connected, or meets); directional relationships are orientation-dependent and include *metric angle of azimuth* and *relative orientation* (in front, behind, above, below); proximity relationships describe the distance of separation either *quantitatively or qualitatively* (close to, far from). In this context, the adopted ways of expressing spatial relationships are *overlap* (including equivalence and partial equivalence), *containment*, *parallel/perpendicular, distance*, *adjacency* (disjoint), *orientation, closeness* (close to and far from), and *access.* These expressions have proven sufficient to describe the relationships among facilities on tunnel construction site.

Distance relations express the preference for an object to be located within, or not within a certain distance from another object on site (Sadeghpour 2004). To define a distance metric on site, there are *Rectilinear-distance* (Manhattan) and *Euclidean-distance. Rectilinear-distance* corresponds to the distance between two points measured along axes at right angles. *Euclidean-distance* refers to the straight-line distance between two points. Figure 4-5 gives an illustration for the two metrics. The latter distance metric is the one used in this study.

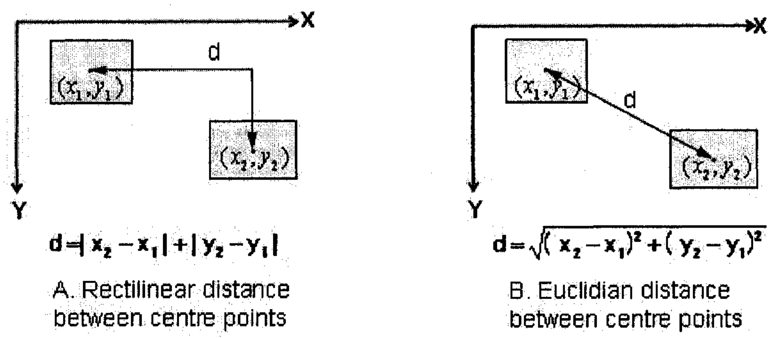


Figure 4-5 Graphical Representations for Two Distance Metrics

At this stage, all facilities, obstacles and relationships among them are translated into a set of X, Y coordinates and rotating angles. These representations will be utilized in the constraints-defining procedure and optimization procedure.

4.4.2 Hard Constraints

Hard constraints represent two-dimensional geometric relationships between two facilities or between a temporary facility and an obstacle that MUST be met. Common hard constraints for generic site layouts are non-overlapping occurring between any facilities and all temporary facilities inside site boundaries (containment). These two constraints, along with some specific constraints for tunnel site layout, will be explained in detail in the following sections.

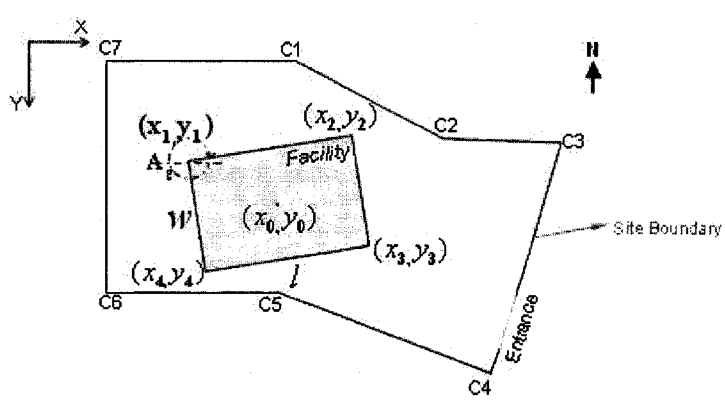


Figure 4-6 Facility Representation

Considering the simplified site layout of Figure 4-6, given the coordinates (x_1, y_1) of one of its corners (detected by *Simphony*), the length of the facility l (user-defined), the width of the facility w (user-defined), and the clockwise rotating angle Ag (from when the long side is parallel to the X-axis), then the coordinates of the other three corners and centre point can be attained by the following equations.

$$x_2 = x_1 + l \times \cos(Ag) \qquad \text{(Equation 4-2)}$$

$$y_2 = y_1 + l \times \sin(Ag) \qquad \text{(Equation 4-3)}$$

$$x_3 = x_1 + l \times \cos(Ag) - w \times \sin(Ag) \qquad \text{(Equation 4-4)}$$

$$y_3 = y_1 + l \times \sin(Ag) + w \times \cos(Ag) \qquad \text{(Equation 4-5)}$$

$$x_4 = x_1 - w \times \sin(Ag) \qquad \text{(Equation 4-6)}$$

$$y_4 = y_1 + w \times \cos(Ag) \qquad \text{(Equation 4-7)}$$

$$x_0 = (x_1 + x_3)/2 \qquad \text{(Equation 4-8)}$$

$$y_0 = (y_1 + y_3)/2 \qquad \text{(Equation 4-9)}$$

4.4.2.1 Non-Overlapping Constraint

- *No more than one facility can be set up on one specific area.*

For any normal construction site, it is of utmost importance that not more than one facility be set up in the same area if they coexist on site, in order to avoid overlapping. Overlapping should be prevented from happening between any two temporary facilities, a temporary facility and a permanent facility, or between a temporary facility and a dedicated area. Some exclusive conditions include aerial utilities appearing on site and specific requirements by users. For example, on the site plan representation abstracted, a hoist normally overlaps with the shaft, since the hoist is always placed over the shaft; however, essentially, they do not occupy the same piece of ground.

Overlapping relations mentioned in this study include equivalence and partial equivalence between facilities. In the previous section, the assumption was made that all temporary facilities and dedicated areas of the tunnel construction site were rectangular in shape, thus here considerations are given to overlapping between a pair of rectangular facilities/obstacles as well as between a rectangular temporary facility and a circular shaft.

A-1 Rectangle VS Rectangle

A-1-1 certain corners of one rectangle are inside the other rectangle

As shown in Figure 4-7 to Figure 4-9, one or more corners of one rectangle are interior to the other rectangle; in this case, intersections are identified by comparing half of the perimeter of facility 2 and the sum distance from each corner of facility 1 to the four sides of facility 2 and vice versa. Figure 4-7 may be used for illustration, given the coordinates of C_1^1 (x_1^1, y_1^1) and rotating angle of facility 1(A_g^1), corner C_4^2 (x_4^2, y_4^2) is inside facility 1, then the sum distance between C_4^2 and each side of facility 1 ($d_1 + d_2 + d_3 + d_4$, calculated by equation 4-10 to 4-13) is l_1 plus w_1, which is the sum of the length and width of facility 1. The sum distance between any point outside facility 1 and four sides of facility 1 is greater than l_1 plus w_1.

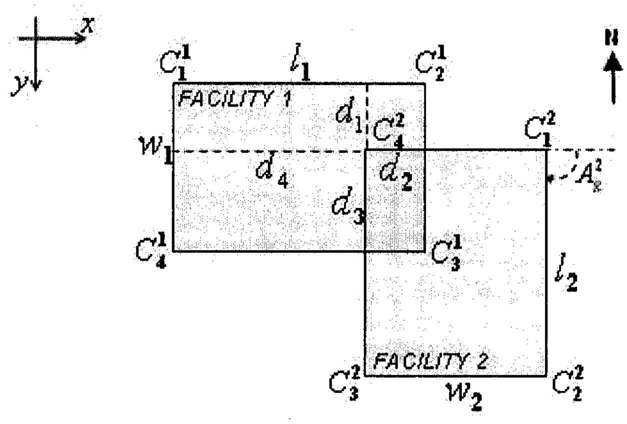


Figure 4-7 Rectangular Facility and Rectangular Facility (1-1)

$$d_1 = x_4^2 \times \sin(A_g^1) - y_4^2 \times \cos(A_g^1) + y_1^1 \times \cos(A_g^1) - x_1^1 \times \sin(A_g^1) \quad \text{(Equation 4-10)}$$

$$d_2 = -x_4^2 \times \cos(A_g^1) - y_4^2 \times \sin(A_g^1) + y_1^1 \times \sin(A_g^1) + x_1^1 \times \cos(A_g^1) + l_1 \quad \text{(Equation 4-11)}$$

$$d_3 = x_4^2 \times \sin(A_g^1) - y_4^2 \times \cos(A_g^1) + y_1^1 \times \cos(A_g^1) - x_1^1 \times \sin(A_g^1) + w_1 \quad \text{(Equation 4-12)}$$

$$d_4 = -x_4^2 \times \cos(A_g^1) - y_4^2 \times \sin(A_g^1) + y_1^1 \times \sin(A_g^1) + x_1^1 \times \cos(A_g^1) \quad \text{(Equation 4-13)}$$

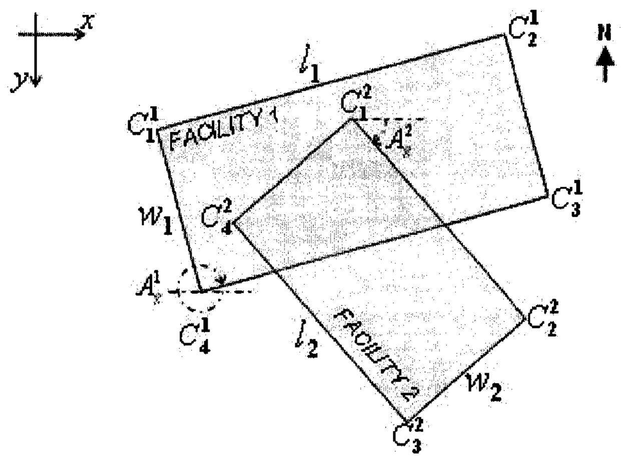


Figure 4-8 Rectangular Facility and Rectangular Facility (1-2)

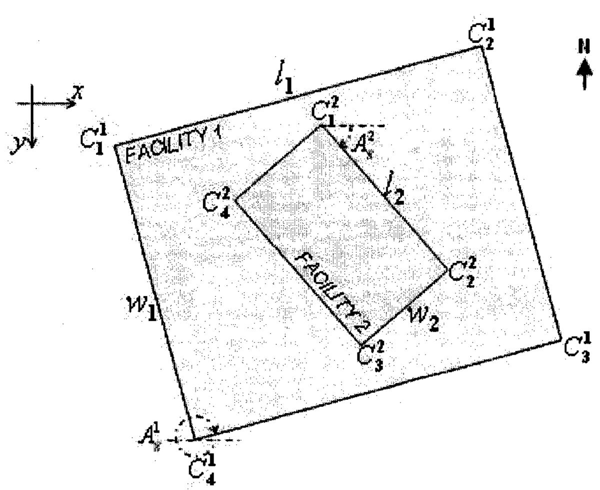


Figure 4-9 Rectangular Facility and Rectangular Facility (1-3)

A-1-2 no corner of one rectangle is inside the other rectangle

Methods discussed in A-1-1 cover all facility colliding cases except that shown in Figure 4-10. If none of the rectangle's corners is inside the other, then one of the two diagonals of one rectangle must be intersecting with no less than one diagonal of the other rectangle once overlapping happens.

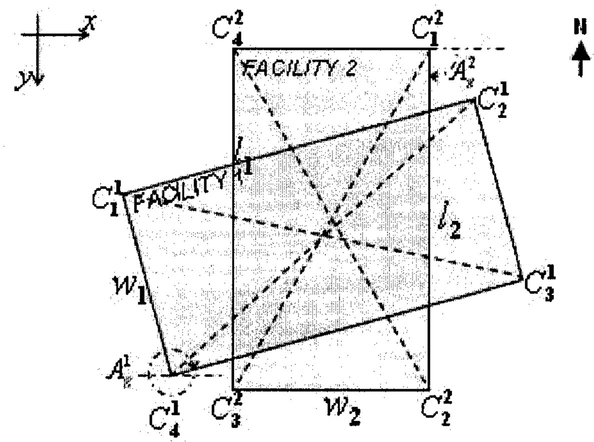


Figure 4-10 Rectangular Facility and Rectangular Facility (2-1)

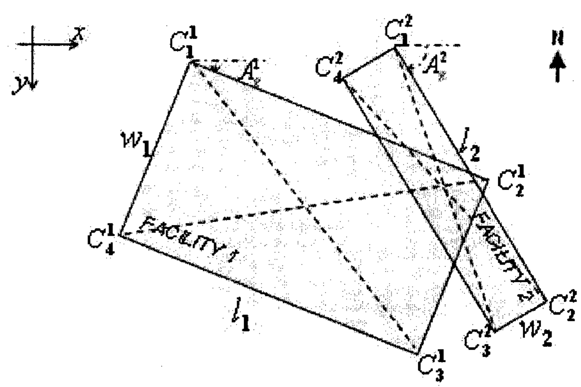


Figure 4-11 Rectangular Facility and Rectangular Facility (2-2)

If the coordinates for Corners C_1^1, C_3^1, C_1^2, C_3^2 are $(x_1^1, y_1^1), (x_3^1, y_3^1)$, (x_1^2, y_1^2), and (x_3^2, y_3^2), respectively, then the respective diagonal equations connecting C_1^1 and C_3^1, C_1^2 and C_3^2 are as follows:

$$y = \frac{y_3^1 - y_1^1}{x_3^1 - x_1^1} \times x + \frac{x_3^1 \times y_1^1 - x_1^1 \times y_3^1}{x_3^1 - x_1^1} \quad \text{(Equation 4-14)}$$

$$y = \frac{y_3^2 - y_1^2}{x_3^2 - x_1^2} \times x + \frac{x_3^2 \times y_1^2 - x_1^2 \times y_3^2}{x_3^2 - x_1^2} \quad \text{(Equation 4-15)}$$

Note that equation 4-16 and equation 4-17 are used instead when the diagonal lines are perpendicular to X-axis.

$$x = x_1^1 \quad \text{(Equation 4-16)}$$

$$x = x_1^2 \quad \text{(Equation 4-17)}$$

Similarly, equations can be applied to the other two diagonals. A maximum 4 points of intersection can be obtained. If one intersection point's coordinates are (x_k, y_k), the next step will be to check whether either of them are inside both rectangles by applying the following inequalities:

$$(x_k - x_1^1) \times (x_k - x_3^1) \leq 0 \quad \text{(Equation 4-18)}$$

$$(y_k - y_1^1) \times (y_k - y_3^1) \leq 0 \quad \text{(Equation 4-19)}$$

$$(x_k - x_1^2) \times (x_k - x_3^2) \leq 0 \quad \text{(Equation 4-20)}$$

$$(y_k - y_1^2) \times (y_k - y_3^2) \leq 0 \quad \text{(Equation 4-21)}$$

Once inequalities 4-18, 4-19, 4-20 and 4-21 are all satisfied, point (x_k, y_k), which is one of the intersection points between facility 1 and facility 2, can be declared as an overlapping area that exists between two facilities.

The same method is to be applied when checking temporary facilities and the rectangular shaft.

A-2 Rectangle VS Circle

A-2-1 centre of circle is interior to rectangle

Suppose the circle has a diameter d and is centered at C_0 (x_0, y_0) ; the distance between C_0 and each edge of facility 1 is d_1, d_2, d_3 and d_4, respectively (Figure 4-12). A similar method to A-1-1 can be applied to check if C_0 is inside of facility 1. Refer to equation 4-10 to 4-13 as distance between a point and a line.

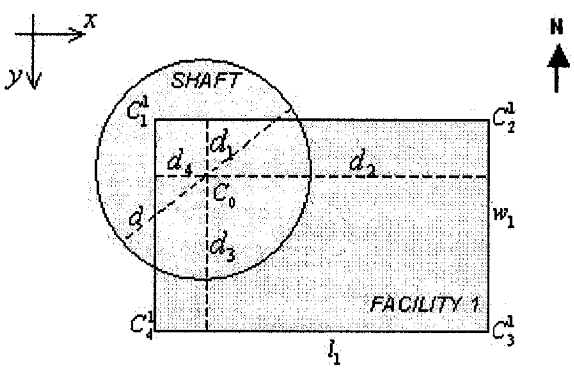


Figure 4-12 Rectangular Facility and Circular Shaft (1)

A-2-2 center of circle is outside rectangle

Overlapping still could exist even if the center of the circle is not interior to the rectangle; examples include Figure 4-13 and Figure 4-14, which basically cover all other overlapping cases.

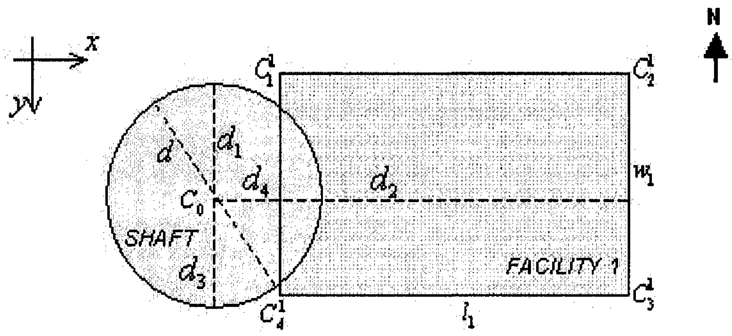


Figure 4-13 Rectangular Facility and Circular Shaft (2)

In both figures, d_1, d_2, d_3 and d_4 are used to express distances between circle center C_0 and rectangle sides. They can be easily calculated using equations 4-10 to 4-13. If the minimum value among d_1, d_2, d_3 and d_4 is $d_{\min}$, and the corresponding side is E_j, then if

$$d_{\min} < \frac{d}{2} \qquad \text{(Equation 4-22)}$$

is satisfied, then we proceed to test the following conditions.

