

TUNNEL_SIM: DECISION SUPPORT TOOL FOR PLANNING TUNNEL CONSTRUCTION USING COMPUTER SIMULATION

Mohamed Marzok
Moatassem Abdallah
Moheeb El-Said

Structural Engineering Department,
Faculty of Engineering, Cairo University
Cairo, EGYPT

ABSTRACT

Tunnel construction are essentially infrastructure projects that includes many interfered and sophisticated tasks. This paper presents a decision support tool, *Tunnel_Sim*, for planning tunnel construction projects using computer simulation. The proposed tool assists contractors in estimating time and cost, required for the construction of tunnel projects. Five construction techniques are coded in the proposed tool to capture the construction of open/closed rectangular cross-section tunnels and circular cross-section tunnels. The decision support tool divides the construction of tunnels into working zones. It estimates the total duration and cost for each zone. The proposed tool selects the best construction technique from a set of alternatives based on a decision making method that utilizes fuzzy numbers. An application example is presented to demonstrate the characteristics of the proposed *Tunnel_Sim*.

1 INTRODUCTION

Tunnels are considered one of infrastructure projects that are characterized by large construction budget, long duration, and execution complexity. In the last few decades, tunnel construction has increased to improve the transportation networks due to the increased number of population and transportations flow. Tunnels are usually constructed in urban areas. Therefore, they should be constructed with reasonable amount of time and with minimum disturbance to the surrounding structures and transportation flows. Tunnels are constructed in different site conditions such as complex task execution, equipments breakdown, unfavorable weather conditions, and unexpected site conditions. These conditions lead to complexity and uncertainty in the construction operations. As such, a deviation in the project overall plan might occur. The traditional planning methods don't take into account the uncertainties that might occur during construction. In addition, they don't plan the con-

struction operation along with the total available number of resources.

Tunnels projects are constructed in a cyclic manner which proposes computer simulation as suitable modeling technique to mimic construction tasks. Computer simulation has proved to be an efficient way in planning construction projects. It succeed in improving the planning process by defining tasks durations using probability density functions to account for uncertainties that might occur during construction. A lot of efforts have been made in modeling construction operations using computer simulation. This includes earthmoving operation (Marzouk 2002), concrete operations (Hassan and Gruber 2008), bridges (Marzouk et al. 2006), and tunnels (Tanaka 1993, AboRizk et al. 1999, Luo and Najafi 2007). This paper presents a decision support tool for planning tunnel construction utilizing computer simulation to assist contractors in estimating the total duration and cost. It aids in selecting the best construction method among a set of alternatives. The paper provides an overview of the developed *Tunnel_Sim* tool and its components. An application example is provided to illustrate the characteristics of the proposed decision support tool.

2 PROPOSED TOOL

The developed decision support tool, *Tunnel_Sim*, aids contractors in planning tunnel construction projects by performing two main tasks; i) estimating total duration and cost and ii) selecting the best construction alternative. These two tasks are performed using three modules: tunnel analyzer module, simulation module and decision making module. The first two modules are responsible for estimating the tunnel duration and cost. While, the third module is responsible for selecting the best alternative. Figure 1 illustrates the main components of *Tunnel_Sim* and the interaction amongst them. The following sections describe the three main components of the developed decision tool.

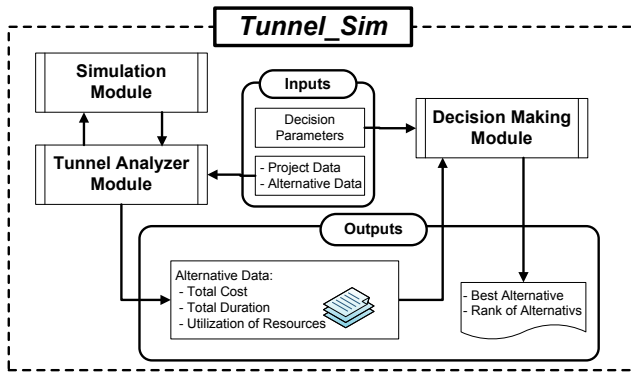


Figure 1: Main components of *Tunnel_Sim*

2.1 Tunnel Analyzer Module

Tunnel analyzer module carries out planning functions of *Tunnel_Sim*. It analyzes the project and breaks it down into zones. It provides five techniques for the construction of tunnels, 1) cut and cover using diaphragm walls, 2) cut and cover using secant pile walls, 3) cut and cover using soldier piles and lagging, 4) cut and cover using steel sheet pile walls, and 5) segmental tunneling using slurry TBM. Tunnel analyzer module breaks the project into zones based on the following aspects:

