Models for the Analysis of Tunnelling Construction Processes

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Abstract

In general, tunnelling construction processes are considered to be quite complex. They involve many variables which interact with each other and the resourced used. Hence, it is quite difficult to explain the reasons for scheduled delay and cost overruns in these processes. In order to understand and improve the tunnelling construction processes, and consequently minimize the sources of delay and increasing costs, various types of methods and tools have been developed. In construction management, models are often used to solve problems related to planning and control, project scheduling, cash flow management and resource management.

This study focuses on tunnelling processes, with the goal to develop methods and tools to be used to gain understanding of these processes, and to analyze them. Both, deterministic and simulation models were proposed, describing the behaviour of tunnelling construction using different systems to deal with the issues of excavation and materials handling.

The deterministic model was developed and applied on three case studies, these are: Laval metro tunnel project, Bathurst & Langstaff sewer tunnel project and the Parramatta rail link tunnel project. A sensitivity analysis was carried out on each of the case studies, to identify and analyze the most sensitive tunnelling variables affecting productivity. Based on the sensitivity analysis and the comparison between the actual productivity and the calculated productivity, the validity and effectiveness of the model was assessed. Subsequently, two simulation models of the Laval metro tunnel were developed using EZstrobe simulation software and similar sensitivity analysis were carried out. Once it was determined that the simulation models produced reasonable results, they were than used to experiment with different resource combinations to evaluate the impact on productivity and cost. Based on productivity and cost, also a comparison was made between the road header and drill and blast excavation methods. Such information can be used in real projects by the project manager to make decisions as to what excavation method or resources to use.

The testing of the models showed that both of them produce credible results compared with the actual information collected from the real case study. The results of the analysis showed that some variables are more sensitive to the productivity of the model than others. The following variables, determined from the simulation study of the Laval metro tunnel project, affect the tunnel advance rate: number and capacity of trucks; number of road headers; road header penetration rate; number and productivity of loaders, number

of drill jumbos, number of platform trucks, and number of excavators. Furthermore, the affect of the swell factor of soil; cross section area of tunnel; and excavated length per cycle, on the tunnel advance rate was investigated.

In conclusion of the thesis, the deterministic and simulation modelling approaches were compared to each other. The comparison is based on the productivity calculations and sensitivity analysis of both modelling methods on the same case of the Laval metro tunnel project. Finally, the advantages and limitations of both modelling approaches were discussed.

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Table of contents

1. Introduction

In this chapter the definition of the research problem will be described in depth. The chapter consists of the research objective and the research methodology. The research objective describes the general objectives the research is addressing. Based on the sub-objectives derived from the overall research objective, the method of research is chosen and described. In the research methodology section a description will be given regarding the way the research is carried out.

1.1 Complexity of construction processes

The construction industry is considered to be different from other industries, because of a number of unique characteristics associated with it. The first important characteristic of the construction industry is that many different resources (e.g. labour, special machinery and materials) are involved simultaneously during the construction process. The second characteristic is the one-off nature of the products that are produced. Every construction project is different for a variety of reasons, for example the materials used, the participants involved, and the ground and weather conditions on site. A third important characteristic of the industry is that construction is executed under uncontrolled circumstances. The construction environment is effected by many dynamic and uncertain variables, such as weather, space congestion, crew absenteeism, regulatory requirements, and design changes and reworks (Ahuja and Nandakumar, 1985). Because of these characteristics it has always been very difficult to optimize the construction process in terms of productivity and efficiency.

Due to the issues discussed above, construction processes are considered to be quite complex. This complexity may lead to difficulty to understand the interaction between the various processes involved in construction. The processes involve many variables which interact with each other and the resourced used. Hence, it is quite difficult to explain the reasons for scheduled delay and cost overruns in these processes.

In order to understand and improve the construction process, and hence minimize the chances that these problems occur, various types of methods and tools are found to be useful. For example, in construction management, mathematical models are often used in addressing problems of planning and control, such as project scheduling, cash flow management and resource management. Simulation models are also found to be effective for modelling, analysis and understanding processes related to planning, scheduling and cost forecasting of construction projects, like tunnelling, road paving, and pipe installation. The reason that simulation is suitable for modelling and analysis of these types of projects is that the construction processes involved, consist of many repetitive construction cycles (Er et al., 1999). Using simulation, real operations can be modelled reasonably accurate and the whole construction process can be analyzed in depth, so that potential problems can be identified. This is usually carried out by conducting experiments in a controllable and low-cost environment. Also in doing so it is possible to analyze a wide range of aspects of construction, such as: the costs of the entire project, productivity, the number of resources needed to enhance productivity (resource allocation), and site planning. This information can be useful and valuable for construction managers in the field, so that processes can be redesigned and resources reallocated if necessary, to improve productivity and cost-efficiency of construction operations.

1.2 Research objectives

This research is related to the use of deterministic and probabilistic models using simulation, to study and analyze construction processes. The general goal of this research is to develop models for tunnelling construction, and analyzing the results for better understanding of the processes and the efficiency of these processes.

The overall objective of this research is to model tunnelling construction operations using deterministic and stochastic models in order to analyze the processes and identify the variables that affect the productivity (in terms of tunnel advance rate) and cost of the construction process. Also simulation is used to determine the 'best' resource allocation, as well as to compare the various methods of excavation of the Laval metro tunnel, based on productivity and cost.

The overall objective of the research is defined as:

"Analysis of tunnelling construction processes using deterministic and simulation modelling, in order to identify and analyze the most sensitive tunnelling variables affecting productivity."

In order to achieve the research objective the following sub-objectives are identified:

To develop the deterministic and simulation models

- Identify the main activities and resources involved in tunnelling construction.
- Determine the relationships of the activities and resources in the simulation model.
- Develop a deterministic model of the tunnelling construction processes.
- Develop simulation models based on a real tunnelling project in Canada.

To refine and validate the deterministic model

- Refine and validate the deterministic model by applying the model to actual tunnel construction projects.

To refine and validate the simulation models

- Refine and validate the simulation models by using the case study of the Laval metro tunnel project as a basis.

To conduct experiments and analyze the results using the deterministic and simulation models

- Identify the important variables that affect the productivity (in terms of tunnel advance rate) of tunnelling construction by performing sensitivity analysis.
- Analysis of the resource allocation of a real tunnelling project in Canada based on productivity and cost, using simulation as a decision analysis tool.
- Comparison of the drill and blast, and road header excavation methods based on productivity and cost, using simulation as decision analysis tool.

1.3 Research methodology

As described in the previous section, the main research steps are: 'developing generic deterministic and simulation models of tunnelling processes', 'refining and validating the deterministic and simulation models using data from actual tunnel construction projects', and 'conducting and analyzing experiments' (see figure 1). The research methods based on the research objective are discussed in the following paragraphs.

The first step of the research consists of gathering information about activities and resources used in tunnelling construction. This is mainly done by means of a literature study and through interviews with experts of tunnelling construction projects. In order to identify the main variables of tunnelling construction a deterministic model is constructed. The deterministic model is used to help to understand the processes involved in tunnelling construction, and identify the model variables for which information needs to be collected. Based on this information generic construction simulation models have been developed using EZStrobe simulation software. Subsequently, the deterministic and simulation models need to be refined. Data about; model parameters, probability distributions of time durations of activities, resources and the relationships between model's parameters are examined. In order to get this information, required to build the simulation model, experts will be interviewed to provide complete understanding of the system to be modelled.