If, for the rectangle in Figure 4-13, the two adjacent sides of side E_j are E_{j+1} and E_{j-1}, and assuming that the sum distance between C_0 and E_j, and C_0 and E_{j+1} amount to the length of E_j, then the circle and the rectangle intersect.

Aside from the cases mentioned above, overlap could occur in another condition. As shown in Figure 4-14, and again given the coordinates of four corners C_1^1, C_2^1, C_3^1 and C_4^1, d, as the diameter of the circle, equation 4-23 to equation 4-26 measure the distance between C_0 (x_0, y_0) and each of the corners.

$$d_1 = \sqrt{(x_1^1 - x_0)^2 + (y_1^1 - y_0)^2} \qquad \text{(Equation 4-23)}$$

$$d_2 = \sqrt{(x_2^1 - x_0)^2 + (y_2^1 - y_0)^2} \qquad \text{(Equation 4-24)}$$

$$d_3 = \sqrt{(x_3^1 - x_0)^2 + (y_3^1 - y_0)^2} \qquad \text{(Equation 4-25)}$$

$$d_4 = \sqrt{(x_4^1 - x_0)^2 + (y_4^1 - y_0)^2} \qquad \text{(Equation 4-26)}$$

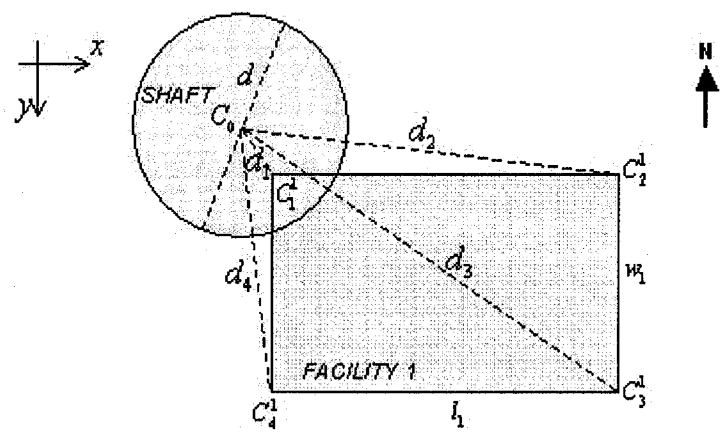


Figure 4-14 Rectangular Facility and Circular Shaft (3)

$$\min(d_1, d_2, d_3, d_4) \le \frac{d}{2} \qquad \text{(Equation 4-27)}$$

If the inequality in equation 4-27 is satisfied, then the circle and the rectangle are overlapping with each other.

4.4.2.2 Inside Site Boundaries Constraint

- *All temporary facilities should lie inside site boundaries.*

Another vital geometrical constraint is that the space occupied by any temporary facility is limited to the site boundaries (*containment* constraint). In this research, the construction site can be any convex or reentrant polygon with any number of sides. Figure 4-15 shows a construction site in the XY coordinate system; C_1^R-C_2^R-C_3^R-C_4^R is a rectangular bounding box formed by 4 points C_1^R $(x_{\min}, y_{\min})$, C_2^R $(x_{\max}, y_{\min})$, C_3^R $(x_{\max}, y_{\max})$ and C_4^R $(x_{\min}, y_{\max})$ (see also equation 4-28 to equation 4-31 for obtaining $x_{\min}$, $x_{\max}$, $y_{\min}$ and $y_{\max}$). The checking procedure relies on three steps.

$$x_{\min} = \min(x_1^c, x_2^c, x_3^c, x_4^c, x_5^c, x_6^c, x_7^c, x_8^c) \quad \text{(Equation 4-28)}$$

$$y_{\min} = \min(y_1^c, y_2^c, y_3^c, y_4^c, y_5^c, y_6^c, y_7^c, y_8^c) \quad \text{(Equation 4-29)}$$

$$x_{\max} = \max(x_1^c, x_2^c, x_3^c, x_4^c, x_5^c, x_6^c, x_7^c, x_8^c) \quad \text{(Equation 4-30)}$$

$$y_{\max} = \max(y_1^c, y_2^c, y_3^c, y_4^c, y_5^c, y_6^c, y_7^c, y_8^c) \quad \text{(Equation 4-31)}$$

B-1 certain part of one or more facilities are outside bounding box $C_1^R\ C_2^R\ C_3^R\ C_4^R$

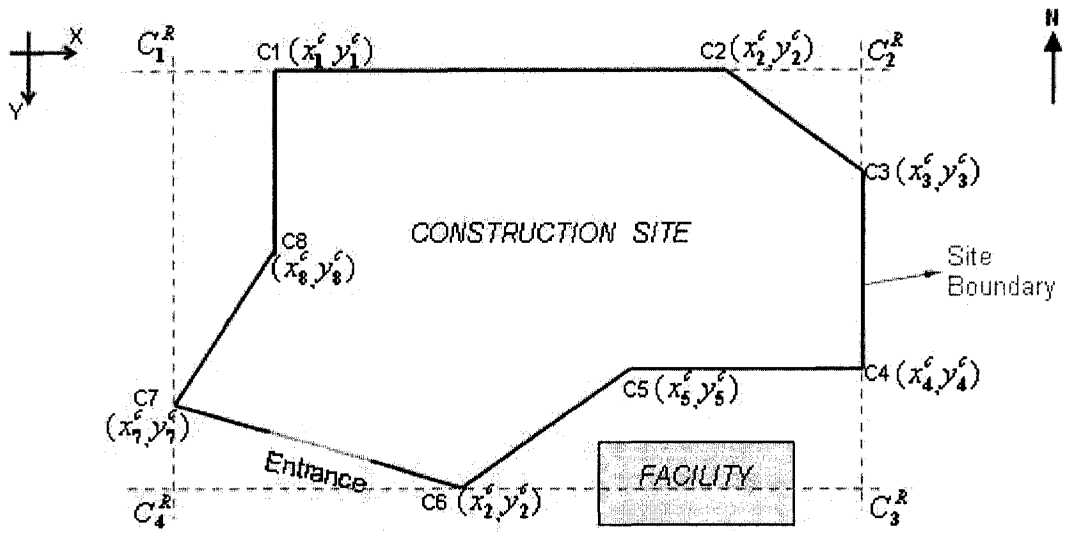


Figure 4-15 Facility inside Site Boundaries (1)

As shown in Figure 4-15, the problem is translated into checking if two rectangles are intersecting with each other; hence, only corners checking are reserved in this step. If it assumed that one corner of facility 1 is positioned at (x_1^1, y_1^1), and if either of the inequalities 4-32 and 4-33 is satisfied, then the result of the inside site boundaries check is false.

$$(x_1^1 - x_{\max}) \times (x_1^1 - x_{\min}) \geq \mathbf{0} \qquad \text{(Equation 4-32)}$$

$$(y_1^1 - y_{\max}) \times (y_1^1 - y_{\min}) \geq \mathbf{0} \qquad \text{(Equation 4-33)}$$

B-2 certain parts of one or more facilities are between the bounding box and site boundaries, while corners of all facilities are inside site boundaries.

The results of checking the constraint can be false when all of the corners of a facility are inside site boundaries; Figure 4-16 is a typical example. This situation could occur only when the site is reentrant polygonal in shape. As long as one intersection point is found between any side of a rectangle and any of the site borders, the rectangle is outside of the site boundaries.

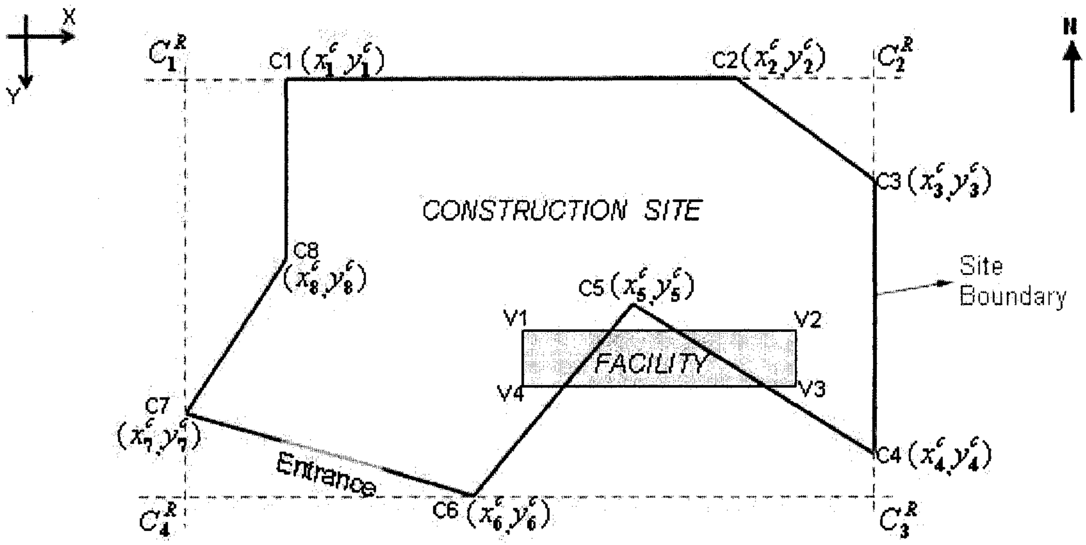


Figure 4-16 Facility inside Site Boundaries (2)

The following expressions are site border equations and facility side equations. Note that equation 4-35 is a substitute of equation 4-34 when the two adjacent site corners have the same x-coordinates. A similar application is made using equations 4-36 and 4-37.

$$y = \frac{y_{j+1} - y_j}{x_{j+1} - x_j} \times x + \frac{x_{j+1} \times y_j - x_j \times y_{j+1}}{x_{j+1} - x_j} \qquad \text{(Equation 4-34)}$$

$$x = x_j \qquad \text{(Equation 4-35)}$$

$$y = \frac{y_{v+1} - y_v}{x_{v+1} - x_v} \times x + \frac{x_{v+1} \times y_v - x_v \times y_{v+1}}{x_{v+1} - x_v} \qquad \text{(Equation 4-36)}$$

$$x = x_v \qquad \text{(Equation 4-37)}$$

(x_j, y_j) is a set of coordinates of any corner (say Cj) among C1 to C8 in Figure 4-16, while (x_{j+1}, y_{j+1}) are coordinates of Cj's following corner (along clockwise direction);

(x_v, y_v) is a set of coordinates of any corner (say Vv) among V1 to V4 in Figure 4-16, while (x_{v+1}, y_{v+1}) are coordinates of Vv's following corner (along clockwise direction). By setting the two y-coordinates as equal, coordinates for the point of intersection can be worded out; for example, the (x_c, y_c) equation can be employed. Again, if the inequalities below are satisfied simultaneously, facility 1 will be detected outside site boundaries.

$(x_c - x_v) \times (x_c - x_{v+1}) \le 0$ (Equation 4-38)

$(x_c - x_j) \times (x_c - x_{j+1}) \le 0$ (Equation 4-39)

$(y_c - y_v) \times (y_c - y_{v+1}) \le 0$ (Equation 4-40)

$(y_c - y_j) \times (y_c - y_{j+1}) \le 0$ (Equation 4-41)

B-3 certain corners of one or more facilities are between bounding box $C_1^R\ C_2^R\ C_3^R\ C_4^R$ and construction site borders

It is to be noted that users are restricted in obeying a clockwise direction when inputting the coordinates of site corners (C1 to C8 as shown in the figure below) in the template developed. Other than the conditions mentioned above, facilities could be positioned between site boundaries and the bounding box. In this case, corners of each facility can be checked by the method presented below.

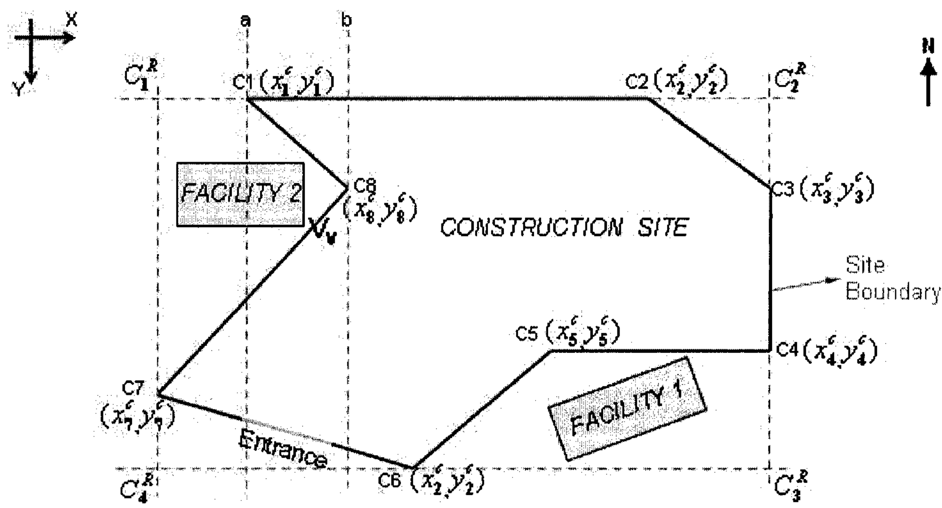


Figure 4-17 Facility inside Site Boundaries (3)

Coordinates C_j (x_j, y_j), C_{j+1} (x_{j+1}, y_{j+1}), V_v (x_v, y_v) and V_{v+1} (x_{v+1}, y_{v+1}) are defined in Section B-2. A special condition is that x_j equals to x_{j+1}, checking concludes with false if any of the following items is satisfied:

- $y_j < y_v < y_{j+1}$ and $x_v \geq x_j$
- $y_{j+1} < y_v < y_j$ and $x_v \leq x_j$
- $y_v = y_j$ or y_{j+1} and $y_j > y_{j+1}$ and $x_v \leq x_j$
- $y_v = y_j$ or y_{j+1} and $y_j < y_{j+1}$ and $x_v \geq x_j$

If none of these equations are satisfied, for each V_v, first we count the number of site borders (named Ns) with x-intervals containing x_v. Next, another parameter named Nc with an initial value of 0 is used for the following statements:

a. If $x_j > x_{j+1}$ and x_v is contained by the interval (x_{j+1}, x_j) and $y_v < kx + m$
b. If $x_j < x_{j+1}$ and x_v is contained by the interval (x_j, x_{j+1}) and $y_v > kx + m$

Where: $y = kx + m$ is equation of the line connecting C_j and C_{j+1} ; k and m can be attained by applying equation 4-31.

If items a or b or both are satisfied, then Nc is increased by 1. Third, having obtained the values for Nc and Ns, we evaluate the following conditions:

c. If Ns=2 and Nc<2
d. If Ns=3 and Nc<2
e. If Ns=4 and Nc<3
f. If Ns>4, item a or item b is partially satisfied ($y_v \geq kx + m$ for a or $y_v \leq kx + m$ for b) when applying site border $C_j\ C_{j+1}$ as well as any other borders adjacent to $C_j\ C_{j+1}$

The facility is outside of the site boundaries if any of the above items is satisfied.

In Figure 4-17, for example, Ns equals 4 and Nc equals 2, corresponding to the Point V_v shown. Thus, test result from the application of the method is that facility 2 is outside of site boundaries.

4.4.2.3 Orientation Constraint

- *Spoil Muck Bin and Draw Works should be located on different sides of the shaft.*

This constraint deals with the position of one temporary facility in relation to another. Expressions such as "left of", "right of", "in front of", "behind", "north of", "west of", and "south-east of" are frequently used by researchers.

$$(x_0^2 - x_0^0) \times (x_0^1 - x_0^0) \leq 0 \qquad \text{(Equation 4-42)}$$

$(y_0^2 - y_0^0) \times (y_0^1 - y_0^0) \le 0$ (Equation 4-43)

Considering the example given above (graphical representation is shown in Figure 4-18), if it is assumed that facility 1 represents the spoil muck bin and facility 2 represents draw works with the corresponding coordinates shown in Figure 4-18, then once equation 4-42 and equation 4-43 are met simultaneously, the orientation constraint between the two facilities is satisfied. Note the condition that two facilities having the same x- or y-coordinates are included by these two equations.