- Selected construction technique of the zone.
- The assigned resources for each zone are independent of each other. For example, a project that is divided into two zones, a construction method is defined for each zone. Resources are assigned differently for each construction zone even if both of them are constructed with the same method.
- Logic and sequence of construction. For example, separate construction zones are defined if they are executed simultaneously or successively with time lag.

The user is required to define a set of data to tunnel analyzer module as follows (see Figure 2):

1. Project general data such as number of working hours per day, number of working days per week, project start date, number of zones in the project and indirect cost required for the project. Also, the user is required to set the number of simulation runs.
2. Zones' construction methods and their associated data such as number of segments, tasks duration, required and available resources in each zone, labor and equipment rates, and materials costs. Then, the module saves the collected data and sends it to simulation module.

Subsequently, simulation module is triggered to estimate the duration and resources' utilization for each zone. Then, simulation data are sent to tunnel analyzer module in order to calculate project execution time and cost. Project duration is calculated based on the relationship between zones.

While, the project cost is estimated based on labors and equipments utilization, materials costs, and indirect costs. Figure 2 illustrates the designed functions of tunnel analyzer module.

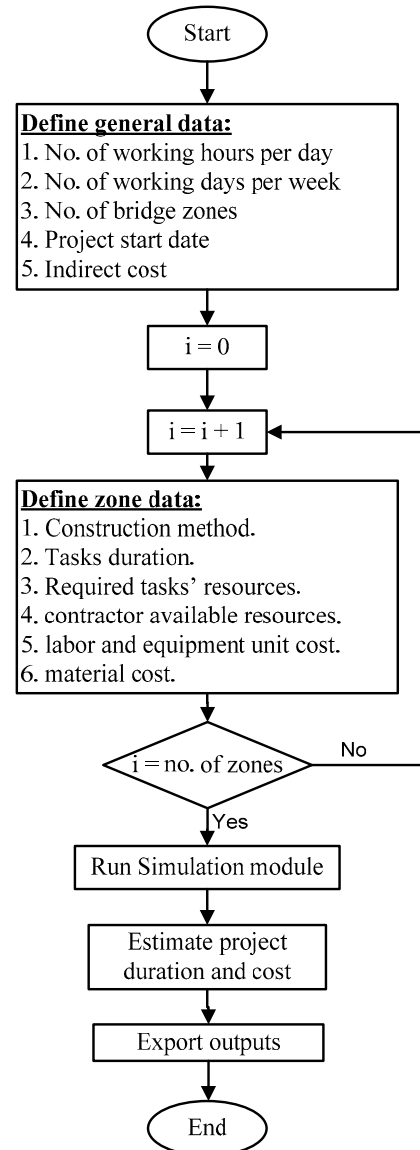


Figure 2: Flowchart of tunnel analyzer module processes

2.2 Simulation Module

The simulation module is responsible for estimating the duration and resources utilization in each zone of the project under consideration. The module utilizes STROBOSCOPE as a general purpose simulation engine (Martinez 1996). It is implemented using Microsoft Visual Basic 6.0 to control and facilitate data flow from/to STROBOSCOPE program. Five construction techniques have been coded and developed to form simulation models as per Table 1. These simulation models were developed using the elements of STROBOSCOPE simulation lan-

gauge to capture the sequence of construction found in the construction site. Simulation module is responsible for the following tasks (see Figure 3):

1. Simulation module receives project data from tunnel analyzer module, then, it depicts the model that represents the construction execution technique for each zone from the five models, available in simulation module library. Subsequently, each model is fed by its data (tasks' duration, required and available resources, and number of replications) to generate the simulation model(s) that represents the project, described in tunnel analyzer module.
2. STROBOSCOPE is triggered to run the generated model(s) in order to estimate total duration and resources' utilization for each zone.
3. The output data are transferred to tunnel analyzer module to perform the calculations of total project duration and cost.