The next step in the process is refining and validating of the deterministic and simulation models. It's important to identify model variables that have a significant impact on the desired measure of performance. These variables have to be modelled accurately. In order to validate the models, the output data of the deterministic and simulation models is compared with the data from real tunnelling projects. If the output of the models is similar to actual output of the case studies, the model can be considered 'valid', and experiments can be conducted to analyze the different processes and variables.

The last step involves conducting experiments and analyzing the results. A sensitivity analysis is carried out on real tunnelling case studies, to identify and analyze the most critical tunnelling variables affecting productivity of tunnelling construction processes. Critical variables are the variables that have major impact on productivity (and cost) of tunnelling construction. Sensitivity analysis is performed for both the deterministic model and the simulation models. On the basis of the results produced, the 'best' resource allocation regarding a real tunnelling project is determined. Also, a comparison will be made between the road header and drill and blast excavation methods. These analyses are done based on productivity (in terms of tunnel advance rate) and cost.

The research methodology described in the previous paragraphs can be graphically represented as shown in figure 1.

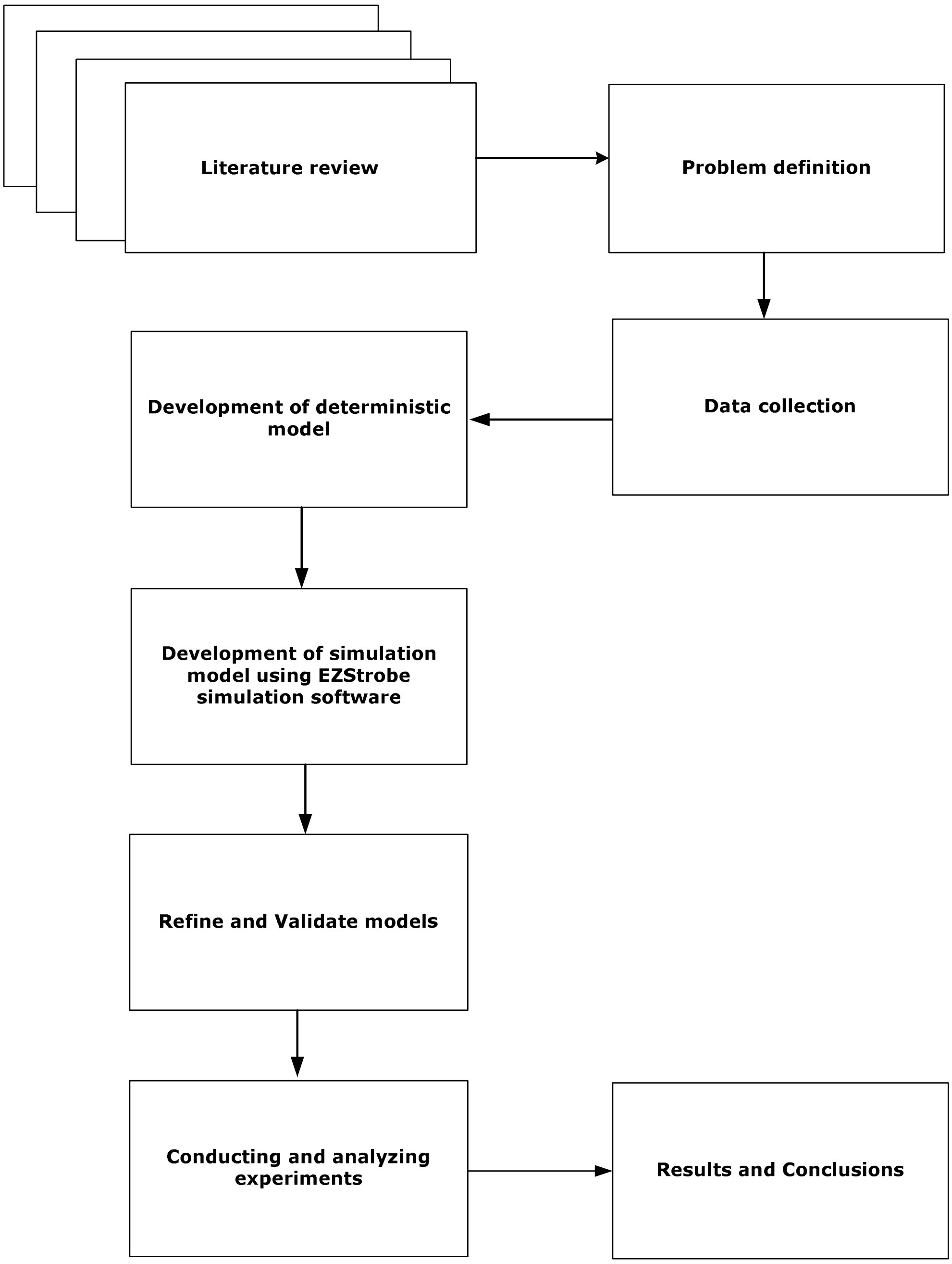

Figure 1. Graphical representation of research methodology

2. Processes of tunnel construction

Before a tunnelling construction project can be analyzed, it is important to define the tunnelling system. Decisions have to be made concerning the modality of excavation (e.g. drill and blast, TBM, road-header), the material handling process, and the tunnel support system. In this chapter the various activities related to the tunnelling construction process will be explored. The purpose of this literature study is to get a general overview of the different construction processes involved in tunnelling, and the interaction of the various processes in the context of tunnelling construction.

In the first paragraph the focus will be on the main excavation methods, namely drill and blast, tunnel boring machine (TBM), and road-header. Because of the importance of the material handling processes and tunnel support systems of tunnelling construction, an extensive literature review concerning specifically these subjects will be provided subsequently. The chapter ends with a description of the influence factors affecting productivity of tunnelling construction.

2.1 Excavation methods

At present drill and blast and TBM tunnelling can be considered the most common excavation methods used in tunnelling. One of the differences between the use of TBM or drill and blast is that the performance (rate of advance) for drill and blast is lower in most cases. The total labour cost using drill and blast-method is higher, but the investment cost is lower than TBM technology (relatively low capital cost for equipment). According to Girmscheid and Schexnayder (2002), drill and blast technology is cost efficient when the length of the tunnel to be excavated is less than three kilometres. The cost efficiency decreases as tunnel length increases. Comparing both methods there are also other significant differences. Tunnel excavation using TBM requires a predetermined tunnel diameter, which can be excavated accurately. Using drill and blast the cross section can be created to any shape. Another difference between both methods is that the drill and blast-method will perform better as compared with TBM as geology of the soil becomes complex and there are zones of disturbance (Girmscheid and Schexnayder, 2002).