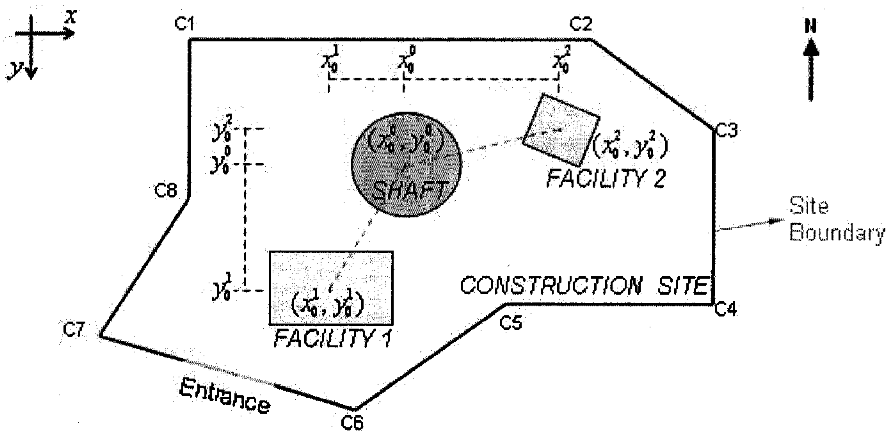


Figure 4-18 Representation of Orientation Constraint

4.4.2.4 Access Constraint

- *Traffic routes are required to have a width of 4m between every pair of specific facilities.*

This constraint identifies the existence of unobstructed routes with specified widths between two facilities or between one facility and the site entrance, to enable resources (labour, material, and equipment) or dirt to be brought onto site, taken off site, and moved around site; this is termed *access*. In this study, the access-related facilities are comprised of *site parking, spoil pile, area for allocated for Tracks, Rail ties, timbers, miscellaneous*

Supplies, area for storage and heating of concrete segments and *area for offloading material from tractor trailers*. Figure 4-19 depicts the graphical representation of this constraint, with unobstructed routes among entrance, F1, F2 and F3, which are access-related facilities on the shown site. It is obviously a qualified layout in terms of satisfying access constraint.

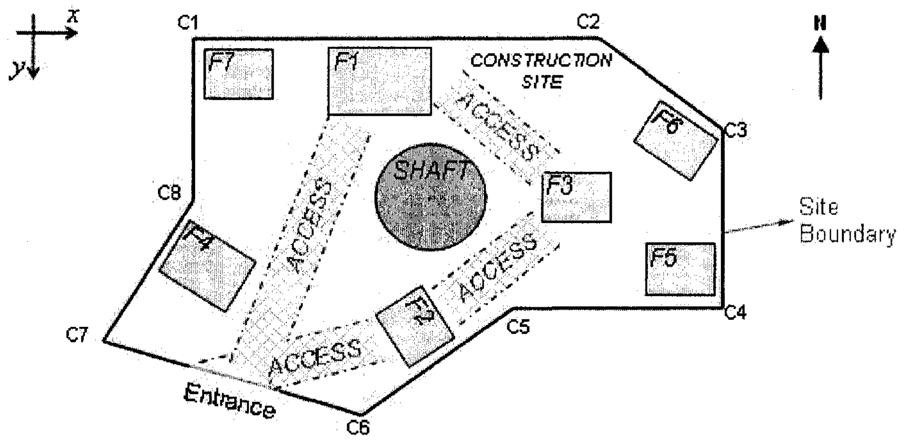


Figure 4-19 Representation of Access Constraint

4.4.3 Soft Constraints

If we assess the satisfaction scheme of the constraints with functions, then hard constraints would be represented by some discrete function, such as binary functions, taking a value of 0 or 1 using a threshold value; conversely, a suitable continuous function would be utilized to represent soft constraints. Soft constraints express less strict preferences in terms of the conditions' proximity weights. The function value rises or falls in a continuous manner according to the nature of the specific soft constraint it represents. The corresponding function of each soft constraint might reflect two facilities' orientation desirability, equipment accessibility, closeness desirability, and so on, as detailed in the following sections.

4.4.3.1 Distance Constraint

- *The distance between the centre points of the spoil muck bin and hoist is preferred to be 6m.*

This constraint limits the distance between centers of two temporary facilities, or between a temporary facility and a dedicated area or shaft, to be greater or less than a specified value. Given the centre points' coordinates (x_0^1, y_0^1) and (x_0^2, y_0^2) of two interacting facilities, the distance between them can be measured using equation 4-44.

$$d_i = \sqrt{(x_0^2 - x_0^1)^2 + (y_0^2 - y_0^1)^2} \quad \text{(Equation 4-44)}$$

In Figure 4-20, it is assumed that the preferred distance between facility 1 and facility 2 is 7m exactly; the weight of the constraint *(Wt)* is assigned a value of 10, the satisfaction score between the constrained and constraining facilities can be mathematically attained by equation 4-45.

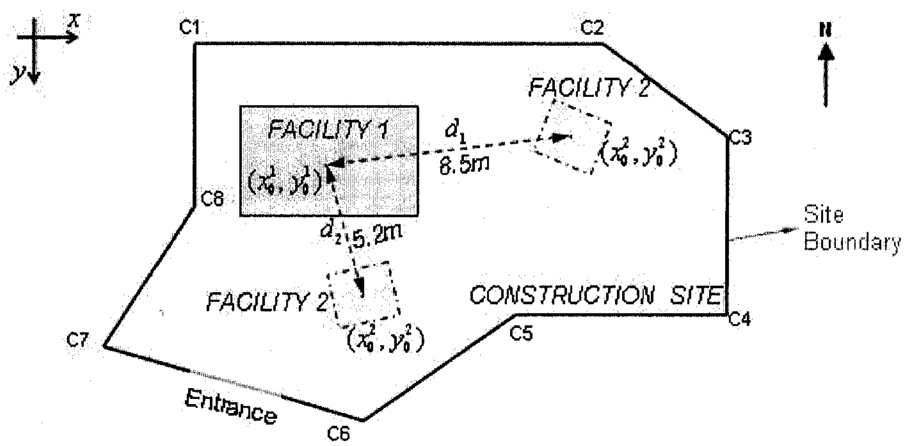


Figure 4-20 Representation of Distance Constraint

By applying equation 4-45, location 2 gets a satisfaction score of 6.78, while location 1 gets a score of 5.52. Thus, regardless of other constraints, location 1 is preferred over location 2 for placing facility 2.

$$FitS = \begin{cases} Wt \times d_{ac}^2 / d_{std}^2 & (\text{if } d_{ac} < d_{std}) \\ Wt \times d_{std}^2 / d_{ac}^2 & (\text{if } d_{ac} > d_{std}) \end{cases}$$ (Equation 4-45)

Where: *FitS* represents the satisfaction score, d_{ac} is the actual distance between the pair of facilities; d_{std} is the required distance between the facilities; *Wt* represents the weight of the specified condition among all other conditions.

4.4.3.2 Adjacency Constraint

- *Two tool cribs should be placed next to each other.*
- *The mole cable lay down platform should be next to the gear switch.*

Adjacency constraint tests whether the facility at hand is located next to another facility, dedicated area, or site boundaries. In this study, adjacency is defined as two facilities having a central distance equal to half of the sum of their respective largest dimensions, or a facility having a distance of half of its largest dimension to the site boundary. An assessing equation similar to equation 4-45 is given to measure the satisfaction score.

$$d_{std} = (l_1 + l_2)/2$$ (Equation 4-46)

$$FitS = \begin{cases} Wt \times d_{std}^2 / d_{ac}^2 & (\text{if } d_{ac} > d_{std}) \\ Wt \times d_{ac} / d_{std} & (\text{if } d_{ac} < d_{std}) \end{cases}$$ (Equation 4-47)

Where: *FitS* represents the satisfaction score, d_{ac} is the actual distance between the pair of facilities; d_{std} is the required distance between the facilities; l_1 and l_2 correspond to length of the two rectangles representing the facilities; *Wt* denotes the weight of the specified condition among all other conditions.

Note that in equation 4-47, linear function is used instead of exponential function once the distance between the two facilities reaches the desirable distance d_{std}. This is to prevent the satisfaction score from being arbitrarily high when the actual distance is less than the desirable distance. Despite being adjacent, the two facilities in question are disjointed from each other, controlled by the hard constraint—no overlapping.

For example, in Figure 4-21, if Wt has a value of 10; l_1 and l_2 are 5m and 1.2m, separately; d_{ac} for the two locations is 4m and 5.5m, correspondingly; then, based on equation 4-46 and equation 4-47, the satisfaction scores for the two locations are 6.01 and 3.18, respectively. Location 2 is preferred over location 1 regardless of other constraints.

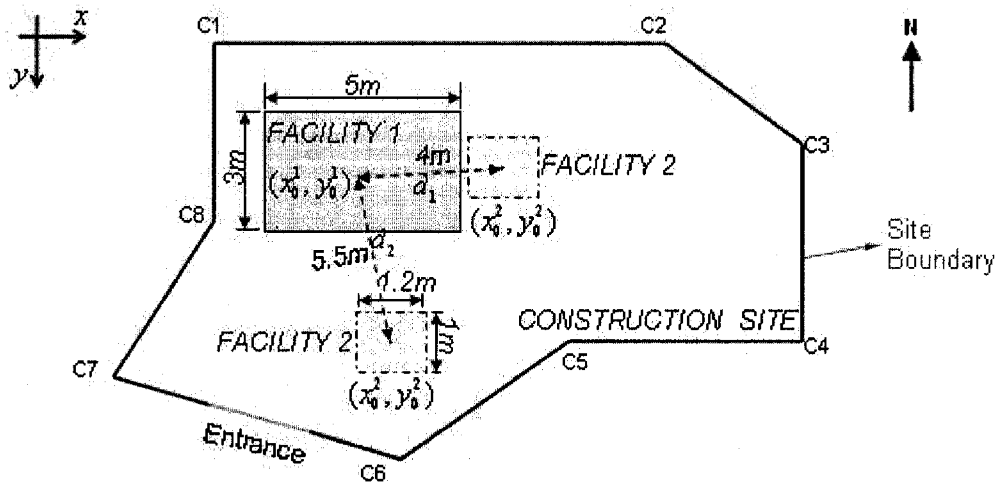


Figure 4-21 Representation of Adjacency Constraint

4.4.3.3 Parallel / Perpendicular Constraint

- *Power trailer runs parallel to tunnel centre line.*

This constraint limits the orientation of one facility to be either parallel or perpendicular to another, and it is commonly used on tunnel construction sites. Subsets of this constraint are the largest edges of the interacting facilities parallel to each other (condition (a)), and any edge of one facility is parallel (or perpendicular) to the other one (condition (b)). In the first case, rotating angels of the two facilities are identical, or have a difference of 180^0; conversely, in the second situation, the difference of the two rotating angels can be any integer times of 90^0. Once the facilities are parallel or perpendicular, as required, a full satisfaction score is obtained; otherwise, descending scores of different conditions can be calculated accordingly. Two equations expressing the mentioned conditions were inferred and shown below, used for assessing condition (a) and condition (b), respectively.

$$FitS = Wt \times \frac{(90 + 180 \times \text{int}(|A_g^1 - A_g^2|/180) - |A_g^1 - A_g^2|)^2}{90^2} \qquad \text{(Equation 4-48)}$$

$$FitS = Wt \times \frac{(|45 + 90 \times \text{int}(|A_g^1 - A_g^2|/90) - |A_g^1 - A_g^2|| \bmod 45)^2}{45^2} \qquad \text{(Equation 4-49)}$$

Where: *FitS* represents the satisfaction score; *Wt* denotes the weight of the specified condition among all other conditions; A_g^1 and A_g^2 are clockwise rotating angles of the two interacting facilities.

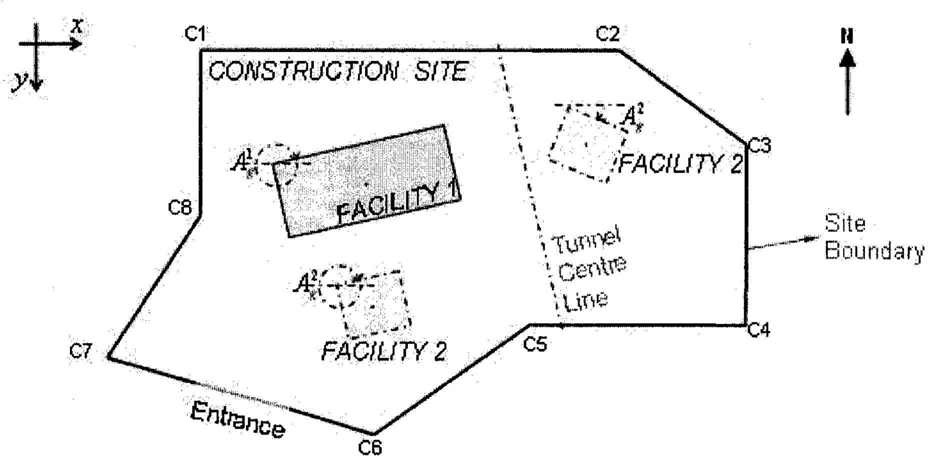


Figure 4-22 Representation of Parallel/Perpendicular Constraint

If facility 1 and facility 2 in Figure 4-22 are supposed to satisfy the parallel constraint in any manner, then evidently location 2 for facility 2 would have a higher satisfaction score. Similarly, if facility 1 represents the power trailer, since the slope of its short edge equals that of the tunnel centre line in Figure 4-22, then this layout has a full satisfaction score in satisfying the sample constraint mentioned above.

4.4.3.4 Closeness Constraint

- *Electrical facilities should be closed to each other.*
- *Propane tank should be farthest away from the shaft.*

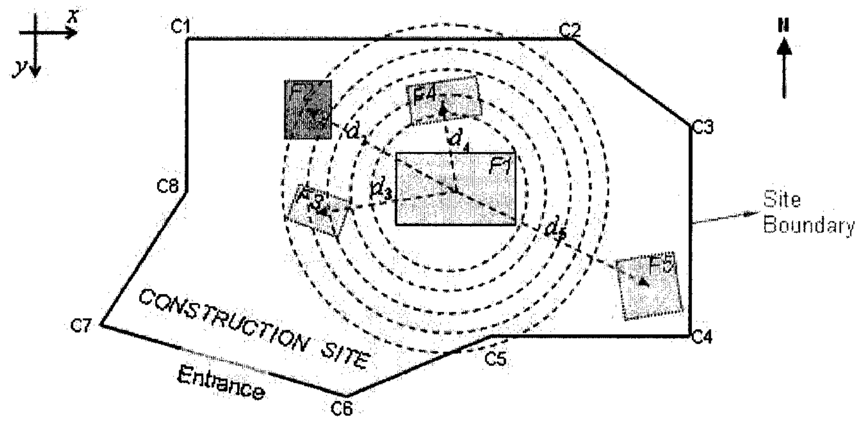


Figure 4-23 Representation of Closeness Constraint

This constraint is somewhat similar to "Adjacency Constraint". It tries to limit a group of facilities being located *close to* or *far from* each other. In this study, this constraint is measured using the polar distances of the interactive facilities, taking a constraining facility as the reference point. For the "close to" relation, it is the most desirable situation that all constrained facilities are closer to the reference point than any other facility. In other words, for the rings formed by the center points of all constrained facilities circumscribing the constraining facility in Figure 4-23, all and only constrained facilities are preferred to be placed within the largest ring; conversely, for the "far from" relation, if the constrained facility is placed further than any others to the reference point, a full satisfaction score can be obtained; otherwise, the score decreases to a minimum value of 0. Equations 4-50 and 4-51 mathematically express the "close to" and "far from" relations, respectively.

In the above example and Figure 4-23, supposed F1, F3, F4 and F5 are electrical facilities on site, F2 is some facility not belonging to the "electrical" group, F1 is a reference facility; d_2, d_3, d_4 and d_5 are assigned values of 5m, 4m, 3m and 6m, respectively; *Wt* is 10; then the satisfaction score for this layout can be calculated, which is 6.94. Similarly, if the second example mentioned above is represented by Figure 4-23, a satisfaction scale can be measured by applying equation 4-51.

$$FitS = \begin{cases} Wt \times d_{min}^2 / d_{max}^2 & \text{if } d_{max} > d_{min} \\ Wt \times d_{max} / d_{min} & \text{if } d_{max} < d_{min} \end{cases}$$ (Equation 4-50)

Where: *FitS* represents the satisfaction score; d_{min} indicates the minimum distance between the reference facility and all *un-constrained* facilities; d_{max} is the maximum distance between the reference facility and all *constrained* facilities; *Wt* denotes the weight of the specified condition among all other conditions.

$$FitS = \begin{cases} Wt \times d_{min}^2 / d_{max}^2 & \text{if } d_{max} < d_{min} \\ Wt \times d_{max} / d_{min} & \text{if } d_{max} > d_{min} \end{cases}$$ (Equation 4-51)

Where: *FitS* and *Wt* are referred to equation 4-50; d_{min} indicates the minimum distance between the reference facility and all *constrained* facilities; d_{max} is maximum distance between the reference facility and all *un-constrained* facilities.