Cut and cover using diaphragm wall is one of the techniques that is used for construction of tunnels with rectangular cross-section area. It involves eight processes with forty one tasks which are listed in Table 2. It is worth to note that tasks' duration are defined for the tunnel's segments included in each zone. Figure 4 depicts the simulation model of tunnel construction using diaphragm wall. Detailed description of the five simulation models can be found elsewhere (Abdallah 2008).

Table 1: Developed simulation models

Model	Description
Cut&cover1	Tunnel construction by cut and cover method using diaphragm walls.
Cut&cover2	Tunnel construction by cut and cover method using secant pile walls.
Cut&cover3	Tunnel construction by cut and cover method using soldier pile and lagging walls.
Cut&cover4	Tunnel construction by cut and cover method using steel sheet pile walls.
TBM	Segmental tunneling using slurry tunnel boring machine (TBM).

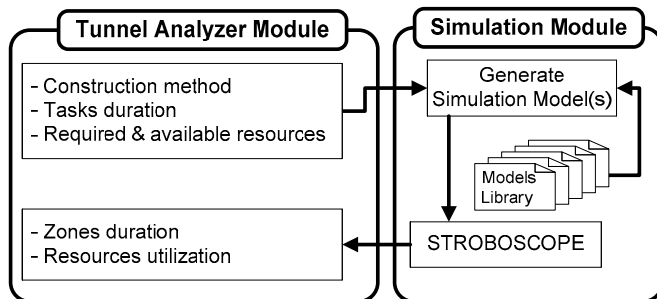


Figure 3: Interaction between tunnel analyzer module and simulation module

Table 2: Cut and cover technique using diaphragm wall

Process	Task	Description
Preparation	candc101	Segment survey
	candc102	General excavation and leveling
Guide wall	candc103	Excavation of the guide wall
	candc104	Steel work
	candc105	Shuttering of forms
	candc106	Concrete pouring of guide wall
	candc107	Concrete curing
	candc108	Removal of forms
	candc109	Backfilling guide wall
	candc110	Paneling and marking of guide wall
Diaphragm wall	candc111	Preparing and fixing of steel cage
	candc112	Trench excavation
	candc113	Position steel cage into excavated Panel
	candc114	Concrete pouring
Plug and dewatering	candc115	Survey for injecting points
	candc116	Drilling and injecting soil with cement
	candc117	settlement of cement in one segment
	candc118	Drilling of dewatering wells
Top slab segments	candc119	Excavation of top slab segment
	candc120	Trimming of diaphragm wall head
	candc121	Pouring plain concrete between the diaphragm walls
	candc122	Shuttering of top slab
	candc123	Steel work for tunnel top slab
	candc124	Concrete pouring for top slab
	candc125	Concrete curing
	candc126	Forms removal of one segment
	candc127	Settlement of concrete
Bottom slab segments	candc128	Excavation of bottom slab segment
	candc129	Pouring plain concrete between the diaphragm walls
	candc130	Water insulation
	candc131	Steel work for bottom slab
	candc132	Shuttering for bottom slab and installing of water stop
	candc133	Concrete pouring for bottom slab
	candc134	Concrete curing
	candc135	Forms removal
	un-casted segments	candc136
candc137		Steel work for the
candc138		Concrete Pouring
candc139		Concrete curing
candc140		Forms removal
Backfill	candc141	Backfilling of one segment