2.1.1 Drill and blast method

The drill and blast process is a cyclic operation; each round consists of four successive operations, namely: drill, blast, muck and installation of primary support. The drilling operation consists of drilling a series of small blast holes in the tunnel face, by a so called "drill jumbo". The number of holes and location are dependent of the type and condition of the rock, the type of explosive and the blasting technique used (Likhitruangsilp, 2003). After all the required holes are drilled, they will be loaded with explosives. Once the explosives are loaded in the blast holes, the tunnel face is cleared and the explosives are then detonated. This operation will lead to excavated soil, which must be removed subsequently. Also pieces of loosened rock remaining on the tunnel roof and walls have to be removed, before the mucking process begins. Once this is finished mucking machines and materials handling equipment are mobilized, and the muck is hauled out of the tunnel face. After the mucking operation, primary support systems are installed to stabilize the opening. Primary support systems are installed at the same time as the excavation operation to keep the opening stable during construction. For the drill and blast method, primary support is usually installed after the mucking operation is completed in each round, but before or during the drilling operation for the next round (Likhitruangsilp, 2003). The supporting systems, such as air, electricity, and ventilation, and the tracks are subsequently extended to the new tunnel face. Final lining is installed at some later stage after the installation of primary support. In general final lining occurs after the tunnel has been entirely excavated and supported. Common lining systems are: monolithic concrete lining, steel segments, and pre-cast concrete segments.

2.1.2 Tunnel boring machine (TBM)

Tunnelling construction involves three main processes, namely excavation, dirt removal and tunnel support (Ruwanpura, 2001). The construction of a tunnel (using TBM) begins with the excavation and liner support of the vertical shaft. In the construction of a tunnel using TBM the following operations can be distinguished:

1. Excavation and support of the undercut area
2. Excavation of the tunnel and tail tunnel
3. Disposal of dirt from the tunnel face
4. Hoisting dirt to ground level
5. Lining the tunnel
6. Extending the services and rail tracks
7. Excavation and support of the removal shaft.

Two types of tunnelling boring machines are used in the tunnelling construction practice, namely the open-face and closed-face shielded machines. Both methods are used in different circumstances. The open- face boring machines is used when excavating through stable soils. When the soil conditions become less stable, because the soil consists of for example silt or sand, closed-face shielded machines are used. Important properties in the excavation processes using TBM are the excavation rate and stroke length of the tunnelling boring machine. The excavation rate is dependent on the soil conditions and TBM horsepower. The stroke length determines how often the TBM will need to be reset.

Dirt handling involves the transportation and disposal of spoil from the tunnel face to the shaft, from where it is transported to the surface. Different methods are used to haul the spoil from the tunnel face to the shaft; examples are trains and belt conveyors. Using trains to haul spoil has many advantages. First of all it is compatible with most excavating and loading methods, and can be used in almost all sizes of tunnels. Another advantage is that besides hauling of spoil, also labourers and support liners can be transported using trains. Depending on the tunnel diameter, a single or double-track system can be used. Belt conveyors on the other hand have the advantage that it can provide a continuous spoil removal system. The spoil that is hauled to the shaft of the tunnel using trains and / or belt conveyors subsequently has to be lifted up to the surface. Hoisting dirt can be done using different methods, these are: with a skip, a clamshell bucket, a crane, a gantry or a derrick hoist. The working shaft is also used to transport construction material and personnel (Ruwanpura, 2001).

Two important tunnel support systems consist of rib-and- lagging and concrete segments. The rib-and-lagging support system is used as a primary lining system. When tunnelling excavation is finished cast-in-place concrete is placed as final lining. Pre-cast concrete segment lining acts as primary and final lining. The segments are installed inside the shield of the TBM, and expanded against the soil as it leaves the shield (Ruwanpura, 2001). For tunnelling by TBM there are also other primary support systems used, namely: steel sets, rock reinforcement systems, and shotcrete (Likhitruangsilp, 2003).

2.1.3 Road header

Road-header machines (partial-face tunnelling machine) were initially developed for the coal mining industry, but are increasingly being used in rock tunnelling. The machine consists of a rotating cutting head mounted at the end of the boom to a crawler frame. This crawler frame contains a power system, a muck gathering system, and a conveyor that transports the muck to the back of the machine. The muck is then loaded into the muck handling system and hauled out of the tunnel. Road-headers can achieve a better advance rate than the drill and blast-method, but significant lower than the tunnel boring machine. The advantages of this method are similar to the TBM method, such as continuous operation, limited non-productive time, and quality of the tunnel opening. However, road-headers are more flexible than the tunnel boring machine, because they can be applied to various types, shapes, and sizes of underground excavation (Likhitruangsilp, 2003).

Tunnelling construction using road-headers involves three main processes, namely: excavation, dirt removal and tunnel support (Obeidat et al., 2006). Excavation is done using road-header for a certain amount of time. In order to start the next process the road-header is pulled back. The removal of dirt from the face of the tunnel can be done by using a conveyor belt, trucks or trains. After the road-header has excavated for a certain amount of time it gets pulled back, so that scaling and the installation of mechanical bolts can start. Subsequently installation of initial support is done. This operation involves installation of wire mesh or shotcrete at their designed locations.

2.2 Materials Handling Processes

Bickel et al. (1996) stated that the materials handling is the key element in the tunnelling construction process. To achieve the designed productivity, all tunnelling activities depend upon the materials handling systems. Also the facilities required to support the tunnelling operations are mainly oriented toward keeping the material handling systems operating efficiently and at their planned rates of production (Bickel et al., 1996).

Touran and Asai (1987) studied the tunnel advance rate in the construction of a tunnel, and investigated the affect of different variables on the tunnel advance rate. One of the conclusions of this study is that the main problem in long tunnels with a small diameter is the logistics. It was stated that the reduction of the tunnel advance rate is not due to the power and capacity of the TBM, but the complex interaction between the logistical processes inside the tunnel.

Nestor (1974) stated that the reason material handling considerations are important in planning tunnel operations is because TMB capability is often greater (due to technological development) than that of the back-up system. Any increase in for example TBM capability must be matched or exceeded by improvements in the material handling and other components of the back-up system to be effective.

2.2.1 Logistical processes

Materials handling systems essentially deal with materials going into the tunnel face and materials leaving the face to go to the surface. The materials that enter the tunnel are essentially the materials and equipment for all tunnel systems and personnel. The materials that leave the tunnel are usually: muck, drainage water, gases, equipment for repair and replacement of personnel. These activities occur at the surface of the tunnel, vertically, at the shaft of the tunnel. Beside the principal materials handling, this also implies the material handling service systems for water, ventilation and high air, drainage, fuel and power (Cooper and Sigman, 1974).

The logistical processes distinguished by Touran and Asai (1987) regarding tunnelling construction are:

- Transfer of the excavated material from the tunnel faces to the shaft area;
- Vertical material handling at the shaft;
- Transfer of tunnel support system to the tunnel face;
- Installing the support system;
- Switching trains, moving forward and backward in the tunnel.

2.2.2 Transportation systems

The material handling process can be divided into two parts, namely the vertical and horizontal material handling. The vertical material handling concerns hoisting the excavated material up the shaft, and carrying tunnel support and personnel to the bottom of the shaft. The horizontal material handling consists of the transportation of the excavated material, personnel and tunnel supports inside the tunnel, from the face of the tunnel to the shaft and visa versa (Touran and Asai, 1987).