It should be noted that when applying the aforementioned constraints, d_0 instead of d (Equation 4-52) is used with respect to precision, since the dimensions of most facilities in question are not negligible compared to the suggested or required distance.

$$d_0 = d - l_1/2 - l_2/2 \qquad \text{(Equation 4-52)}$$

Where: l_1 and l_1 denote the lengths of interacting facilities' long edges; d is referred to equation 4-44.

4.5 PROPOSED GENETIC ALGORITHMS MODEL

Having defined the proposed site layout model in terms of site, facility and obstacle representation, and a set of constraints implemented, an optimization-search procedure is developed using GA in a simulation environment (*Simphony*) to seek optimum or near optimum locations for temporary facilities on tunneling site. The implementation of the *Simphony* environment facilitates the visualization of site facilities and the construction layout as a whole, as well as the geometric reasoning of site analysis. Furthermore, its programmable features and integrated capabilities with MS Visual Basic facilitate developing the optimization engine. In the following sections, the functionality, objectives, and mechanism of the proposed template will be presented in detail.

4.5.1 Solution Encoding

Usually, the two main components of genetic algorithms are problem encoding and evaluation function. The way in which candidate solutions are encoded is a key factor in the success of a genetic algorithm. According to Goldberg (1989), when encoding, users should select a proper form so that short, low-order schemata remain relevant to the underlying problem and relatively unrelated to schemata over other fixed positions; also, the representation should be a minimal complete expression of a solution to the problem.

Since the chromosome length and the associated combinatorial explosion can greatly impact the performance of a genetic algorithm, only feasible and meaningful genes should be included. One of the most common forms of encoding is binary encoding in spite of its sometimes unnatural and unwieldy manner for representing some problems. The initial work using GA was held as this encoding scheme, and much of the existing GA theory is based on the assumption of fixed-length, fixed-order binary encoding.

Some empirical comparisons have shown that real-valued encoding performed better than binary encoding in certain cases (Wright 1991); an example is applications with problems where complicated values are used. In this study, the representation follows the real-valued encoding. Figure 4-24 illustrates the encoding of a certain solution to assigning *n* temporary facilities. As mentioned previously, the tunnel construction site is represented by a polygon in a reference frame; temporary facilities are represented by their dimensions, the coordinates of facilities' central points, and rotating angles (*A*). Permanent facilities have fixed positions in the coordinate system; hence, they are not directly associated with the genes. Nevertheless, they do participate in objective functions, as well as determining temporary facilities' dimensions. Thus, each gene has two attributes: its ID (sequence number) and the facility rotating angle or either of the coordinates, depending on its sequence in the chromosome. The number of genes corresponds to three times the number of temporary facilities. To help map attributes of temporary facilities to gene positions, all temporary facilities are ranked backstage once created in *Simphony* based on their ID. In this way, the first facility is mapped to the first three genes' positions and the second facility occupies the subsequent three positions, and so on. Therefore, the objective of solving the site layout problem is transformed into a matter of finding the optimum set of values for the genes in the chromosome matrix (from *X1* to *An* in Figure 4-24).

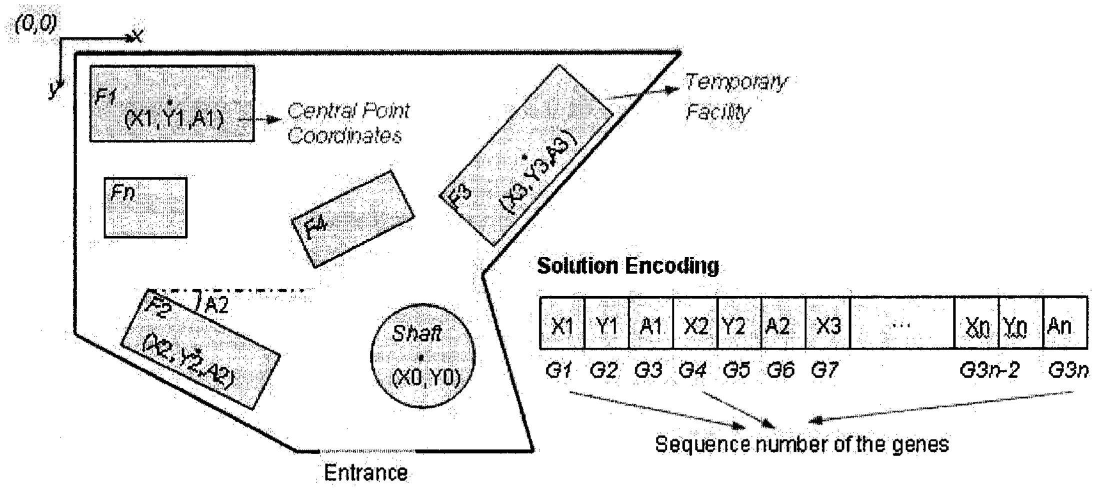


Figure 4-24 GA Encoding of Two-Dimension Space

4.5.2 Genetic Operators

The following is a description of the various genetic operators that have been developed specifically for this research.

- Selection and Elitism operator This is the first operator applied to a population with the goal of enabling chromosomes with good fitness to have a higher probability contributing offspring in the next generation. As mentioned above, *roulette wheel selection* is a classical and the most commonly used method. This method selects a parent chromosome with the probability proportionally corresponding to its fitness; however, errors associated with this method have been reported, especially in cases when a generation has a few chromosomes with arbitrarily high fitness value. Often, these chromosomes and their descendents will multiply quickly in the population, in effect preventing the GA from doing any further exploration, which is known as *"premature convergence"* (Mitchell 1999). Thus, potentially rich genetic information would be lost from the population due to a domination by a small number of chromosomes.

An alternative selection scheme used by researchers to prevent overhasty convergence is named *rank selection*. Instead of using absolute fitness for scaling, chromosomes are ranked based on their fitness and linear values are given to them for selection accordingly in order to reduce the selection pressure if the fitness variance is too high. Despite leading to a more successful search than proportionate selection, rank selection has a possible disadvantage if slowing down selection pressure means the GA will in some cases be slower in finding highly fit chromosomes (Mitchell 1999).

In this research, a variation of rank selection with elitism is used as a selection scheme. As illustrated in Figure 4-25, all chromosomes from *C1* to *Cm*, mainly in a population, are sorted by fitness descending, each of which is associated with a selection probability (P_i) determined by equation 4-53. A certain number of chromosomes (say N_{el}) with the highest fitness value (C1 to C4) is retained and passed onto the next generation directly. By generating random numbers and comparing the numbers with each P_i (corresponding to the length of each gray interval shown in Figure 4-25) repeatedly, (N_{ch} - N_{el})/2 pairs of parents are selected for performing the next operation and the remaining chromosomes are abandoned. In this way, the best chromosomes in each generation are kept to test again and assigned more chances to control offspring allocation. As a result, reliable fitness estimates are increasingly gained. It should be noted that such a selection does not alter the genes of chromosomes, and the number of chromosomes within a population keeps constant through the entire GA operation processes.

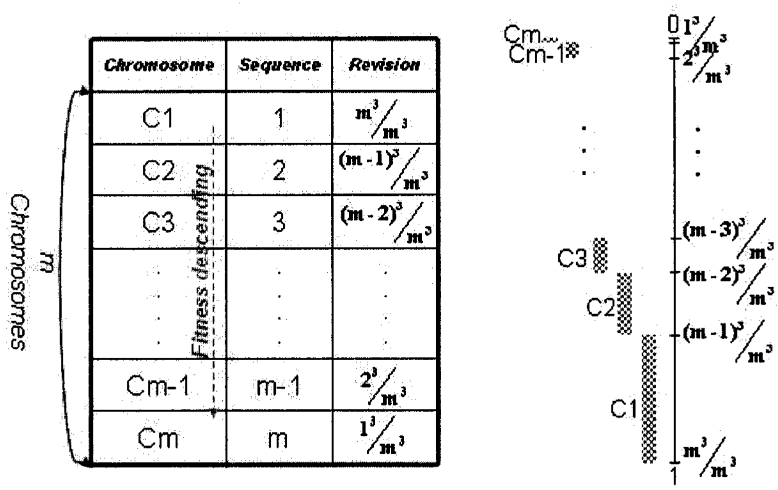


Figure 4-25 GA Selection Operator

$$P_i = \frac{(N_{ch} + 1 - i)^3 - (N_{ch} - i)^3}{N_{ch}^{\ 3}} \qquad \text{(Equation 4-53)}$$

Where: P_i is the possibility of the chromosome i being selected, N_{ch} is the number of chromosomes in one population (corresponding to m in Figure 4-25).

- Crossover operator: The selected pairs of chromosomes from the anterior operator partially exchange information with each other. The simplest form, one-point crossover, has been revealed having some defects—*position bias* (the schemas that can be created or destroyed by a crossover depend strongly on the location of the bits in the chromosome) and *endpoint effect* (the segments exchanged between the two parents always contain the endpoints of the chromosomes) (Mitchell 1999). The operator might therefore negatively impact the quality of an existing good solution especially the long ones (Goldberg 1999). Uniform crossover, on the other hand, can completely overcome positional bias, yet the feature prevents co-adapted genes from ever forming in the population.

Two-point crossover technique is adopted in this research so as to get rid of endpoint effect and reduce positional bias. To perform the operation, two random numbers R_{C1} and R_{C2} are generated according to equations 4-54, 4-55 and 4-56, and the pair of chromosomes undergo crossover at the cut-off points R_{C1} and R_{C2}. Repeatedly, the new population then consists of N_{el} elites and (N_{ch} - N_{el}) chromosomes created by selection and crossover. Note that by employing equation 4-55 and equation 4-56, every group of genes together representing a temporary facility is protected from being destroyed. When the integer part of R_{C1} equals that of R_{C2}, the method has the same performance as in a one-point crossover; if both variables are at the edge of the interval, then the offspring are identical to their parents since the pair proceeds without crossover, and mutation at certain probabilities will take place despite the absence of a cross. An illustration of the operation with two cut-off points is shown in Figure 4-26.

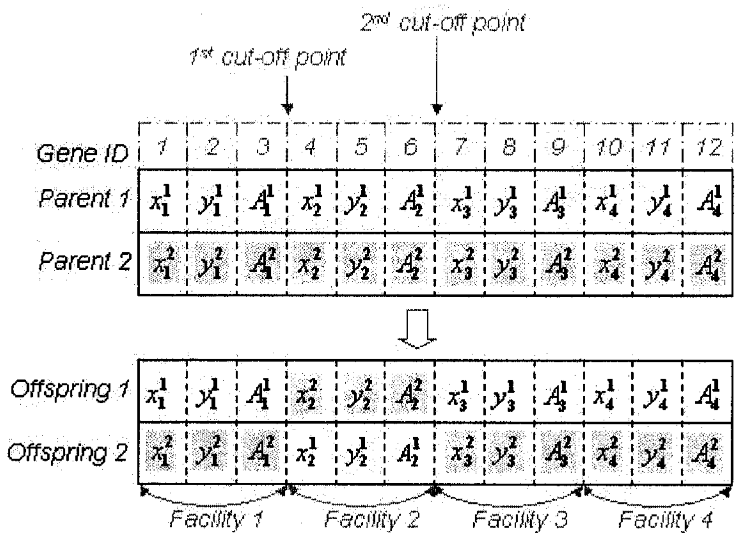


Figure 4-26 Two-Point Crossover Operation

$$R_C = Rnd \times (3 \times NF) \quad \text{(Equation 4-54)}$$

$$\text{If } \operatorname{int}(R_C \bmod 3) = 2 \text{, then } R_C = R_C + 1 \quad \text{(Equation 4-55)}$$

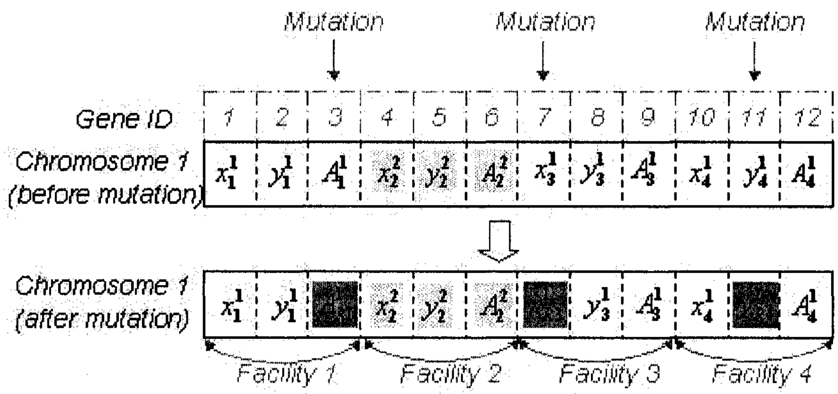
$$\text{If } \operatorname{int}(R_C \bmod 3) = 1 \text{, then } R_C = R_C + 2 \quad \text{(Equation 4-56)}$$

Where: R_C is the value required for seeking the cut-off point, *NF* represents number of temporary facilities appearing on the tunnel site; *Rnd* is a random number in the range of 0 to 1 inclusively generated by *Simphony.*

- *Mutation operator:* As a background role in GA, this operator is mainly used to interrupt current stagnation in improvement by introducing new genetic information into the population in a random manner. It is carried out after the creation of the new population in order to ensure that the new chromosomes are not uniform (Goldberg 1989). Not every search region would be explored if the mutation operation is not applied. Generally, three methods are used to perform mutation operation. *Swap mutation* is an operator that swaps two randomly selected genes. *Bit inversion* is a mutation form performing only with binary encoding: the value of a randomly selected gene is flipped from 0 to 1 or vice versa. Another type of the operation named *random offset mutation* is where a random offset is added to a gene. A modified random offset mutation operator is developed in this research to attain the required function.

Figure 4-27 is an illustration of the mutation operator used in this study. A probability of mutation P_M is set to be 0.2, i.e., twenty percent of (N_{ch} - N_{el}), chromosomes (elite members are excluded) implemented by selection and crossover operators that will be partially mutated. *Chromosome 1* in Figure 4-27 is an example chromosome derived from Figure 4-26. To carry out mutation operations, each gene in the selected chromosome is visited and replaced by a new randomly generated value at certain probabilities, termed *mutation rate* (R_M). R_M is assigned to be 0.3 in the proposed template after many trials. Results of the experiments from many previous researchers show that a too high mutation rate makes the algorithm perform only as well as a random search, while the traditional applications of GA, in turn, underestimate the power of mutation, which leads to hill-climbing strategy behaviour even better than GA.

Note that to guarantee that valid positions of the facilities are generated or assigned, random values given to the genes mutated are limited within ranges, shown in Figure 4-27. As defined previously, the values of X_{max}, X_{min}, Y_{max}, Y_{min} represent the maximum and minimum values of X-coordinate and Y-coordinate of the tunnel site boundaries' corners in the 2D orthogonal system, respectively (refer to equations 4-28 to 4-31). The operator repeatedly operates on all selected chromosomes, and once it is done, the current population is entirely replaced by the newly generated one.



Note: A_{R1}^{1} is a random value in [0,360].
x_{R3}^{1} is a random value in [Xmin, Xmax].
y_{R4}^{1} is a random value in [Ymin, Ymax]

Figure 4-27 Mutation Operation

4.5.3 Fitness Function

Fitness function provides a measure by which it can be evaluated how far each incorrectly placed number is from its correct place. Being mainly problem-dependent, a fitness function is normally a mathematical function with many parameters. The construction of an appropriate fitness function is crucial for any successful application of GA. This function might change dynamically as the evolutionary process continues, and it must consider the constraints of the problem. In a word, all its effort and features are to facilitate the work of *selection* operator (Copper 2004).