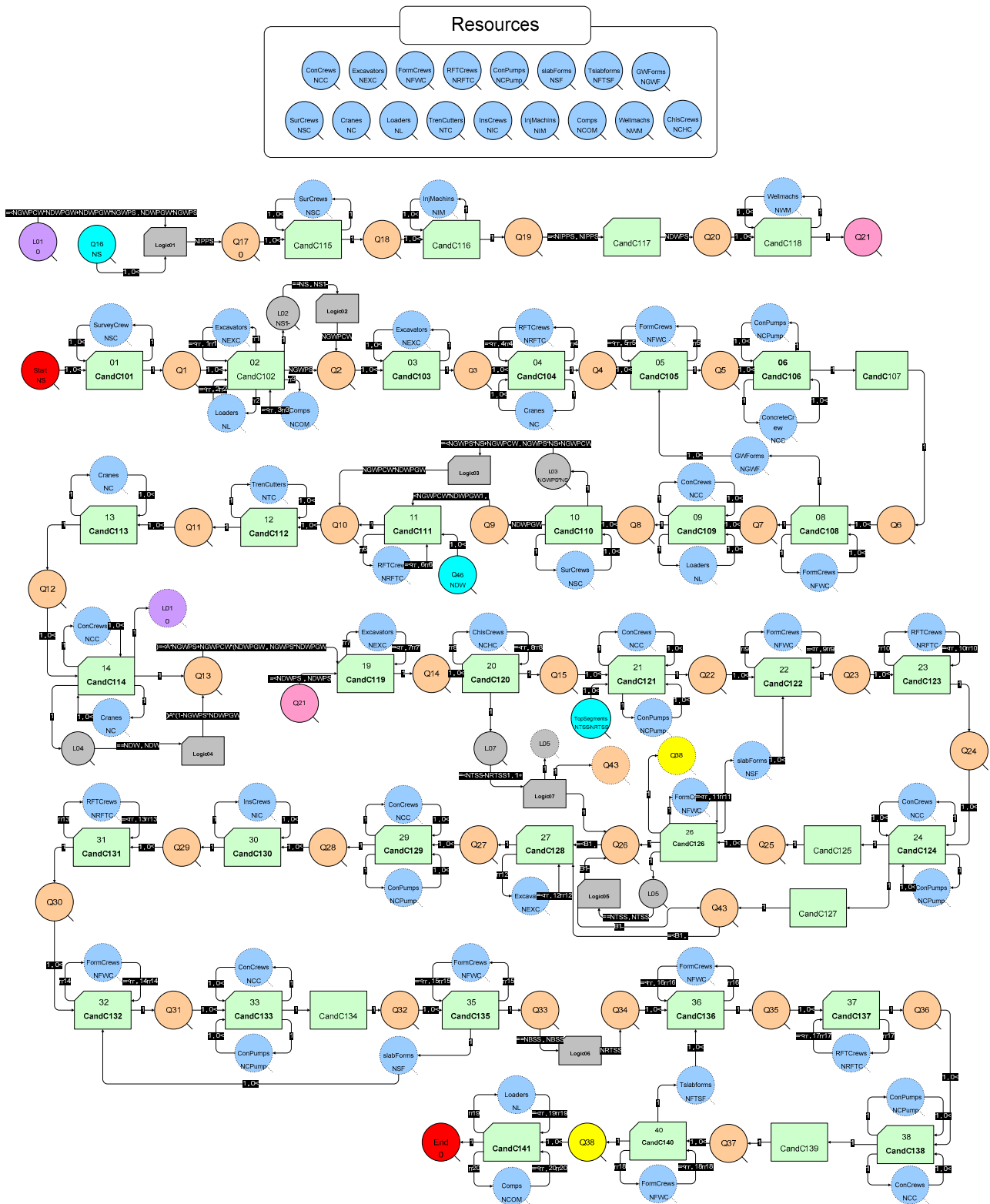


Figure 4: Simulation model of cut and cover technique using diaphragm wall

2.3 Decision Making Module

Decision making module is responsible for selecting the best alternative of tunnel construction based on a set of pre-defined criteria. A group of decision makers provides their feedback on the pre-defined criteria. The proposed decision making module utilizes a fuzzy group decision making method (Zhang and Lu 2003) for selecting best alternative. The procedure that is followed for selecting the best alternative as follows:

1. Defining selection criteria, experts define criteria that will be used to benchmark alternatives. Decision making module defines each criterion by dividing it into three ranges (*Low*, *Medium* and *High*) which are required to be defined by the user (see Figure 5). Decision making module accounts for three main criteria: project cost, project duration, and resources utilization. It is flexible in away that it allows the user to define two more criteria that are deemed important (e.g., utilization of specific piece of equipment). At this stage, criteria weights and experts' years of experience are defined by each expert through five levels of importance as listed in Table 3.
2. Defining criteria values of alternatives, the output data from *Tunnel_Sim* (including project cost, duration, and/or resources utilization) are entered as criteria values of alternatives.
3. Categorizing alternatives, the decision making module uses fuzzy group decision making method to choose best alternative which has the highest preference value.
4. Refining result, for alternatives with small far preference value, experts can ignore them and restart the decision making process.