When making a choice for a transportation system for underground and shaft hauling, the following factors are important: cost calculation, existing machines, traffic in the tunnel, traffic safety, possible hindrances at site, and ventilation requirements (Maidl et al., 1995). According to Nestor (1974) the material handling system chosen depends upon the following variables, namely: type of formation, diameter of the tunnel, length of the tunnel, whether access to the tunnel is through a shaft or portal, location of and space available at the shaft or portal, and, from a economical standpoint, the material handling system already available to the contractor.

The factors that make the muck haulage system complex according to Faddick and Martin (1977) are: problems of confined space, wide variation of mucking rates, wear of equipment, the noise and dust inside of the tunnel.

2.2.3 Basic transportation

Two basic types of transportation, for moving personnel and materials inside of the tunnel, are distinguished for tunnelling. One is the use of a railroad track and different types of cars. The other uses a roadbed for rubber-tired vehicles (Bickel et al., 1996).

Rail

The most energy efficient handling of materials inside the tunnel is provided by rail haulage (Bickel et al., 1996). Rail haulage consists of a train system using multiple trains on either a single track with passing tracks, or a double track with cross over for passing trains. The main advantages of this type of system are that it is an easily maintained traffic way, compatible with most excavating and loading materials, it is adaptable to almost all sizes of tunnels, and it can transport personnel and material into the tunnel. There are also a few disadvantages, including a constant requirement of extension at the heading, and in case there is an accident the entire system needs to be shut down. Different kind of track layouts are common using train haulage for tunnelling construction, namely the so called 'Californian switch', the 'Jacobs sliding floor' (drill and blast), and the 'Navajo blanket'. These allow trains to move in opposite directions and pass each other at various points in the tunnel. The portable or Californian switch consists of a section of double track with turnouts and ramps at each end, all of which slides on the main track. The Jacobs sliding floor consists of a steel floor occupying most of the invert width. It is built in three or more sections so that it can be moved along as the heading advances. The 'Navajo blanket' provides for extending the track in the heading, in standard rail-length increments (Bickel et al., 1996). Bickel et al. (1996) also describes which possibilities are available regarding the propulsion of the trains inside the tunnel. Likewise, considerations concerning the track itself (e.g. the selection of the track gauges, the weight of the rail, the track accessories, and track ballast) and the construction of the roadbed are described.

Rubber-tired vehicles

In contrary to rail haulage, transportation with rubber-tired vehicles is more flexible, because they don't need fixed facilities. The use of rubber-tired vehicles has a number of important advantages, these are: in a wide tunnel passing locations can be selected at will, when accidents happen the entire system doesn't have to be shut down, and the work on tunnel invert is usually simplified. The main disadvantages that come with this system are: Roadbed is difficult to maintain, it is not compatible with all excavating and loading equipment, and vehicles are often not usable in small tunnels. Rubber-tired vehicles are often used for driving in short tunnels in which installation of a track system would not be economical (Nestor, 1974). There are different types of rubber-tired vehicles described in Bickel et al. (1996), namely the load-haul units (standard front-end loaders), dump trucks and special vehicles (for explosives delivery or supply services).

2.2.4 Special muck transporting systems

Beside the basic transportation systems, there are also other methodologies used in special cases to haul the muck. The two main systems are belt conveyors and pipeline.

Belt conveyors

The belt conveyor system is used generally in combination with the tunnel boring machine (TBM) excavation method, and one of the main reasons it is used is because it can transport a great amount of muck relatively fast. Most TMB have a conveyor incorporated into their design for removal of the muck to an intermediate point behind the machine where it is transferred for removal. This method can also be used with any other excavation method, as long as the operating requirements are met. Belt conveyors offer the simplest, most acceptable and generally most economical method of providing continuous transportation. The main advantages using this system are: capable to handle excavated material for any reasonable rate of heading advance, can be used in almost all sizes of tunnels, good reliability and low maintenance, and it guarantees a continuous operation. The disadvantages include the high capital cost, breakdown of one part shuts down entire system, and requires a complicated system for extension in the heading (Bickel et al., 1996).

Pipeline

Pipeline systems can be used when bulk materials have to be transported, using either air or fluids as the medium of transportation. This system seems to be more useful as the tunnel diameter decreases, and hence the volume of the muck to be transported and the space for installation of the muck removal system decreases. Three types of systems are distinguished, namely the slurry system, the hydraulic system and the pneumatic system (Bickel et al., 1996). The slurry system in particular offers high transport capacity with very low space requirements. In tunnels with small diameter, where trains can’t pass each other, a slurry system makes it possible to achieve high advance rates (Maidl et al., 1995). The advantages using a pipeline system include the availability of high capacities, minimum space requirement in the tunnel, and it guarantees a continuous operation. The main disadvantages are: maximum size of material to be handled is limited, it requires a complicated system for extension in the heading, and in case there is any breakdown the entire system needs to be shut down (Bickel et al., 1996).

Faddick and Martin (1977) describe the use of slurry pipelines for muck haulage in tunnelling construction operations. The pipeline systems (slurry, hydraulic and pneumatic pipelines) have the ability to transport high volumes of muck relatively quickly using limited space. A muck haulage pipeline is a system that consists of three elements, namely preparation, transportation and separation. The excavated material needs to undergo a size reduction before it can be transported through the pipeline. The reduction of size and particle shape is done to optimize the pipeline performance. A slurry pipeline for main muck haulage will necessitate two pipelines, an outgoing pipeline to transport the muck slurry and an incoming pipeline to carry water supply (Faddick and Martin, 1977).

2.2.5 Vertical material handling

When the excavated material is brought to the shaft, and dumped into a temporary storage facility it has to be hoisted to the surface. This vertical material handling can be done using different systems, such as: skips, cages, muck car lift-up system, multi-bucket system and vertical conveyors (Bickel et al., 1996).

In the skip system a skip is placed at the bottom of the shaft in which the muck is loaded, and subsequently hoisted through the shaft, and eventually emptied at the surface. When the depth of the tunnel is more then 30 m, often a cage or skip is used with a head frame for hoisting the muck. Cages are used to convey personnel, material and equipment. Even loaded muck cars can be hoisted in a cage. In the muck car lift-up system, the muck cars itself are hoisted to ground level, in a special guide cage that provides for automatically dumping of the car. Vertical conveyors and bucket-type elevators (multi-bucket system) are available for lifting large volumes of tunnel muck, usually generated by TBM, from the tunnel to the surface. However, these systems are not able to supply construction material inside of the tunnel.

2.3 Tunnel support systems

Tunnel support systems are applied in tunnelling for means of stabilization (primary support) before, during or immediately after excavation to provide initial support and to permit safe, rapid and economical excavation. Final lining designates systems installed either shortly or considerably after excavation to provide permanent support and durable, maintainable long-term finishes. The type of systems chosen depends primarily on the ground conditions and on the end use of the tunnel. (Bickel et al., 1996)

2.3.1 Primary support

The purpose of primary support is to stabilize the underground opening until final lining is installed. The main goal for placement of primary support is to ensure health and safety for the working crew during construction of the tunnel. Furthermore, usability of the underground structure is an important reason for placement of primary support as well as the protection of the environment (e.g. neighbouring buildings, lines of communication in or above ground facilities, etc.). The most common elements for the primary support are:

- Rock bolts
- Shotcrete
- Steel ribs and lattice girders
- Wire meshes
- Lagging

The elements can be applied individually or in combination in different types of support, depending on the ground conditions on site, and the design of the tunnel. The elements of primary support are placed, in each round, up to the excavation face of the tunnel for reasons of safety and health, according to structural analysis of the tunnel and the assessment of the ground conditions. (ITA Working group conventional tunnelling, General report on conventional tunnelling method, 2009)

2.3.2 Final lining

An underground structure excavated by drill and blast or road header often needs a final or secondary lining in addition to the primary lining according to the requirements of the project to:

- Cater for all the final load cases

- Fulfil the final safety margin
- Include the necessary protection measures (e.g. water tightness)
- Guarantee the required service life time

In general, there are two options to construct the final lining, namely: the installation of an independent secondary lining to withstand all the final load cases, and the installation of additional layers of shotcrete to strengthen the primary lining for all the final load cases. According to the requirements of the project secondary lining can consist of the placement of shotcrete or cast in situ concrete. This can be unreinforced concrete or reinforced concrete (steel bars or fibres).