According to Goldberg (1989), any optimization problem can be naturally stated in a minimization form or a maximization form in terms of fitness function. The objective of the problem at hand is in the latter form; that is, the chromosome with the highest fitness function value is the most desirable option. The fitness or objective function in the present study can be expressed as equation 4-57, in which *T.F.* represents the total fitness value and *FitS* indicates the proximity weight assigned to each aforementioned constraint based on Table 4-2. The calculation of *FitS* is referred to in the previous section, in which the parameter *Wt* corresponds to the proximity weight in the table followed. Using the proposed fitness function has the advantage of being comprehensive, as multi-objectives can be translated into certain categories of the constraints, thus the system is able to avoid solely minimizing travel distance or travel cost. For example, it is suggested that the *propane tank* always be placed furthest away from the *shaft* among all the temporary facilities in consideration of safety, and the "Closeness" constraint with an assigned weight that can well express this requirement thus can be transformed into a subset of *T.F.*

$$T.F. = \sum FitS \qquad \text{(Equation 4-57)}$$

Table 4-2 is a modified version of one used by Hegazy and Elbertagi (1999), who originally set six levels of relationships for facilities and expressed the proximity weight in an exponential manner. For the hard constraints in the table shown, *T.F.* stays constant once all of them are satisfied; conversely, a value equals to the corresponding weight would be deducted from *T.F.* For example, if a pair of facilities is detected overlapping with each other, a deduction of 200 will be given to the fitness value; if the number of overlapping facilities is increased by one, another 200 will be deducted. As such, if one dedicated area or facility is found fully or partially to occupy the desired traffic access, a value of 100 will be taken from the total fitness for the chromosome. For soft constraints, a relatively high weight value is assigned to a group of facilities with a specified constraint if the relationship is much desirable; a zero value will be taken when the constraint is not met. Accordingly, to achieve a high fitness value, relationships with high proximity weights are always satisfied first. Appendix II presents a more detailed table illustrating the specified constraints for tunnel layout along with their proximity weights.

Table 4-2 Weights of Fitness-Related Constraints

Type of Constraint		Desired Relationship between Facilities	Proximity Weight (Y/N)
Hard Constraints	Non-Overlapping	Must	0/-200
	Inside Site Boundaries		0/-200
	Orientation	Absolutely Necessary	0/-100
	Access		0/-100
Soft Constraints	Distance Adjacency Parallel/Perpendicular Closeness	Necessary	30/0
		Especially Important	20/0
		Important	10/0
		Ordinary	5/0
		Less Important	3/0
		Unimportant	1/0

Note: "Y" indicates if the condition is satisfied; "N" indicates if the condition is not satisfied.

4.5.4 Optimization Procedure

The developed system has been implemented via *Simphony*, the simulation platform with its merits was presented in Chapter 2. The *Simphony* interface enhances users' comprehension, improves communication of technical information and by integrating with the shaft template and tunneling template developed, a comprehensive tunneling simulator can be made possible and more interactions among tunneling activities can be analyzed to better tunneling behavior. Moreover, it has high extendibility in adding new hard or soft constraints related to productivity and safety. Furthermore, it is adaptable to many site layout areas besides tunneling.

As mentioned previously, the developed system requires users to provide temporary facilities' names along with their dimensions, as well as the dimensions and rotating angles of the shaft and dedicated areas. Figure 4-28 shows the optimization procedure flowchart. In the initialization phase, the system generates a set of random yet confined coordinates and rotating angles for the user-defined temporary facilities as genes in each chromosome. The generated x- or y-coordinates are limited in a detected range $(x_{\min}, x_{\max})$ or $(y_{\min}, y_{\max})$ (these parameters were defined by equations 4-28 to 4-31), while the range for the rotating angle is $(\mathbf{0^0}, \mathbf{360^0})$ so as to avoid the infeasible positions and narrow down the search space. Each chromosome is a layout solution that can be evaluated according to the total fitness calculated.

Table 4-3 GA Parameters and Values

Parameters	Symbols	Values	Parameters	Symbols	Values
Number of Generations	N_G	1000	Number of temporary facilities	NF	User-defined
Number of Chromosomes	N_{ch}	100	Probability of Mutation	P_M	0.2
Number of Elites	N_{el}	4	Mutation Rate	R_M	0.3
Probability of Crossover	P_i	Equation 4-53	Value for seeking cut-off point	R_C	Equation 4-54

Following the initial generation, the genetic operators are applied to evolve the generation into better ones. Note that in Table 4-3, N_G and N_{ch} appear as input parameters for one modeling element and can be easily altered for users' convenience; N_{el} is essentially four percent of N_{ch}; other parameters, except for user-defined ones, are able to be changed in the developed code. The evolutionary phase repeats the *Selection-Crossover-Mutation-Fitness Calculation-Chromosomes Arrangement* procedure, with the termination criterion being the maximum number of generations N_G. Here N_G is set at 1000 to ensure that the optimization stays constant until no further improvement in the population occurs.

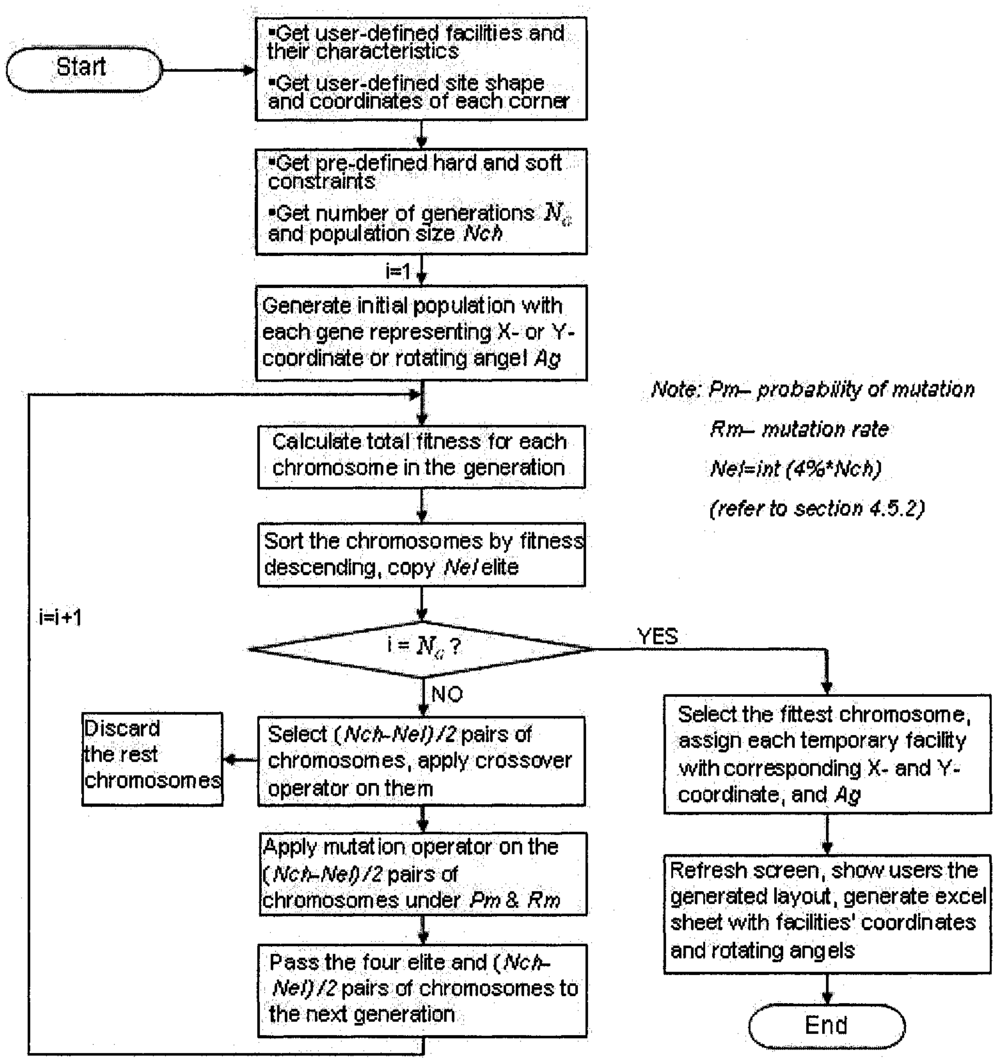


Figure 4-28 Generic Algorithm Flowchart

Once the optimum layout solution is found in the last generation, the coordinates and rotating angles represented by the genes in the chromosome are automatically assigned to the corresponding temporary facility, and each facility abstracted on the screen in the *Simphony* environment then adjusts its own position and angle; thus the graphical output is obtained. A summary for the output is created simultaneously through *MSExcel*.

4.5.5 Simphony Tunnel Layout Modeling Elements and Functions

The proposed template is integrated with Shaft template explained in Chapter 3 in the *Simphony* environment. The tunnel site layout section is comprised of four modeling elements, namely the *root* element, the *site facility* element, the *outline* element and the *shaft* element, which has been introduced previously. Figure 4-29 shows the elements from the developed template used to generate a tunnel site layout model. A review of the features of the layout modeling elements along with their functions is presented in this section.

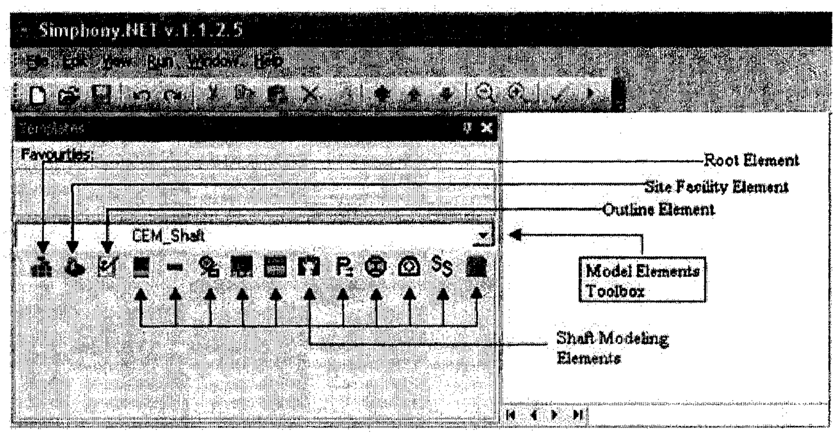


Figure 4-29 Tunnel Site Layout Modeling Elements

4.5.5.1 Root Element

The root element is a parent element designed to encompass all other modeling elements developed. It is also the main container of the site layout optimization procedure code. This element represents a whole tunnel construction site, which is simulated with shaft construction process included since "shaft" element exists as one of its child elements. A default circular "shaft" element with 14'8'' diameter and a default "soil profile" element with three layers are defined inside the element upon creation. Table 4-4 lists the input parameters for this element, in which users participate in creating the model using their knowledge and requirements to function and analyze problems. No output parameter or statistic is included in this element.

Note that among these input parameters, the number of "*X-Coordinates of each Site Polygon Corner*" or the "*Y-Coordinates of each Site Polygon Corner*" is always in accordance with the *"Number of Site Corners"*, which represents, once the *"Number of Site Corners"* is altered, the values of the coordinates of each site polygon corner. These values are changed to default and the number of these parameters increases or decreases accordingly. Two pairs of entrance coordinates are value-required from users.

Table 4-4 Root Element Input Parameters

Input Parameters	Type/ Comment	Default Values	Input Parameters	Type/ Comment	Default Values
Description	Text	Tunneling Site	Shaft Centre X-Coordinate	Numeric (fixed by this element)	50
Number of Site Corners	Integer [3,20]	7	Shaft Centre Y-Coordinate		75
Angle from East to Tunnel Centre Line	Numeric [0,180]	30	Test hole Centre X-Coordinate	Numeric (fixed by this element)	25
X-Coordinates of each Site Polygon Corner	Numeric (associated with "*Number of Site Corners*")	N/A	Test hole Centre Y-Coordinate		40
Y-Coordinates of each Site Polygon Corner			Visual Scale	Numeric [1,10]	6
Entrance X-Coordinates	Numeric (two for each)	100/100	Number of Generations	Integer	1000
Entrance Y-Coordinates		24/30	Number of Chromosomes		100

Note: All numeric values should be positive.

Simphony provides a hidden orthogonal reference system, depicted in Figure 4-30. To facilitate simulation modeling, the x-axis is specified as an eastern (positive) orientation or western (negative) orientation while the y-axis is specified as south (positive) or north (negative). A tunnel centre line is defined by an angle from the east direction to the line and shaft centre point coordinates. It should be noted that all coordinates shown on the abstracted layout are central coordinates of the elements.

Simultaneously, an arrow indicating northern orientation as well as tunneling site sides is added, removed, or updated automatically whenever any input parameter is modified. The arrow is maintained outside the right upper corner of the site polygon. As such, the tunnel centre line is drawn automatically after all parameters are assigned values and it is capable of updating itself in accord with its angle and shaft centroid coordinates.

The "Shaft" element and the "Soil Profile" element are centered at the corresponding points associated with the parameters of *"Shaft Centre Coordinates"* and *"Soil Profile Coordinates"*. If users are not satisfied with their positions, they are required to change the values in the "root" element rather than moving the elements themselves.

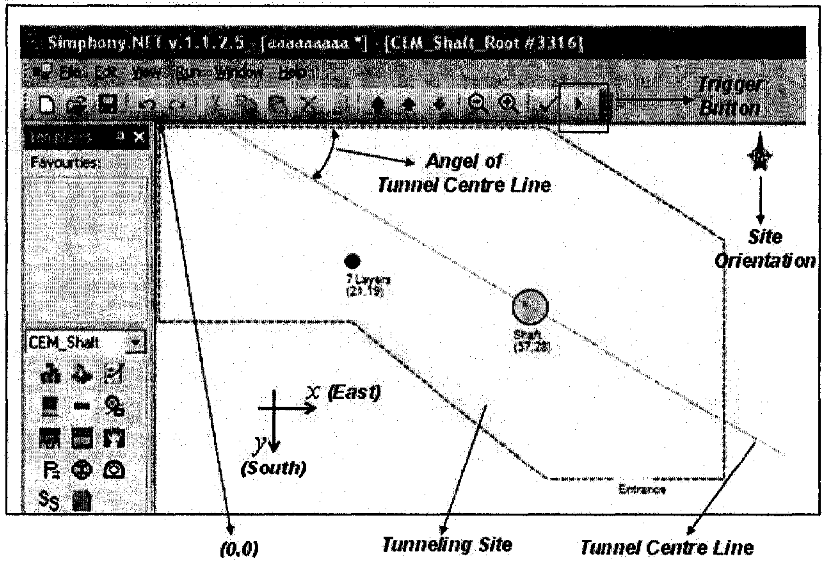


Figure 4-30 Child Window of "Root" Element

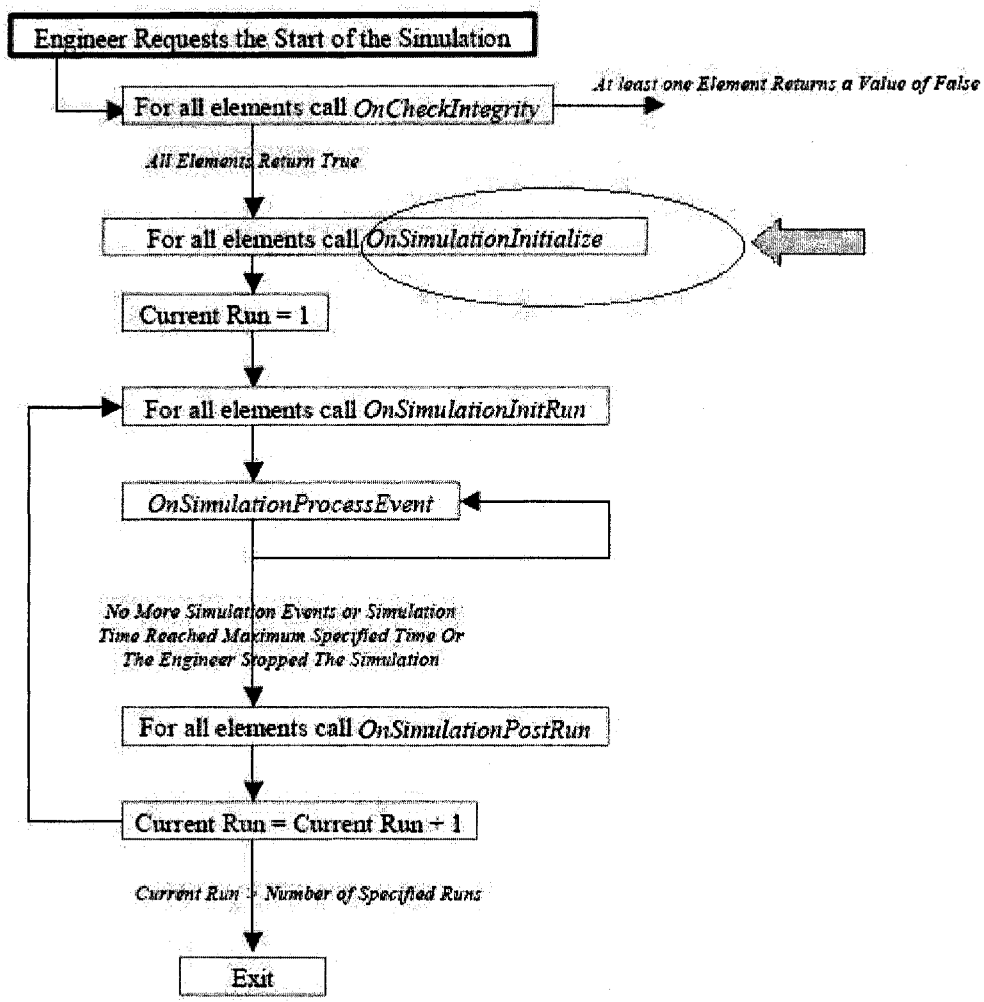
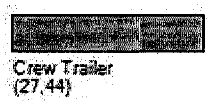
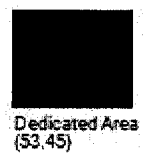


Figure 4-31 Simphony Events Occurring Sequence
(Simphony Developer's Guide 2004)

All dedicated areas and temporary facilities are represented by the "Site Facility" element, introduced in the following section. Obstacles with complex shape can be transformed into a compositeness of many rectangular dedicated areas. Once all site facilities and dedicated areas along with their dimensions and other inputs are set, the generated model starts running by clicking the "trigger button". Figure 4-31 cited a diagram illustrating the event sequence triggered by *Simphony* when an engineer requests that simulation be initiated. The codes expressing GA optimization procedures are divided into several subroutines, called by the *"OnSimulationInitialize"* event. In this way, if the model portion indicating shaft construction is requested to run more than one time, a multi-run of the optimization procedure is not needed and much time would be saved. In other words, the model starts with reading input information, followed by optimizing the site layout, obtaining the optimum layout and subsequently calling the shaft construction process, which is repeated as users specify.