Detailed description of decision making module can be found elsewhere (Abdallah 2008).



Figure 5: Defining criteria ranges

Table 3: Leveling criteria and experts; years of experience

Linguistic weight	Years of experience	Quantitative scale
Unimportant	< 5	1
Less important	5 - 10	2
Important	10 - 15	3
Rather important	15 - 20	4
Very important	> 20	5

3 APPLICATION EXAMPLE

The application example considers the construction of Giza tunnel project. This tunnel aims at solving a traffic jam problem existing in Giza square by eliminating a traffic signal at the intersection of Morad street and El-Giza street (see Figures 6 and 7). The tunnel has a total length of 450 meters with an average width of 8.5 meters. The tunnel is constructed using open cut method with secant pile wall except for the mid part (Zone III) which is constructed using cut and cover method with secant pile wall. The total contract value of the tunnel is 50 millions Egyptian pounds and was planned to be executed in two years. The contract scope of work includes the execution of tunnel body, diverting of existing utilities in the tunnel path, and tunnel's finishes. Table 4 lists zones construction methods and their respective information. Table 5 lists the duration of tasks in the tunnel's five zones. Once the case data are fed to *Tunnel_Sim*, it estimates the project duration and cost for construction of the tunnel body (see Table 6). *Tunnel_Sim* estimated the mean total cost of the tunnel body to be 26,230,395 L.E. While, the mean expected total duration of the tunnel body was estimated to be 371 working days (i.e., 433 calendar days).

Table 4: Characteristics of tunnel's zones

Zone	X-Sec	Length (m)
1	Retaining Wall	40
2	U Sec.	135
3	Box	80
4	U Sec.	135
5	Retaining Wall	46

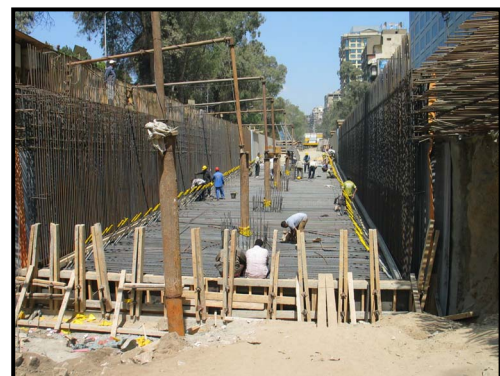


Figure 6: Steel work for tunnel bottom slab (Zone II)