2.4 Tunnelling productivity factors

Research has been done regarding the factors that affect the productivity of tunnelling construction using different excavation methods. Shaheen (2005) identified the factors that affect the TBM advance rate in soft ground soils. The factors were divided in six different groups: tunnel properties, soil properties, TBM properties, Operator's performance, Shift related, weather related. These factors were analyzed and assessed by experts in the field. It was found that the factors: 'tunnel alignment' (shape of tunnel), 'soil behaviour' (type, plasticity and moisture content), 'inclusion of boulders', 'contaminated soil' (time lost in ventilation testing and safety), 'TBM age' (in meters), 'TBM type' (right machine for right soils), 'operator's experience' (amount of meters excavated), and 'shift type' (day vs. night), were perceived to be very significant factors regarding the penetration rate of excavation using TBM.

Kalamaras (1996) describes that the most important factors in determining the required span of time for the completion of a tunnelling project. These factors are the method of excavation and the geo-mechanical conditions. Other important factors identified in this research are the experience and technical know-how of the personnel with the particular geological conditions and the method of excavation, accessibility to the site and availability of resources.

Obeidat et al. (2006) describes the productivity factors using the road-header excavation method. The factors can be classified in three different categories, namely: geological conditions, machine conditions and management conditions. The geological conditions will affect the cutting rate and the bit wear of the road-header machine. Cutting rate in rock is affected by the type and features of road-header's power, cutting head type, and mounted cutting tools ('machine conditions'). Also 'management conditions' is an important factor.

Efficient and smooth operation, continuous maintenance, organized back-up system, well ground treatment, skilled labour, and successful management of the project will lead to high cutting performance.

In the calculation of the productivity the important factors concerning tunnelling construction should be included. The following factors will be assessed based on the opinion of experts in the field of tunnelling construction (see table 1):

Productivity factor	Description
Operator's experience	Learning curve: years of experience, technical know-how of personnel
Soil / geologic condition	Type, plasticity and moisture content
Job and management condition	E.g. good communication lines, organized back-up system, availability of resources, skilled labour, etc.
Site condition	Accessibility of site (urban or remote area)
Tunnel alignment	Shape of tunnel
Machine condition	Amount of meters excavated
Shift type	Day versus nightshift

Table 1. Tunnelling construction productivity factors

2.5 Summary

In this chapter general tunnelling construction processes were described. Tunnelling construction consists of three main processes, namely excavation, soil disposal and primary support. Different excavation methods (drill and blast, road header and TBM) and materials handling systems (rubber-mounted, rail-mounted, belt-conveyor and vertical materials handling) were explored, as well as the different systems of tunnel support. Furthermore, the influence factors on productivity of tunnelling construction were identified from literature. These factors will be included in the productivity equation of the deterministic model.

3. Simulation use in construction

In this chapter a broader view on simulation will be presented. The purpose of this chapter is to gain understanding regarding the process of building simulation models. Also a better understanding of the use of simulation for different types of analysis of tunnelling construction processes is pursued. Furthermore, critical tunnelling variables are identified from existing simulation models of tunnelling construction. These variables will be used in the deterministic and simulation models, and analyzed by means of sensitivity analysis.

In the first paragraph the general concepts of simulation in construction are described. The advantages and limitation of using simulation will be discussed, and attention will be given regarding building simulation models, validating them, and the use of sensitivity analysis. Over the years different simulation software tools were developed for modelling construction processes. The paragraph concludes with a brief description of these simulation tools, focussing on the EZstrobe simulation software in particular. In the second paragraph of this chapter focus will be on simulation of tunnelling construction. A literature review will be provided about the work that is already been done regarding the use of simulation for analysis of tunnelling construction operations.

3.1 Simulation of construction processes

In the literature simulation is defined as: *"The process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system"* (Shanon, 1975).

Simulation is used in construction projects to predict the performance of the construction process in terms of process flow and resource allocation (Oloufa, 1993). The reason that simulation is useful to apply in the planning of construction projects is that such projects usually consist of different processes and resources. These processes and resources utilized are all related to each other, and inefficiency in these processes will affect the performance of the entire construction operation. However on its own simulation does not give optimal solutions for a given system. Simulation is especially useful to evaluate and compare the performance of alternative construction methods to select the best one. In order to get optimal solutions mathematical methods need to be used. Mathematical optimization can cause the model to become too complicated to be used (Oloufa, 1993).

Simulation modelling in construction projects has many advantages. It is possible to analyze different aspects of the construction process before actually implementing them on the construction site. Construction project planners can use simulation to predict the performance of the construction operations. Resource allocation, site planning, and productivity are a few aspects that can be analyzed in depth with simulation (Halpin and Martinez, 1999). Nevertheless construction process simulation is not widely used in construction yet. The construction industry is reluctant to implement this tool for a number of reasons. Usually, construction contractors work intuitively based on experience with similar jobs and situations, and refuse using simulation software because it restricts the use of their own knowledge and experience to solve problems (Halpin and Martinez, 1999). Another reason is the complexity of the simulation software to be used for analyzing construction processes. In order for simulation to get accepted and used by the construction industry in general, it has to be simple and graphical. Simulation formats that are too theoretical or analytical tend not to be used (AbouRizk et al., 1992). An example of simple and easy to use simulation software is CYCLONE. CYCLONE is developed by Halpin (1973) and is used as basis of a few construction simulation systems. The difference between CYCLONE and other simulation software is that CYCLONE made the simulation modelling process easier, and therefore construction workers in the field can use it with limited knowledge of simulation (AbouRizk et al., 1992).

3.1.1 Advantages and limitations of using simulation

A few advantages and limitations of simulation were already discussed in the previous paragraph, other advantages and limitations are described in the literature. For example the main advantages of using simulation described by Oloufa (1993) are:

1. It is possible to study a system that is too complex to be described in an analytical model.
2. Different solutions to a problem can be studied and compared.
3. It gives a better understanding into the operations of the system and its components.

There are also a number of limitations of using simulation, these are:

1. Developing a reliable simulation system is quite expensive and time consuming.
2. Simulation can not give optimum solutions for a system; instead it is useful in selecting the best alternatives from several scenarios.
3. The large amount of data requires an informed analysis for accurate conclusions regarding the simulated system and the validity of its model.