4.5.5.2 Site Facility Element





This element is developed to indicate any temporary facility or dedicated area. An input parameter used for differentiation is *"Category"*, which provides a drop-down list consisting of "dedicated area", "electrical equipment", "hoisting equipment", and "miscellaneous". Choosing any item except for "dedicated area" means the element is used to represent a temporary facility, with the input parameters listed in Table 4-5. If "dedicated area" is chosen instead, two more input parameters would be added, shown in Table 4-5 as well. The element's appearance updates along with the alteration of category. A list constituted of 24 temporary facility names and "dedicated areas" (refer to Figure 4-32) offers users the opportunity to specify the name of the facility, appearing as the parameter *"Facility Name"*. An exception is that when the element with *"Category"* is a "dedicated area", the "Facility Name" is changed to "dedicated area" automatically. A complete list including names, functions and dimensions of the temporary facilities for tunnel site can be found in Appendix I. *"Facility Length"* and *"Facility Width"* are two other user-defined parameters. *"Facility Length"*, in particular, is required to be greater than or equal to *"Facility Width"* for integrity.

Table 4-5 Site Facility Element Input Parameters

Element Type	Input Parameters	Type/ Comment	Default Values	Input Parameters	Type/ Comment	Default Values
Temporary Facility *or* Dedicated Area	Facility Category	Text (list)	Miscell--aneous	Facility Length (m)	Numeric ($L \geq W$)	16
	Facility Name		Crew Trailer	Facility Width (m)		3
	Rotating Angle	Numeric [0,360]	0			
Dedicated Area	Desired X-Coordinate	Numeric	50.5	Desired Y-Coordinate	Numeric	50.5

Note: All numeric values should be set to be positive; angle is along clockwise direction.

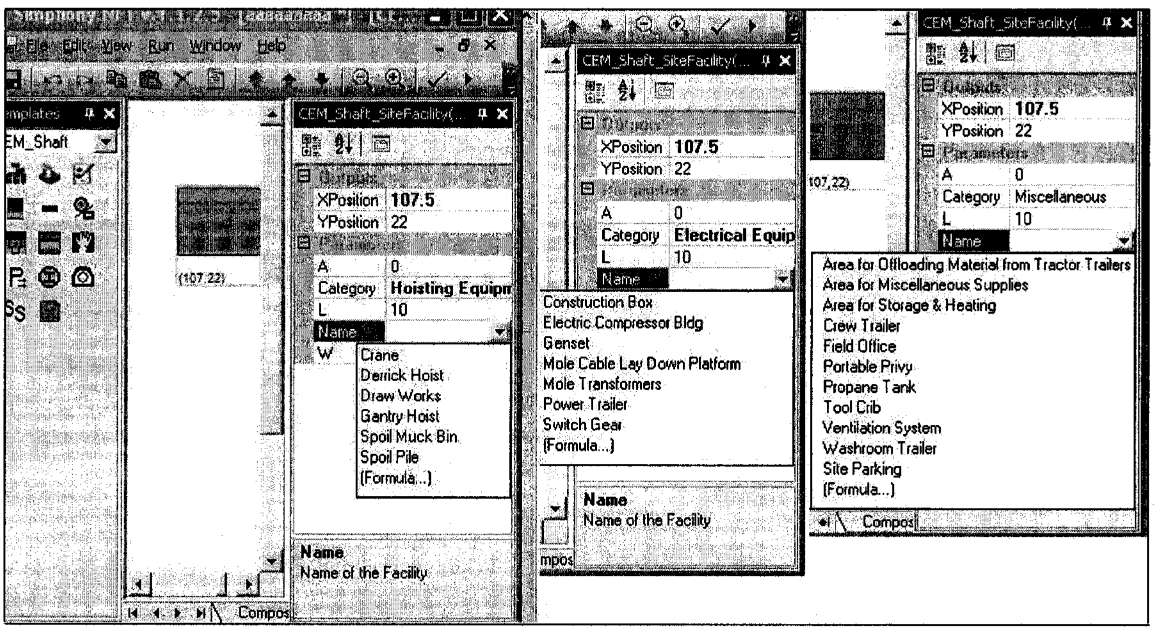


Figure 4-32 "Facility Name" Drop-Down List

When generating a site layout model, users are required to specify values for all of the above-mentioned input parameters; if an element is assigned to indicate a dedicated area, the element's desired coordinates and rotating angle are to be taken care as well. Again in the *"OnSimulationInitialize"* event of the "Root" element, all existing "dedicated areas" are detected, positioned, and rotated according to the elements' properties before the optimization procedure commences, and they keep still once moved to the right position on the simulated site. By default, the long edge of "Site Facility" element is oriented; in other words, the element's long edge parallels to the x-axis with the rotating angle being zero.

The element has two outputs, namely "X-Coordinate" and "Y-Coordinate", representing centroid coordinates of the element. They update themselves whenever the element is moved around the site.

4.5.5.3 Outline Element

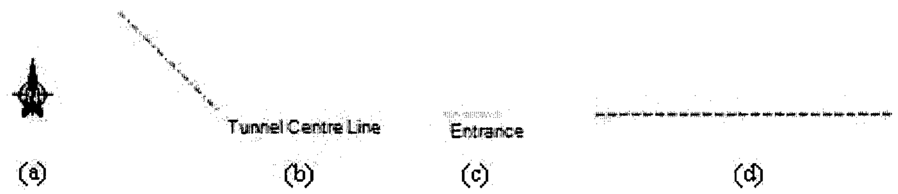


Figure 4-33 Outline Element

This element has no input or output parameter and the user should not use it. It was developed mainly to facilitate drawing the site plan. Figure 4-33 exhibits the formats of this element when used for creating a model. The first two were introduced previously (Section 4.5.5.1); the third one is utilized to represent the site entrance, with its two end points read from the users' input. The last format is used to express construction site edges, a group of which forms a site polygon with each of its corners obtaining coordinates from users' input. Aside from format (b), all other formats are generated, removed, or updated automatically along with the modification of any "root" element's parameter before the simulation starts running. The "tunnel centre line" is created immediately before the optimization phase commences.

4.6 CONCLUSION

This chapter presented a simulation-based model for site tunnel site layout planning using Genetic Algorithm as the optimization tool. The basic components of the system and the constraints adopted were described. Modified genetic operators based on the specific tunnel site problem were introduced. The developed model is flexible in allowing for experimentation with different rules and comparing the final layout results. It also has an open architecture in adding new constraints related to productivity, safety, and security and thus expanding the application area. A case study presented in the following chapter will further prove that the developed model could essentially be compliant with common industry practice as a space-planning tool.

CHAPTER 5: CASE STUDY AND PERFORMANCE EVALUATION

5.1 INTRODUCTION

As mentioned in the previous sections, the development of the integrated systems leads to improvement in many areas, such as modeling any hypothetical constructing alternatives for shaft construction and evaluating various site layouts. In terms of site layout, the template focuses on tunneling layouts, specifically on utility tunnel construction to maintain consistence with the existing tunneling template. This chapter presents the performance evaluation of the developed modeling system via an actual project, analyzing the input information provided and giving a summary of how the modeling result is generated. A tunneling project, with a circular shaft rather than a rectangular shaft, was chosen, as the shape is adopted by most utility tunnel construction projects in the City of Edmonton. The functionality and usability of the template is witnessed through several aspects stated below.

- Testing the template for shaft and undercut construction stage, comparing the simulation results such as project construction duration with those provided by the project engineers.

- Evaluating two alternatives at the project planning stage of the studied project with respect to shaft construction.

- Seeking an optimum location for each of the temporary facilities given, comparing the alternative with the layout adopted by the project planners.

The final discussion of the case study and the performance of the system are presented in Section 5.5 as conclusions.

5.2 PROBLEM STATEMENT

The selected project is part of the NEST (North Edmonton Sanitary Tunneling) system undertaken by the City of Edmonton, named NEST NL1-NL2. The NEST system is an \$80 million project that will be constructed in stages over a period of 20 years. The project is a new 2.3m (7.5ft) diameter tunnel with total length of 3707m (12162ft) from 76 Street to Manning Drive underneath the alignment of 153 Avenue in Edmonton, with an overflow weir structure connecting the existing NL1 pump station and NL2. At the preliminary design stage, two tunneling approaches were more desirable among all the options: namely, two-way tunneling commencing with the construction of a working shaft at 59A Street, and one-way tunneling with a working shaft located at Manning Drive and heading for west. The developed simulation template is tested based on the former option in this chapter, since the limited construction site and the deep working shaft proposed can better illustrate the functionality of the modeling system. Afterwards, through risk analysis and a constructability review of the alternatives, the City of Edmonton made the decision on the construction method, choosing the latter option.

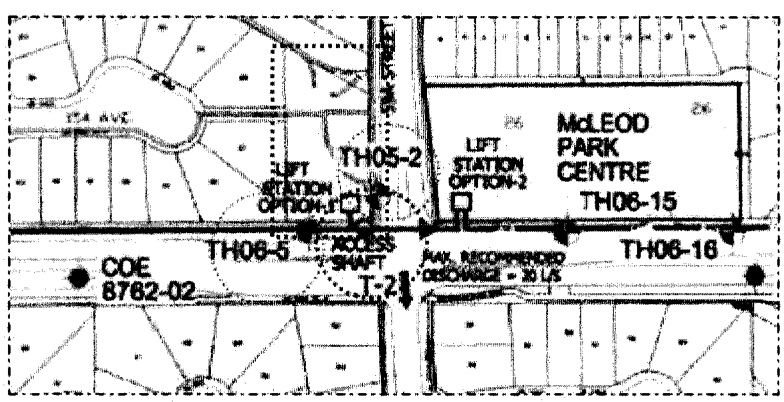


Figure 5-1 Overview of the Tunneling Site Adjacent Area in NEST NL1-NL2 Project

The tunneling site at 59A Street has a near polygon shape with an approximate area of 2,500 m^2 and was required to accommodate 17 temporary facilities listed in Table 5-1. An overview of the tunneling site adjacent area is shown in Figure 5-1. Permanent facilities and dedicated areas are shown in Figure 5-2, with site corners and entrance indicated. The site can be categorized as a medium size utility tunneling site.

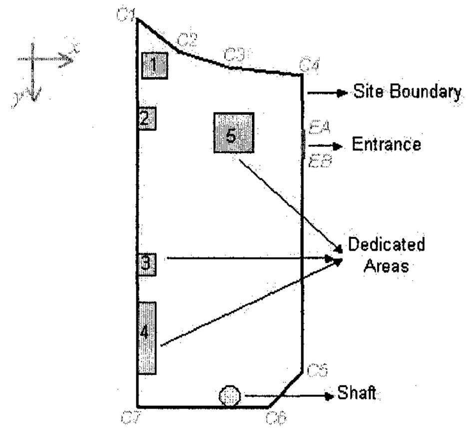


Figure 5-2 Simplified Layout of Permanent Facility and Dedicated Areas

Table 5-1 Temporary Facilities and Dimensions Adopted for NEST NL1-NL2 Project

Temporary Facility		Number of Facility	Dimensions (for each)	
Category	Name		Length (m)	Width (m)
Miscella- -neous	Field Office	1	16	3
	Site Parking (9 stalls)	1	27	6
	Portable Privy	1	1.5	1
	Ventilation System	1	4.3	1.2
	Tool Crib	2	3	2
	Propane Tank	1	2	1
	Area for Miscellaneous Supplies	1	8	4
	Area for Storage & Heating of Concrete Segments	2	12	3
Hoisting	Crane	1	11.5	6
	Spoil Pile	1	7	7
Electrical	Mole Cable Lay Down Platform	2	12	4.5
	Electric Compressor Building	1	5.5	2.5
	Switch Gear	2	3	1.5

The working shaft of the project is set up at the position shown in Figure 5-1. Its end diameter is the standard 14ft8in (4.47m, with rib and lagging support) and its depth is 33 m (108.27ft). A soil log report was obtained from City of Edmonton, with the information of the two closest test holes to the working shaft TH05-2 and TH06-5 illustrated in Figure 5-3. (Relative position of TH05-2 and TH06-5 from the shaft can be seen from Figure 5-1.) The boreholes reveal that the shaft will be built mainly in bedrock, encountering four primary soil categories, namely Top Soil/Fill, Clay, Bedrock, and Coal. Table 5-2 presents the machine penetration and support installation rate, hand excavation rate, and swell factor for each of the soil types summarized from the historical data and the personnel at the City of Edmonton. Note that although the modeling system was developed to allow the input of statistical distribution or formula, only constant values are used in this case due to the lack of sound database. Comprehensive data collection is expected from future work on the developed integrated system.

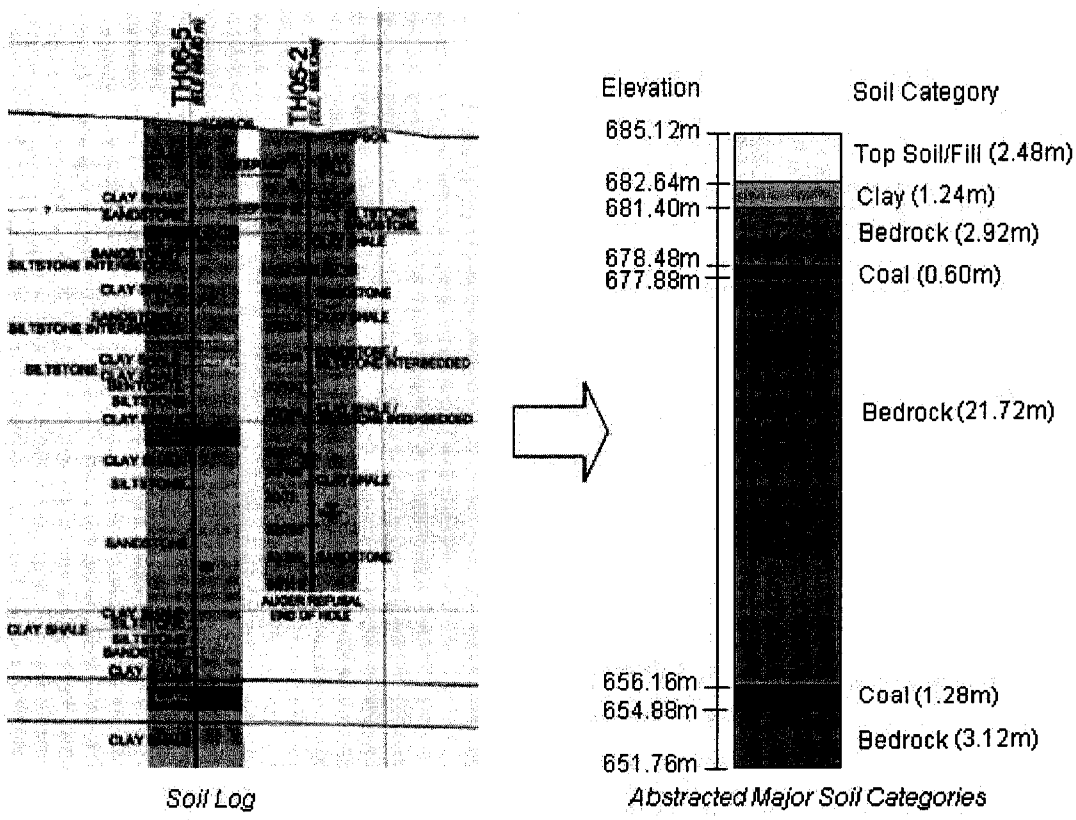


Figure 5-3 Borehole TH06-5 and TH05-2 Profile and Abstracted Soil Information

Table 5-2 Shaft Soil Information for NEST NL1-NL2 Project

Soil Type	Machine Excavation and Support Installation Productivity		Hand Excavation Productivity (m/hr)				Swell Factor
			Expansion		Excavation		
	ft/8hrs	m/hr	ft/8hrs	m/hr	ft/8hrs	m/hr	
Top Soil	3	0.1143					1.2
Clay	2	0.0762	2.8	0.1067	1	0.0381	1.25
Bedrock	1.8	0.0686	1	0.0381	0.5	0.0191	1.8
Coal	1.9	0.0724	1.5	0.0572	0.75	0.0286	1.5

The primary shaft construction activities are comprised of assembling shaft liners for the entire shaft; drilling a section 9.75m (31.99ft) in length and 14ft8in (4.47m) in diameter and installing liner; drilling a section 9.75m (31.99ft) in length and 12ft (3.66m) in diameter and installing liner; drilling a section 5.5m (18.04ft) in length and 10ft (3.05m) in diameter and installing liner; hand expanding the sections to 14ft8in (4.47m) in diameter, and hand excavating a section 8m (26.25ft) in length and 14ft8in (4.47m) in diameter. Other activities are identical with the standard shaft for utility tunneling at the City of Edmonton (refer to Figure 3-12 and Figure 3-14 for the construction process illustration). Two-way undercuts are required as part of the shaft construction, one of which partially functions as a tail tunnel for temporarily storing equipments and liners. Dimensions of the undercut are indicated in the following section.