Table 5: Duration of tasks in tunnel's zones

Activity Description	Resources	Zones I and V		Zones II and IV		Zone III	
		No.	Duration	No.	Duration	No.	Duration
Segment survey	---	---	N(12,2) h	---	N(12,2) h	---	N(12,2)h
Locating and installation of Temporary casing	---	---	---	---	N(10,2) m	---	N(10,2) m
Drilling	---	---	---	---	U(15,20) m	---	U(15,20) m
Plastic Concrete Pouring	---	---	---	---	U(20,25) m	---	U(20,25) m
Locating and installation of Temporary casing	---	---	---	---	U(1.5,2) h	---	U(1.5,2) h
Drilling	---	---	---	---	U(15,20) m	---	U(15,20) m
Preparing and fixing of steel cage	---	---	---	---	U(2.5,4) h	---	U(2.5,4) h
positioning steel cage into hall	---	---	---	---	N(45,10) m	---	N(45,10) m
Concrete Pouring	---	---	---	---	U(1.5,2) h	---	U(1.5,2) h
Excavation and Trimming of Piles head for one capping beam	Excavators	---	---	1	U(6,7) d	1	U(6,7) d
Steel work	RFT crews	---	---	3	U(2,3) d	3	U(2,3) d
Shuttering of forms	Formwork crews	---	---	3	U(1,2) d	3	U(1,2) d
Concrete pouring	---	---	---	---	N(4,0.5) h	---	N(4,0.5) h
Concrete curing	---	---	---	---	N(12,0)	---	N(12,0)
Removal of forms	Formwork crews	---	---	2	N(6,1) h	2	N(6,1) h
Drilling of one dewatering well	---	---	---	---	U(1,1.5) d	---	U(1,1.5) d
Excavation till the base of bottom slab	Excavators	1	N(1,0.5) d	2	U(3,4) d	2	U(3,4) d
Pouring plain concrete between the two sides of the Tunnel	---	---	N(6,1) h	---	N(12,1) h	---	N(12,1) h
Water insulation	---	---	N(0,0)	---	U(4,5) d	---	U(4,5) d
Steel work	RFT crews	4	U(1,1.5) d	8	U(2,3) d	8	U(2,3) d
shuttering forms and installing of water stop	Formwork crews	2	N(1,0) d	4	N(12,2) h	4	N(12,2) h
Concrete pouring	---	---	N(8,2) h	---	N(10,2) h	---	N(10,2) h
Concrete curing	---	---	N(1,0) d	---	N(12,0) h	---	N(12,0) h
Removal of forms	Formwork crews	2	N(1,0) d	2	N(12,2) h	2	N(12,2) h
Steel and insulation works	RFT crews	4	U(2,3) d	10	U(10,12) d	10	U(10,12) d
Shuttering of forms	Formwork crews	2	U(2,3) d	6	U(2,3) d	6	U(2,3) d
Concrete pouring	---	---	N(8,2) h	---	N(10,2) h	---	N(10,2) h
Concrete curing	---	---	N(3,0) d	---	N(3,0) d	---	N(3,0) d
Removal of forms	Formwork crews	2	N(1,0) d	4	U(1,2) d	4	U(1,2) d
Shuttering of forms	Formwork crews	---	---	---	---	8	U(7,9) d
Steel work	RFT crews	---	---	---	---	8	U(2,3) d
Concrete pouring	---	---	---	---	---	---	N(10,2) h
Concrete curing	---	---	---	---	---	---	N(7,0) d
Forms removal and insulation works	Formwork crews	---	---	---	---	6	U(2,3) d
Backfilling	Compactors	---	U(1,2) d	---	---	2	U(1,2) d
	Loaders	1		---		1	

U[a,b]: Uniform distribution; a is the lower value; b is the higher value.
 N[a,b]: Normal distribution; a is the mean; b is the standard deviation.
 d is days; h is hours; m is minutes

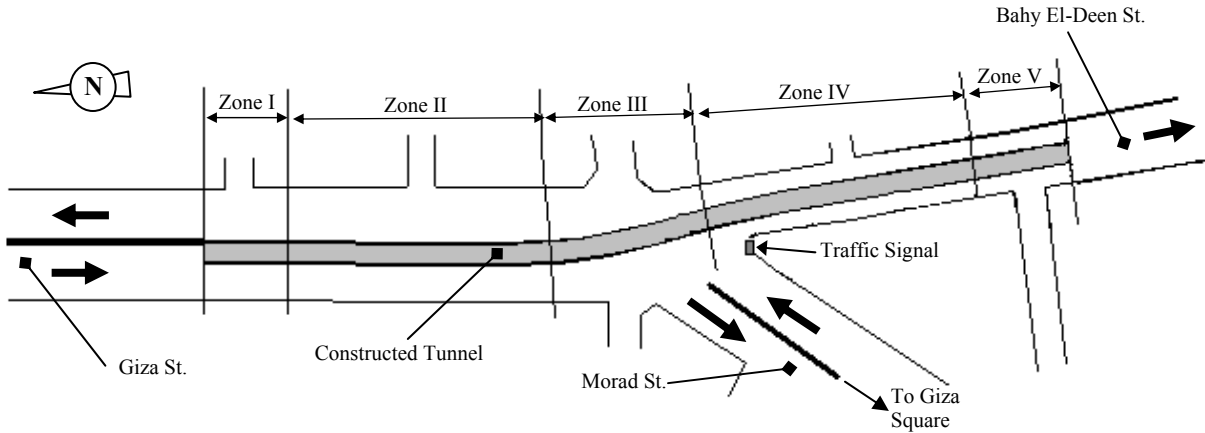


Figure 7: Site layout of the Giza tunnel

Table 6: Tunnel Sim outputs

Zone	Shortest Dur. (Days)	Mean Dur. (Days)	Longest Dur. (Days)	Minimum Direct Cost (L.E.)	Mean Direct Cost (L.E.)	Maximum Direct Cost (L.E.)
1	17	19	21	167,690	174,230	182,760
2	110	114	120	6,637,780	6,710,540	6,792,380
3	103	107	111	6,104,675	6,165,890	6,223,130
4	108	112	116	6,698,310	6,770,110	6,830,810
5	16	19	20	191,470	198,875	204,930
Total	354	371	388	19,799,925	20,019,645	20,234,010