Although using simulation in the construction industry has important advantages, it is still not widely used. According to McCahill and Bernold (1993) a few criteria must be fulfilled in order for simulation to be used by construction managers in the field. First, the simulation system must be flexible enough to represent as close as possible actual site conditions and resource availability. Second, the simulation system must be able to provide a rapid but easily generated response to changes in site conditions and resource availability encountered on the jobsite. Third, the simulation system must be easy to use and produce easily understandable results, for field personnel with minimum training in computers, modelling, or simulation.

3.1.2 Building simulation models

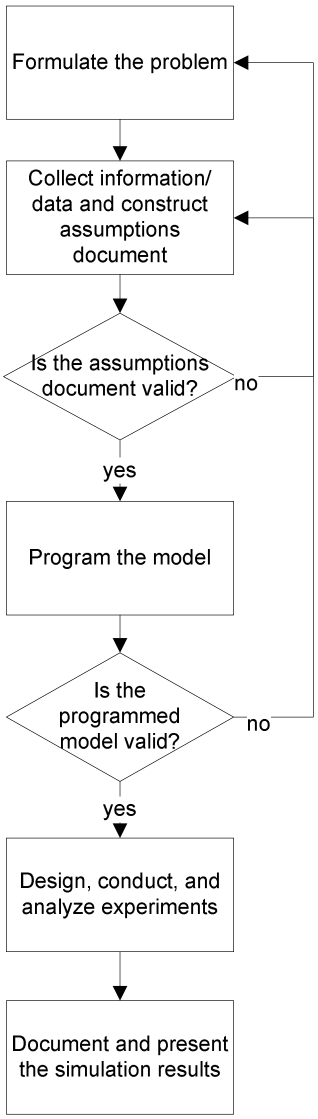

Figure 1. Graphical representaion Seven-step approach (Law, 2006)

Now that the advantages and limitations of applying simulation in the construction industry have been explored, in this paragraph the focus will be on developing simulation models.

Construction projects can be very complex, consisting of a lot of different processes, and different resources utilized, and hence building a valid and credible simulation model can be very difficult (Law, 2006). In order to get some structure in the process of building such complex models, Law (2006) has presented techniques for building valid and credible simulation models. Also a seven-step approach for conducting a successful simulation study is presented. Validation is defined as *"The process of determining whether a simulation model is an accurate representation of the system, for the particular objectives of the study".* Credibility is defined as *"A simulation model and its results have credibility if the decision-maker and other key project personnel accept them as correct"* (Law, 2006).

The seven-steps approach developed by Law includes: 1. Problem formulation, 2. Collect information and construct an assumptions document, 3. Validation of the assumption document, 4. Program the model, 5. Is the programmed model valid, 6. Design, conduct, and analyze experiments, 7. Document and present the simulation results. For a more in depth explanation about this approach see Law (2006). A graphical representation of the seven-step approach is shown in figure 1.

In the literature also the process of building a special purpose simulation model is discussed. Hajjar and AbouRizk (1996) describe the various design stages in the development of a special purpose simulation tool. Special purpose simulation tools are developed for modelling a specific industry. The various design stages that are distinguished by Hajjar and AbouRizk (1996) are: 'preliminary conceptual design', 'interaction points', 'simulation level design', 'data structure design', 'pre-processor design', and 'post processor design'.

3.1.3 Validating construction simulation models

Before actually using a simulation model, it is important to confirm that the simulation model actually represents the real world system accurately, and the simulation results are a valid representation of the performance of the real system.

Oloufa (1993) discussed two different procedures to ensure the accuracy of the simulation model, namely verification and validation. According to Oloufa (1993) validation is *"the process of determining if the conceptual model is an accurate representation of the simulated system".* And verification is defined as: *"a process similar to the debugging of conventional computer programs"*. Beside the importance of validation, Law (2006) also discusses the importance of credibility concerning simulation models. Law (2006) defines credibility as follows: *"A simulation model and its results have credibility if the decision-maker and other key project personnel accept them as correct"*.

A model is accepted and credible if the user is willing to base decisions on the results obtained from it (Shi, 2001). In order for a system to be accepted and perceived as valid and credible, it needs to be debugged, and all mistakes need to be corrected. Shi (2001) distinguishes three types of errors common in simulation, namely type zero errors, type I errors and type II errors. Type zero errors occur when the wrong questions are asked, and the model does totally the wrong thing. Type I errors occur while a valid model is wrongly rejected because there is always a probability that an error may occur. Type II errors occur while a false model is accepted because of the accuracy of the statistics.
There are different methods for ensuring the validity of a simulation method. Shi (2001) presents three methods for validating construction simulation. These methods can be used to ensure that the simulation is correctly conducted. The first method reports a simulation

experiment in chronological order so that the user can examine the operating sequence of the model. The activities should start in the right sequence and at appropriate times. This can be done for example by examining a tracing report, in which all the activities are listed. The second method is examining the simulation output data, such as the operating counts and the mean duration of the activities, so it can be examined whether the activities are correctly executed. It is for example important to be sure that relationships between activities and resources are correctly defined, and the resources are released to the right locations. The third method produces a cyclic report of a selected resource entity, so that it can be examined whether the entity is moving in the correct and chronological order during simulation. In order to examine the operating cycles of resource entities, the life cycle of each entity must be traced in the simulation model. A cyclic report of a certain resource entity lists all the activities that the entity has done in a chronological order during the simulation.

3.1.4 Sensitivity analysis

Managers are continually attempting to evaluate the impact of their decisions on the existing state of the production system and its productive output. They want to know what will happen if the level or setting of one of the controllable management variables is changed. The ability to investigate the system and examine the system parameters and statistics may lead to new insights and indicate the need for a system redesign (Halpin and Riggs, 1992).

In the literature of simulation, sensitivity analysis is defined by Kleijnen (1995) as*: "the systematic investigation of the reaction of the simulation responses to extreme values of the model's input or to drastic changes in the model's structure."* Sensitivity analysis is conducted to get specific information out of the model. In a simulation study usually the 'What if' question is important: what happens if the analysts change parameters, input variables or modules of the simulation model? The simulation inputs and outputs are investigated, and from this input and output behaviour the affects of the factor are estimated (Kleijnen, 1995). Sensitivity analysis is done by selecting an important factor, and changing the value of this factor while the other factors have fixed values. This way it is possible to see which factors have a big impact on the overall performance of the simulation model.

Although sensitivity analysis is widely used in construction projects, it has a few important disadvantages (Wang and Halpin, 2004). In order to get an accurate estimation of the effects a lot of runs need to be done. It is also not possible to estimate the interactions between factors. The conclusions from this type of analysis are not general, and it can miss optimal settings of factors.

3.1.5 Simulation software

Different simulation software tools are available for modelling construction processes. A few of these simulation tools will be highlighted in this paragraph. Subsequently, the focus will be on the EZstrobe simulation software, because this simulation software will be used in this research. EZstrobe is used in this research as simulation tool mainly for two reasons. The software is available for academic purpose and can be easily obtained for free from the website (www.ezstrobe.com). Furthermore, it is an easy to learn system that is ideal as a first simulation tool, capable of modelling moderately complex problems with little effort.