5.3 SIMULATION MODEL

In mapping the NEST NL1-NL2 Project construction site onto *Simphony* interface, the modeling system starts with generating the tunneling site and objects. Site boundaries and site entrance are created firstly once the coordinates of seven site corners identified are finished being input, appearing simultaneously with the shaft and test hole, which are automatically generated with default positions. Once the orthogonal two-dimensional reference system shown in Figure 5-2 is defined, the coordinates and dimensions of the dedicated areas and the shaft, as well as coordinates of the seven site corners and site entrances are presented as Table 5-3. "Site Facility" elements representing dedicated areas are then created based on the site geometry according to the specified coordinates and dimensions. Note that all dedicated areas in this case have rotating angles of zero. Next, the seventeen temporary facilities are generated as well with the specified dimensions, located anywhere within the *Simphony* interface.

Table 5-3 Dimensions and Coordinates of Site, Entrance, Dedicated Areas, and Shaft

Site Corners Coordinates			Object Name	Dimensions (m)		Coordinates (Centre Point)	
Corner	X	Y		Horizontal	Vertical	X	Y
C1	0	0	Shaft	4.47		21	83
C2	9.2	7.7	Dedicated Area 1	6	6	4	11
C3	21.3	14.2	Dedicated Area 2	4	5	2	22.5
C4	37.5	19	Dedicated Area 3	4	5	2	55.5
C5	37.5	80	Dedicated Area 4	4	16	2	72
C6	30	88	Dedicated Area 5	10	9.5	22.6	28.6
C7	0	88					
EA	37.5	31.5					
EB	37.5	38.5					

At the commencement of laying out the site in the system, the permanent facility, i.e. the shaft, and dedicated areas are relocated based on the positions assigned to the corresponding representing elements or to the parent element. In succession, the tunnel centerline is generated accordingly. Orientation of the tunnel is simply east-west direction in this case. GA optimization of the temporary facilities' locations is activated subsequently. Two parameters *"Number of Generations"* and *"Number of Chromosomes"* retain the default values, i.e. 1000 for the former and 100 for the latter. All other GA parameters use default values.

An eight-hour-shift per day is employed in constructing shaft and undercut. A shaft construction model is presented in Figure 5-4 and Figure 5-5, generated as the child windows of the "Shaft" element and the "Soil Profile" element, respectively. Other input information related to shaft modeling is provided in Table 5-4. Note that the shaft liner are being assembled for shaft sections that are not on critical path, thus duration for those activities are not considered in this model. Any parameter that is not mentioned in Table 5-4 uses its default value.

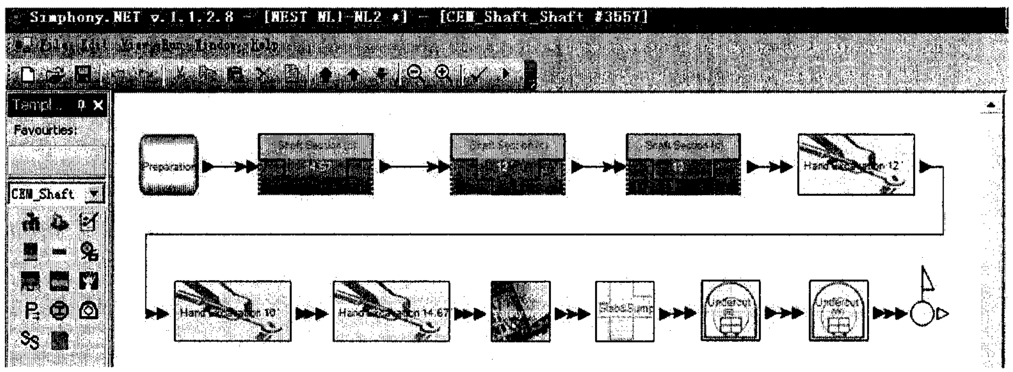


Figure 5-4 Child Window of "Shaft" Element—Shaft Construction Model

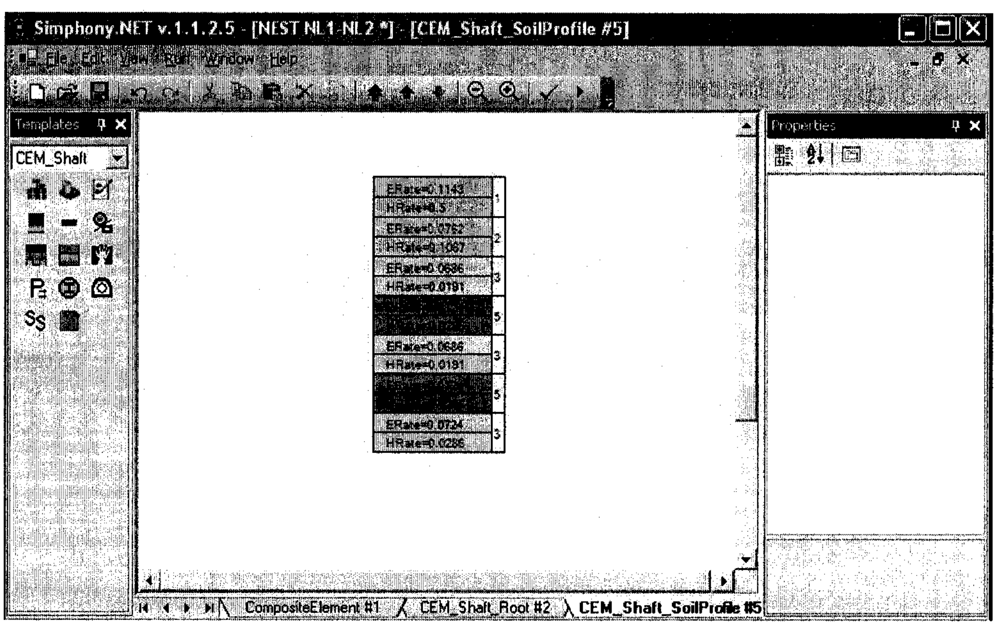


Figure 5-5 Child Window of "Soil Profile" Element—Shaft Construction Model

Table 5-4 Other Input Information for the Shaft Construction Model

Element	Input Parameter	Value	Input Parameter	Value
Preparation	Duration	Constant (1) day		
Circular Shaft Section (14.67')	Duration for installing beam and hang shaft	Constant (1) day	Segment depth	9.75m (31.99ft)
Circular Shaft Section (12')	Segment length	9.75m (31.99ft)		
Circular Shaft Section (10')	Segment length	5.5m (18.04ft)		
Hand Excavation	Segment length	9.75m (31.99ft)	Segment diameter	12ft (3.66m)
Hand Excavation	Segment length	5.5m (18.04ft)	Segment diameter	10ft (32.81ft)
Hand Excavation	Segment length	8m (26.25ft)	Segment diameter	14.67ft (4.47m)
Safety Wall	Duration	Constant (2) day		
Slab & Sump	Duration for excavating sump	Constant (2) day	Duration for pouring slab	Constant (2) day
	Diameter of the sump	2.2m (7.22ft)	Depth of the sump	2.75m (9.02ft)
Undercut (E)	Swell Factor	1.8		
Undercut (W)	Undercut length	24m (72.74ft)	Section 1 length	6.765m (22.19ft)
	Direction	W	Section 2 length	15m (49.21ft)
	Section 0 length	2.235m (7.33ft)		

The simulation system performed GA-based layout optimization and shaft modeling of the NEST NL1-NL2 project in a total of 150 minutes running on a Pentium (R) 1.7GHz processor. The initial generated layout (before the model is triggered) from the modeling system is shown in Figure 5-6; a comparison of the generated layout from the optimization system associated with the layout from project engineers is shown as Figure 5-7. Note that five dedicated areas were moved to the indicated positions after the model is triggered, but none of the facilities' shapes or dimensions was changed.

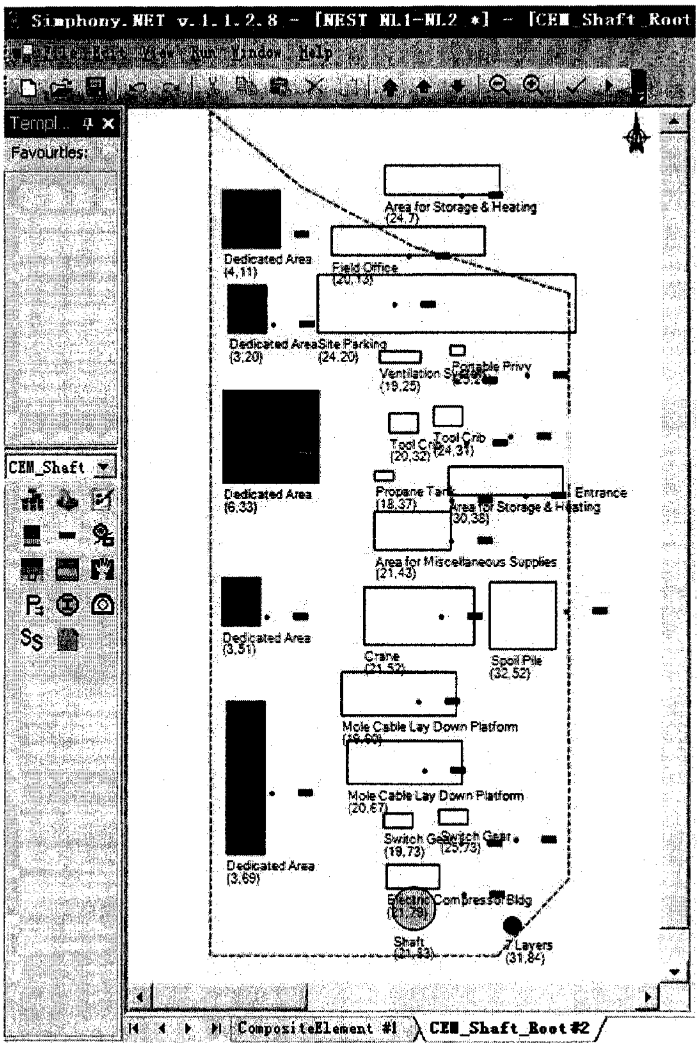
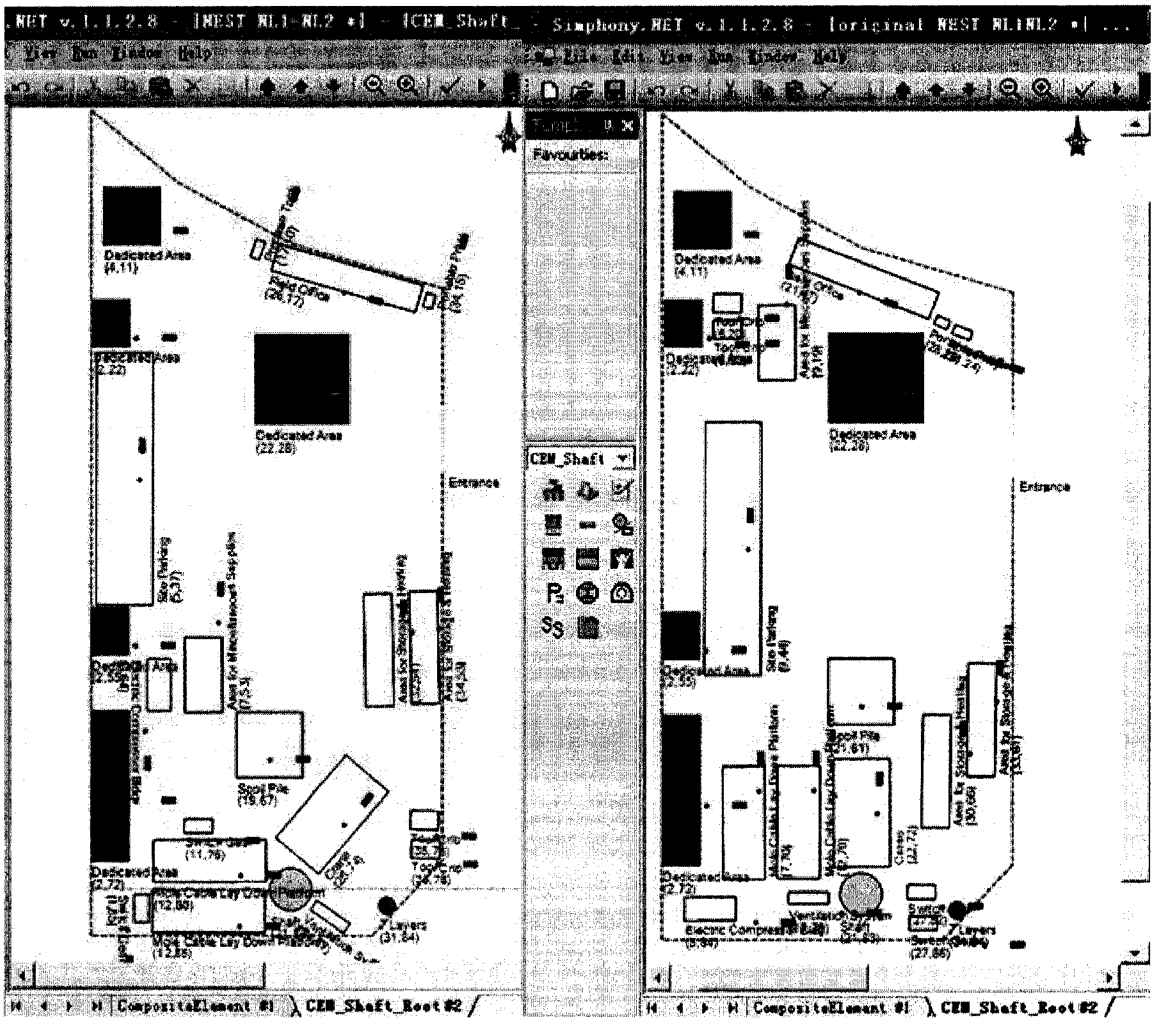


Figure 5-6 Initially Generated Layout

The generated layout shown in Figure 5-7 (A) received a total fitness value of 220, compared to 108, of the layout from project engineers (Figure 5-7 (B)), using the evaluating constraints listed in Appendix II. In general, the developed system was able to generate a site layout close to the actual tunneling site arrangement, with some differences that were in favor of the constraints assigned for this study. For example, in the layout generated by the modeling system, traffic routes among site entrance, site parking, spoil pile, area for miscellaneous supplies, and area for storage and heating concrete segments were kept as rectilinear with widths equal to 4 meters as preferred by the constraints. In the layout created by project engineers, routes are curved rather than rectilinear. This difference has an impact on the entire layout arrangement.



(A) (B)

Figure 5-7 Comparison of Automated System Assignment of Temporary Facilities (A) and the Proposed Site Layout by Project Engineers (B)

Simulation result shows that a mean value of 71.8 days is required to construct the shaft and undercut area, while the duration estimated by project planners is 69 days under an eight-hour shift per day. Analysis of the simulation result shows that hand excavation is the activity that mainly delays the project, which is unavoidable due to the thick bedrock layer in the shaft adjacent area. A total dirt amount of 1095 m^3 could be accumulated from the excavation. This output helps with deciding the area kept for spoil pile on the construction site, and helps with analyzing in order to further control the frequency of muck removal truck's arrival. The generated site is not guaranteed to be an ideal construction site for the interacting facilities for this project, but it is a near optimum one based on the constraints adopted since it basically satisfies all constraints well. It should be noted that the "area for storage & heating concrete segments" on the site shown is sufficient for one-day's lining only, an additional area for storing concrete segments is provided in an adjacent site in the planners-proposed plan, which is about 20 meters from the main site. In order to evaluate the modeling result and get feedback from its essential functions, the site planner was presented with the final layout result generated by the integrated system. He considered the modeling result satisfactory and the developed system a useful site layout assisting tool, and that the modeling system had the potential in being adopted in construction practice.