4 CONCLUSION

Tunnel projects are characterized by complexity, repetitive operations, difficult construction environment, and different construction techniques. Such characteristics lead to uncertainties with respect to the estimated duration and construction cost. This paper presented a decision support tool, named *Tunnel_Sim*, that assists contractors in planning of tunnel projects. It performs two main functions: i) estimating tunnels duration and cost, and ii) selecting the best alternative from different available construction alternatives. *Tunnel_Sim* provides five techniques for construction of tunnels: cut and cover using diaphragm walls, cut and cover using secant pile walls, cut and cover using soldier piles and lagging, cut and cover using steel sheet pile walls, and segmental tunneling using slurry TBM. The paper provided an overview for *Tunnel_Sim*'s modules: tunnel analyzer module, simulation module, and decision making module. An application example was presented to demonstrate the important features of *Tunnel_Sim*.

REFERENCES

Abdallah, M. 2008. *Decision support tool for planning tunnels projects using computer simulation*. M.Sc. the-

sis, Structural Engineering Department, Cairo University, Egypt.
 AbouRizk, S. M., J. Y. Ruwanpura, and K.C. Er Siri Fernando. 1999. Special purpose simulation template for utility tunnel construction. In *Proceeding of the 1999 Winter Simulation Conference*, ed. P. A. Farrington, H. B. Nembhard, D. T. Sturrock, and G. W. Evans, 948–955. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.
 Hassan, M. M., and S. Gruber. 2008. Simulation of concrete paving operations on interstate-74. *Journal of Construction Engineering and Management* 134(1): 2-9.
 Luo R., and M. Najafi. 2007. Productivity study of micro-tunneling pipe installation using simulation. *Journal of Infrastructure Systems* 13(3): 247-260.
 Marzouk, M. 2002. *Optimizing earthmoving operations using computer simulation*. Ph.D. thesis, Department of Building, Civil, and Environmental Engineering, Concordia University, Canada.
 Marzouk, M., H. Zein, and M. Elsaid. 2006. A framework for planning and optimizing bridge deck construction using computer simulation. In *Proceeding of the 2006 Winter Simulation Conference*, ed. L. F. Perrone, F. P. Wieland, J. Liu, B. G. Lawson, D. M. Nicol, and R. M. Fujimoto, 2039–2046. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

- Martinez, J. C. 1996. *STROBOSCOPE, State and resource based simulation of construction processes*. Ph.D. Thesis, University of Michigan, USA.
- Tanaka, Y. 1993. Cycle time simulation of shield-tunneling operation. Proc., In *Proceeding of Fifth International Conference on Computing in Civil and Building Engineering*, ASCE, Reston, 1386–1389.
- Zhang G., and J. Lu. 2003. An integrated group decision making method dealing with fuzzy preferences for alternatives and individual judgments for selection criteria. *Group Decision and Negotiation* 12(6):501-515.

AUTHOR BIOGRAPHIES

MOHAMED MARZOUK is Associate Professor at Department of Structural Engineering, Faculty of Engineering, Cairo University. He received his B.Sc. and M.Sc. in Civil Engineering from Cairo University in 1995 and 1997, respectively. He received his Ph.D. from Concordia University in 2002. His research interest includes simulation and optimization of construction processes, O-O simulation, fuzzy logic and its applications in construction, risk analysis, and decision analysis. His e-mail is mm_marzouk@yahoo.com.

MOATASSEM ABDALLAH is Teaching Assistant in Department of Structural Engineering, Faculty of Engineering, Cairo University. He received his B.Sc. and M.Sc. in structural engineering from Cairo University in 2005 and 2008, respectively. His research interest includes simulation, decision support systems, and construction technology. His email is engmoatasseem@yahoo.com.

MOHEEB ELSAID is Professor of construction engineering and management at Department of Structural Engineering, Faculty of Engineering, Cairo University. His research interest includes productivity, schedule risk assessment, life cycle costs, and simulation. His e-mail is elsaid1204@yahoo.com.