In general, simulation modelling can be distinguished into two main categories, namely 'general purpose simulation systems' and 'special purpose simulation systems'. General purpose simulation tools target a very broad domain and can be used to model a wide range of construction operations. Examples of general purpose simulation systems are CYCLONE, RESQUE, COOPS, CIPROS, STROBOSCOPE, and DISCO. Special purpose simulation models, on the contrary, target a narrow domain such as for example tunnelling construction, and are designed for specific construction tasks. SIMPHONY is an example of a special purpose simulation tool. The use of special purpose simulation tools can satisfy the need for a tool that is accurate but at the same time reduces the level of complexity general purpose simulation programs are known for. General purpose simulation tools are very flexible, but require a high degree of abstraction. In contrast it was found to be more effective to develop a special purpose simulation tool for a specific sector in the industry (AbouRizk and Hajjar, 1998). AbouRizk and Hajjar (1998) define special purpose simulation 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*".

3.1.6 EZstrobe

EZStrobe is a simulation system designed for modelling construction processes. However it is also possible to model other types of systems, because it is domain independent. EZstrobe is based on the principals of Activity Cycle Diagrams and uses the Three-Phase

Activity scanning paradigm. It is designed to satisfy the need for an easy to learn and simple tool capable of modelling complex problems with little effort (Martinez, 2001).

The EZstrobe model represents the various activities that take place in a construction operation, and the various resources utilized. Basically the three main factors the model focuses on are: the activities, the condition under which the activities can happen, and the outcomes of the activities when they end. The models are represented using activity cycle diagrams (ACD). ACD's are networks of circles and squares that represent idle resources, activities and their precedence. Rectangles, circles and lines can be distinguished in the models; rectangles representing activities, circles representing idle recourses, and lines representing the flow of recourses. In EZstrobe models, all activity start-up conditions and outcomes are in terms of resource amounts (Martinez, 2001).

EZstrobe consists of the following basic modelling elements (Martinez, 2001):

- Queue: a named element that holds idle resources.
- Conditional Activity (Combi): a named element that represents tasks that can start whenever the resources that are available in the Queues are sufficient to support the task. A Combi consists of the name of the activity, a number representing the priority, and a formula representing the duration of the activity. This duration formula is written as a probability distribution.
- Bound Activity: a named element that represents tasks that start whenever an instance of any preceding activity ends. To determine the duration of the activity, a duration formula (probability distribution) is shown.
- Fork: a probabilistic routing element. When a preceding activity finishes, the Fork chooses one of it successors. The likelihood that a successor is chosen depends on the chance 'P'.
- Draw Link: connects a queue to a Conditional Activity. A Draw Link describes the conditions for the successor to start, in terms of the content of the Queue connected to it. It also describes the amount of resources from the Queues it uses every time the activity starts.
- Release Link: connects Activity to any other node except for a Conditional Activity. The Release link describes the amount of resource that will be released after each instance of the predecessor Activity ends.
- Branch Link: connects a fork to any other node except a Conditional Activity. A Branch Link also indicates the chance 'P' that the successor connected to it will be selected, each time it needs to choose a successor.

A graphical representation of the basic elements of EZstrobe is shown in figure 2.

Simulation is done to obtain statistical data regarding the performance of the real-world system that is under investigation (Martinez, 2001). Different types of data are of interest and are provided by EZstrobe concerning the queues and activities. For example regarding the resources EZstrobe records the amount of resources to have ever entered, the average waiting time, the minimum content, and the maximum content. Data is also provided about each activity. It shows for example the number of times the activity is being performed, the total number of times it has started, the average duration, the standard deviation of the duration, and the minimum or maximum duration of the activity. Also data is given about the process in general, for example the average time between successive starts, the standard deviation of the time between successive starts, and the minimum or maximum time between successive starts.

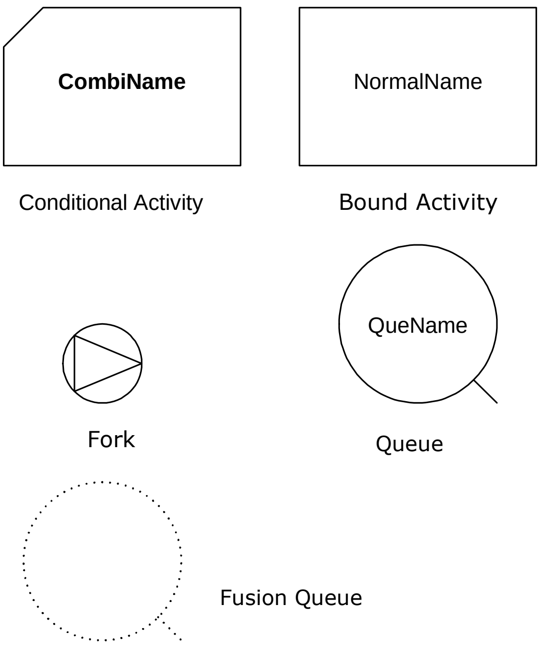

Figure 2. Basic elements EZstrobe

EZstrobe has features that can be very useful modelling large construction operations. It is for instance possible to build multi-page models, parameterize input, customize output, and run animations of models for model verification (Martinez, 2001). Multi-page modelling is especially useful regarding simulation of large operations. This feature makes it possible to break up the simulation model into different parts, and analyze them separately. Dividing the simulation model into different parts also reduces the complexity of the simulation model, because it makes the model more orderly and therefore easier to understand. The simulation model consists of different activities and resources. The performance of a system depends on the values of the important variables. In order to facilitate experimentation and minimize mistakes because of inconsistent changes, the model’s parameters can be located and controlled in a single place in EZstrobe. After developing the simulation model it is important to be sure it provides a correct representation of the system. By running the model some errors may be detected, others may go undetected. With EZstrobe it is possible to debug the model by means of model animation. The animator illustrates the dynamic state of the simulation and the events that take place during simulation. This feature makes it possible to learn how EZstrobe modelling actually works by doing experiments and see how the system reacts.

3.2 Simulation of tunnelling construction

The previous paragraph dealt with the process of building a simulation model. Different aspects regarding this subject were described, such as the design stages of building a simulation model, validating the model, conducting sensitivity analyses, and the simulation software used especially for modelling construction operations. In this paragraph the focus will be on simulation of tunnelling construction. Different aspects of the tunnelling construction process are already described and analyzed by other authors using simulation. In this paragraph a literature review will be provided about the work that is already been done regarding the use of simulation for analysis of tunnelling construction operations. However, this chapter will start with a general description about the purpose of simulation for construction processes.

3.2.1 Purpose of simulation of construction processes

It is generally accepted that tunnelling projects are perceived to be high-risk construction projects. Accurate project planning is critical on these kinds of projects in order to save time and cost, resulting in a productive construction project (Ruwanpura et al., 2001). Likhitruangsilp and Ioannou (2004) describe the risks involved in tunnelling construction. One of the most important decisions in tunnelling is to determine the optimal sequence of tunnelling methods and support systems along the tunnel profile. The primary factors (risks) that have influence concerning these decisions are: geologic uncertainty, geologic variability, uncertainty in tunnelling productivity, and risk sensitivity. Tunnelling methods are selected primarily on the expected geological conditions of the tunnel. The state of important rock mass properties must be known. Even after conducting research on it, the geological condition can not be perfectly known until the construction starts (geologic uncertainty). In addition most tunnels have to do with different geological conditions. It is very difficult to determine in advance the locations and the extents with certainty (geologic variability). The selected tunnelling methods must be adaptable to all anticipated geological conditions. Also uncertainty regarding tunnelling productivity is an important factor that has influence on tunnelling decisions. Uncertain variables in this regard are the construction equipment performance, the workers output, and unexpected events. A contractor's risk aversion and its degree of risk exposure can also have a major influence on construction decisions. Therefore also risk sensitivity is an important factor regarding tunnelling decisions. Using simulation in tunnelling construction operations, these risks can be analyzed and controlled effectively. Consequently all the activities involved in the tunnelling construction process can be planned efficiently (Likhitruangsilp and Ioannou, 2004).