5.4 CONCLUSIONS

The aim of this chapter was to establish the functionality and usability of the integrated modeling system developed. As an extension of the existing tunneling template and a significant step towards a revised and completed tunneling template in the future, the presented modeling system primarily enables users to test the validity of shaft construction planning strategies, and to evaluate various site layout options.

A case example of an actual project from City of Edmonton named NEST NL1-NL2 was analyzed using the developed modeling system. The capability of the integrated system in laying out the construction site was demonstrated by locating sixteen temporary facilities on the identified site through satisfying a variety of constraints. The generated site better satisfied the defined constraints, compared to the actual layout designed by project engineers. The analysis of shaft modeling result shows that the simulation system can be very useful in predicting and evaluating shaft construction duration of various options. As a powerful construction planning-assistance tool, the developed system will be of great help in decision-making and evaluating the feasibility of tunnel construction methods, in identifying and allocating site spaces, and in the visualization of tunneling construction sites as a mean of describing the site layout to other involved parties.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 RESEARCH SUMMARY

Shaft construction and site layout planning is fundamental to many tunnel construction project functions, such as scheduling, estimating, and project control. A proper site layout and well-organized shaft construction activities enhance productivity on job sites, increase safety and security, facilitate inventory control, and are of great importance to the success of any tunneling project. The primary objective of this thesis research is to develop a framework to model shaft construction processes and to plan construction site layouts using simulation and genetic algorithms techniques. This research was performed with the cooperation of the City of Edmonton Asset Management and Public Works Department and NSERC/Alberta Construction Industry Research Chair in Construction Engineering and Management. The developed system is not intended to replace project planners but to assist them in decision-making by a set of systematic procedures.

To meet the objectives presented in the first chapter, some concepts and ideas were introduced at the first stage of the thesis following the presenting of thesis methodologies and organizations. Computer simulation algorithms and the application to the construction domain were firstly summarized, with the emphasis on the simulation engine employed by this study. Basic concepts of tunnel shafts, tail tunnel, and undercut along with general construction methods were then reviewed, followed by definitions of construction site layout and related terms. Existing site layout models were presented which focused on two aspects: problem representation and solving approach; contributions and limitations of the existing models were analyzed. The section concludes with the application of generic algorithms in the construction field, the site layout function optimizer adopted in this study.

In order to develop the special purpose simulation template, several interviews were conducted to acquire sufficient data for the development of the system. The elements affecting site layout were identified, classified, and properly represented; specific excavating and support methods employed for shaft construction in the City of Edmonton were depicted in detail; background knowledge of genetic algorithms, the introduction of its operators, and the specifically designed optimization system for the problem at hand were also presented in detail. As a modeling system would always necessarily embody a layer of project-specific information, users are required to provide reasonable and comprehensive input parameter values to fulfill modeling tunneling projects.

The modeling system was developed using the *Simphony* platform. It is a simulation tool that supports graphical, hierarchical and modular modeling. Genetic algorithms were integrated with the simulation template and implemented by the programmable feature of *Simphony*. The developed system provides a visual site layout process, with the outcomes of modeling exhibited by graphical representations in a user-defined scale. Spatial detection and analysis are accomplished right before the optimizing layout commences, followed by shaft construction modeling. Construction of both circular shafts and rectangular shafts can be simulated using the fourteen modeling elements created. Productivity information for various soil types is stored in an element named "Soil Profile", from which elements representing hand excavation and machine excavation for circular shaft and rectangular are able to acquire the corresponding penetration and lining rate. Many of the aforementioned features of the developed system enable project engineers and managers to explore alternative options to construct shaft and plan site layout.

To validate the performance of the system, the developed template was tested on an actual tunneling project for the City of Edmonton. The case study involved locating a variety of temporary facilities (contained by the checklist shown in Appendix I) on an irregular-shaped tunneling site and constructing a relatively shallow working shaft, which is circular in shape. The result of the case study shows the functionality of suggested modeling approach for generating well-organized construction site layouts and providing insights into tunnel shaft construction projects.

6.2 RESEARCH CONTRIBUTIONS

The contributions of this research are mainly in the development of tunneling site layout simulation model integrated with genetic algorithms. Along with the shaft modeling section, the presented system can be combined with the existing tunneling template through compilation in order to model the tunneling process assisting in decision-making. The major contributions are summarized below.

- *Site layout representation* Any construction site can be accurately abstracted and represented as a polygon in the developed system with user-defined dimensions. Temporary facilities were represented by rectangles system-generated rotating angles to the site borders.

- *Flexible spatial constraints expressing* Eight categories of hard and soft constraints among site facilities were formularized, and dozens of breakdown constraints specific to the tunneling site were identified, covering issues related to access, material storage and handling, and safety. Hence, the decision of locating facilities is made not only on a distance basis, but also based on several other important factors. The current domain-specific constraints (see Appendix II) may not be comprehensive enough to cover all of the aspects due to the many factors; however, the developed system is fairly flexible in further updating or adding any hard or soft constraints as well as their proximity weights.

- *Integrating simulation with GA* The integrated simulation system managed to benefit from the intricate search and optimization abilities of GA while in turn

Simphony provides a fast, easily-manipulated way and risk-free environment in which to experiment with different alternatives with great ease.

- *Intelligent modeling* The "automatic" feature is present throughout the entire system. For example, excavation elements automatically acquire soil penetration information from a data storing element, the system automatically generates corresponding input parameters according to the shaft shape users specify, and the graphical representation is automatically updated whenever any modification is made to the values of the parameters. This feature greatly saves modeling time and input effort.

- *Compatible, extendable and easily manipulated* Similar to other developed *Simphony* templates, the proposed simulation system can be easily extended to accommodate more disciplines and strategies and to produce more advanced outputs as users require. As such, it is quite compatible for being integrated with other templates, which will facilitate the future work of this study. The developed modeling system enables users who are knowledgeable in tunneling to create a model and experiment with different scenarios without developer's instruction.

6.3 LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

Development of the proposed system can be steered in several directions that are worthwhile for future research efforts. In this section, the directions are classified as overcoming the limitations of the current system, integrating the template with other systems, and extending the existing model for more tasks. Detailed directions are listed as follows.

A. Overcoming Limitations

- *Encouraging more data to be collected to maintain optimum use of the template.* This limitation was evident when the cast study was conducted. For example, despite the development of statistical distributions for soil penetration rates (both hand and machines), it was rather difficult through the limited interviews to collect the ideal form of data for storing; instead, rough and constant values were used. A better performance of simulation modeling relies tightly on proper and comprehensive data.

- *Adding uncertainties such as machine breakdown and maintenance, labor efficiency, and encountering groundwater.* This item is virtually based on the satisfaction of the above-mentioned condition. Once sufficient data are able to be collected, many uncertain factors that affect shaft construction and the laying out of the site should be considered in the developed system. Accuracy and flexibility of the system can thus be improved.

- *Exploring more soft constraints to make the template more comprehensive.* There is the potential for more constraints to be identified. This needs more interviews with the site planners, superintendents and project engineers, and more case testing. For example, if the existing tunneling template is integrated with the developed system, then travel efforts would be considered a main part of the objective function since it tremendously influences the overall productivity. Moreover, all other productivity-related factors should be detected and made to participate in the objective function. A more comprehensive objective function that takes all influencing factors into account can be formulated accordingly.

- *Considering actual paths taken between facilities instead of rectilinear distance.* Rectilinear distances may not necessarily represent the realistic distances of traffic routes on site, especially on congested construction sites when maneuvering around facilities or obstacles. In these cases, the discrepancy of modeling result from the reality is not negligible; therefore, this item is worth being given attention.

B. Extending the System

- *Integrating the current template with tunneling template.* This study is essentially another step toward developing a comprehensive modeling system for tunneling projects. Therefore, a main stream of the future research should focus on investigating the integration and compilation of the two tunneling-related templates. This improvement would require a more rigorous and compete testing phase on several real projects, with the emphasis of each on a different aspect. The complete tunneling modeling system would be of great help to assist in decision-making.

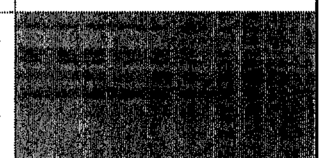
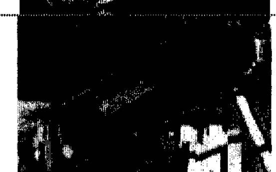
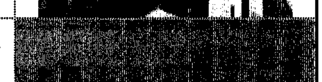
- *Augmenting the site layout part to handle dynamic layout problems.* Most construction layouts are dynamic in nature, that is, layouts change over time as construction progresses. To address this problem, a sequence of layouts spanning the entire project duration should be created, with consideration given to their changing demand for space over time, cost of relocation, time of relocation, and the varying interactions between facilities. Although no significant changes occur on tunneling sites through construction, the developed system would be capable of dealing with site layout problems for most construction projects once the dynamic layout optimizer is included.

- *Producing outputs regarding not only schedule but also cost.* The inclusion of a cost-planning module can assist project engineers and managers in preparing a preliminary range estimating of a tunneling project, and can be further used for evaluating alternatives during bidding as well. To fulfill this item not many modifications are needed for the modeling system; however, substantial data collection work must be conducted.

- *Introducing interface that allows for user interaction and intervention.* Site layout involves design issues that are mainly based on the site planners' expertise and judgment, thus increasing the modeling system's flexibility by utilizing users' domain-specific knowledge and successful historical site layout projects. This enhancement is further comprised of providing several options according to which users can select the interacting temporary facilities and types of constraints, along with the proximity weights of the constraints.

- *Enabling the template to handle more shaft construction and support methods.* The proposed template was developed aiming at the tunneling methods employed by the City of Edmonton; the current system is not quite suitable for other construction and support methods. Industry normally prefers the identical methods and constructing sequence, while new alternatives possibly improve the current practice. Inducting new tunneling methods to the modeling system allows users to experiment with no risk, and the preference could lead to the generation of different construction process with higher efficiency.

APPENDIX I: TEMPORARY FACILITIES AND THEIR FUNCTIONS ON TUNNEL CONSTRUCTION SITE

Facility Name	Functions	Illustration Picture
Derrick Hoist	Hoisting equipment. Cranes and gantry hoists are usually used for shallow to medium depth tunnels (<30m), and derrick hoist with cages or skips are used for deep tunnels. (>30m). However, in the recent ten years, about 90% of tunneling projects adopt crane in spite of tunnel depth.	
Gantry Hoist		
Crane		
Draw Works	It is part of the hoisting system, also known as "jackknife rig". It is the winch used in rotary drilling to raise and lower the drilling column and casing and in some types, to transmit power to the rotary table.	
Spoil Muck Bin	It is where muck cars are emptied after lifted from the tunnel, prior the muck being hauled away from the job site. It is used together with hoists.	
Spoil Pile	As a temporary dirt storing place, it has the same function as spoil muck bin, and is used together with crane.	
Electric Compressor Building	It is a shed activating air tools when hand excavation is employed.	
Construction Boxes	They are inside site sources of electricity, always located close to outside electricity source. They are used on large projects, usually two or three serving the site together.	
Potable Power Supply (Genset)	It is used in small tunnel application where on site power is not available.	
Power Trailer	It provides uninterruptible power systems and generators, used together with spider mole.	
Switch Gear	It is a device that isolates all underground electrical circuits, used for totally enclosed moles.	

Cable Lay Down Area	There two facilities always appear as pairs, serving together for totally enclosed moles.	
Mole Transformers		
Crew Trailer		
Field Office	Evident.	
Site Parking		
Washroom Trailer	Evident.	
Portable Privy	Small washroom, used for limited sites.	
Tool cribs	They are where construction workers request tools on site, usually two serving the site together.	
Propane Tank	It is basically used for heating the field office, crew trailer, and washroom trailer.	
Ventilation System	It is located right beside the shaft, drawing air into the tunnel, thoroughly mixing the air, and exhausting contaminated air.	
Area for off loading materials from tractor trailers		
Area for Storage and Heating of Concrete Segments	Evident.	
Area allocated for Tracks, Rail ties, timbers, miscellaneous Supplies		

APPENDIX II: HARD/SOFT CONSTRAINTS AND WEIGHTS AMONG TUNNEL CONSTRUCTION FACILITIES

Hard Constraints	Interacting Facilities or Statements	Proximity Weight (Y/N)
Non-Overlapping (MT)	All temporary facilities, shaft, and dedicated areas except: 1. Between hoists and shaft. 2. Between hoists and draw works. 3. Between hoists and spoil muck bin. 4. Between crane and shaft. 5. Between crane and spoil pile.	MT: 0/-200
Inside Site Boundaries (MT)	All temporary facilities.	MT: 0/-200
Orientation (AN)	Spoil muck bin and draw works are on different sides of shaft.	AN: 0/-100
Access (AN)	Four meters-wide rectilinear path each pair of the below facilities: 1. Access 2. Site parking 3. Spoil pile and Spoil muck bin 4. Area for offloading material from tractor trailers 5. Area for miscellaneous supplies 6. Area for storage & heating	AN: 0/-100
Soft Constraints	**Interacting Facilities or Statements**	**Proximity Weight (Y/N)**
Distance	Centre draw works drum to centre line of tunnel is: (If existing) 1. 11 meters if derrick hoist is used. 2. 5 meters if gantry hoist is used.	EI: 20/0
	Distance between crane and spoil pile is less than 8m.	IM: 10/0
	Distances between crane and area for miscellaneous supplies, crane and area for storage & heating are both less than 8m.	IM: 10/0
	Required length for derrick/gantry hoist and draw works is 22m/18m. (If existing)	OD: 5/0
	Distance between crew trailer/field office and site parking is less than 10m.	OD: 5/0

	Distance between centre points of muck bin and hoist is 6m. (If existing)	LI: 3/0
Adjacency	Hoist is next to shaft or overlapping with shaft. (If existing)	NS: 30/0
	Crane is brought fairly close to shaft.	NS: 30/0
	Mole cable lay down area is right beside switch gear. (If existing)	EI: 20/0
	Ventilation system lies right beside shaft.	EI: 20/0
	Mole cable lay down area is right beside shaft. (If existing)	IM: 10/0
	Two tool cribs are next to each other.	IM: 10/0
Parallel/Perpendicular	Centre points of hoist, draw works, muck bin and shaft are on the same line, no other facilities lies between any of them. (If existing)	EI: 20/0
	Gantry/Derrick hoist runs perpendicular to tunnel centre line. (If existing)	IM: 10/0
	Draw works and muck bin run perpendicular to tunnel centre line and perpendicular to hoist. (If existing)	IM: 10/0
	Power trailer runs parallel to tunnel centre line. (If existing)	IM: 10/0
	Mole cable lay down area runs parallel to tunnel centre line. (If existing)	IM: 10/0
	Propane tank is parallel or perpendicular to crew trailer or field office.	LI: 3/0
	All crew trailers and field offices parallel or perpendicular to washroom trailer, portable privy and site parking. (If existing)	LI: 3/0
	Crew trailer or field office parallels to the closest site border.	LI: 3/0
	Two tool cribs parallel to each other.	UI: 1/0
	Line connecting centre points of ventilation system and shaft parallels to ventilation system.	UI: 1/0
	Crew trailer/field parallels to washroom trailer, portable privy and site parking. (If existing)	UI: 1/0
Closeness	Propane tank is the farthest away facility from shaft among all temporary facilities.	EI: 20/0
	Shaft is far away from the traffic route that connecting entrance and site parking: the closest distance between shaft centre point to the route line is not less than 8m.	EI: 20/0

	Crew trailer, field office, washroom trailer, and portable privy are closed to each other	IM: 10/0
	Propane tank is closer to crew trailer or field office than to any other facilities.	IM:10/0
	Electrical equipments (refer to Table 4-1) are closed to each other.	OD: 5/0
	Distance between shaft and tool crib is 0.8 to 1.2 times of it between shaft and draw works.	LI: 3/0
	Crew trailer or field office is closer to site entrance than other facilities are.	LI: 3/0
	In general, distance between shaft and hoisting equipments, shaft and electrical equipments, and shaft and miscellaneous are an ascending manner.	UI: 1/0

Note:

1. Y—Condition Satisfied; N—Condition not Satisfied; MT—Must; AN—Absolutely Necessary; NS—Necessary; EI—Especially Important; IM—Important; OD—Ordinary; LI—Less Important; UM—Unimportant.
2. Parallel and perpendicular in this table refer to the interaction between long edges of two facilities or a line and long edge of a facility.

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