The tunnelling construction process involves a lot of different activities; the majority of these activities are repetitive. In the literature these activities are divided in roughly three main processes, namely excavation, dirt removal and tunnel support. It is found that all the activities involved are related to each other, and in order to optimize the productivity the entire process needs to be analyzed. Improvements of the excavation process can be useless if it is not synchronized with for example improvements of the dirt removal process (Ruwanpura et al., 2000). The overall goal of optimization is defined as: *"The system is optimized when wait times are zero and the resources are 100% utilized. It is therefore important to evaluate improvement to an activity that impacts the waiting times and the utilization of resources leading to a minimum unit cost"* (Ruwanpura et al., 2000).

The reason that tunnelling construction operations are especially suitable to analyze using simulation, is that there are many repetitive construction cycles involved in the process. Two repetitive cycles are distinguished and described regarding the construction process, namely the tunnel face cycle, and material handling cycle at the shaft (AbouRizk et al., 1999).

Besides the use of simulation in tunnelling construction in order to enhance the productivity of the construction operations, one of the principal reasons for using simulation to model construction processes is to compare and analyze alternative construction methods (Ioannou and Martinez, 1995). In order to make a valid and reliable comparison a common mode of operation is to construct a simulation model for each method, conduct a limited number of simulation experiments, and compare the alternatives based on the resulting average measure of their performance (Ioannou and Martinez, 1995).

Ruwanpura et al. (2000) described a number of important reasons for using simulation for tunnelling construction operations, these are:

- Project planning: Using computer simulation facilitates the planning of the sequence of work activities, declare the method of operation, select suitable resources, and analyze the productivity.
- Identifying bottlenecks: problems in the construction process could be detected using simulation.

- Examining productivity improvements and optimizing resource utilization: Simulation enabled the planners or engineers to observe the productivity, tunnel advance rate and resource utilization of the project.
- Offering a comparison of alternative tunnelling scenarios: Simulation enables planners to predict the actual results, and also to compare the results using different scenarios.

3.2.2 Use of simulation in tunnelling construction

Simulation in tunnelling construction has been used for various objectives, and had different contributions. In this paragraph a literature review is provided regarding the use of simulation in tunnelling construction projects. A categorization is made on the basis of the different objectives of the simulation studies.

Application of special purpose simulation modelling for tunnel construction

Ruwanpura et al. (2001), AbouRizk et al. (1999) and Er et al. (1999) describe the design, developments and application of special purpose simulation tool for tunnelling construction operations. The modelling and analysis of the tunnelling process for shielded-boring machines is explained in depth, using the special purpose tunnel template developed with Simphony. The developed tunnel template is able to do the following:

- Predicting the tunnel advance rate;
- Balancing the construction cycles at the tunnel face and the shaft, and optimize the use of TBM, crane and trains;
- Predicting of the productivity, cost, schedule, and resource utilization based on simulation analysis.

The tunnel template also has unique features that can be used to analyze the tunnelling construction process, these are:

- Cost planning engine
- Custom-built reports and statistics
- Simulation of hypothetical work conditions

The special purpose simulation model consists of different modelling elements. These elements are: ‘main tunnel parent’, ‘muck car’, ‘shaft- undercut’, ‘shaft-ground’, ‘undercut track’, ‘intersection’, ‘waiting track’, ‘breakout track’, ‘tunnel segment’ and ‘TBM’. These elements have different input parameters for simulation. In table 1 the modelling elements of the model and the important matching input variables are described.

Modelling element	Input variable
main tunnel parent	Tunnel length, TBM type, shift length, mobilization time at start day, break for lunch, implement of intermediate undercut, buffer time at the end of the day.
muck car	Number of trains, number of muck cars (dirt), number of muck cars (material), muck car capacity, speed of trains (to tunnel and from tunnel).
shaft- undercut	Unloading time of dirt car from undercut to shaft, loading time of liners from shaft to undercut, depth of the shaft (m).
shaft-ground	Lifting method from dirt
undercut track	-
Intersection	-
waiting track	-
breakout track	-
tunnel segment	Length (m), soil type.
TBM	TMB diameter, TBM reset time, liner installation method, unloading time of liners, liner installation time.

Table 1. Modelling elements and input variables (Ruwanpura et al., 2001)

In order to identify the critical input parameters of the tunnel template, it has been tested using different data input. The following parameters have been found to be critical:

- Type of soil (and penetration rate of boring)
- Liner installation time
- Swell factor of soil
- The capacity and number of muck cars
- Train speed.

However, the dirt removal times at the shaft have been found to be non critical in one-way tunnelling when two trains are in operation. According to the results the most critical parameter is the capacity of the muck cars. It was found that if the capacity of the muck cars is less than the volume to be hauled for one stroke length of the TBM, the productivity of the entire tunnelling project is reduced.

Simulation, using the special purpose simulation template, is useful in evaluating various tunnelling options, and allows testing the validity of the various construction planning strategies. It is also useful in predicting the productivity of tunnelling and evaluating the cost and duration of various construction scenarios.

Evaluating construction alternatives

Fernando et al. (2003) describes examples of using special purpose simulation templates to help make decisions in a number of tunnelling projects carried out by the City of Edmonton. Three different tunnelling construction projects were described and analyzed using simulation. In one of those projects, the construction of a tunnel (SESS tunnel), different construction methods are analyzed and evaluated using simulation. For every alternative a simulation model is developed. The different alternative methods are compared subsequently based on an estimation of the duration of each alternative, the production rate per shift, the utilization of the TBM and the hoisting system. Based on the results obtained the total cost per construction alternative could be estimated, and a decision made. In the second project, the construction of the Calgary Trail Interchange tunnel (CTIT), simulation is used to evaluate the productivity and evaluate specifically the effect of changing the number of trains used in the construction project. The third project described by Fernando et al. (2004) concerned the construction of the North Edmonton Sanitary Trunk (NEST) tunnel, simulation was used to estimate productivity and analyze different construction alternatives that could affect project cost and duration. Different simulation templates were developed to plan the project and meet the schedule.

Al-Battaineh et al. (2006) describes the use of simulation for the planning of a tunnelling project, called the Glencoe Storm Sewer Upgrade Project in Calgary. This particular tunnel is build to reduce the surface flooding by providing temporary storage of storm water runoff during major storm events. Using simulation the productivity of the tunnelling project and the completion date are modelled. In the planning phase of the project four different construction configurations for the working shafts were identified. In order to analyze every construction configuration, and minimize the uncertainty in de decision making process, a simulation model has been developed for each of the configurations, using Simphony. Subsequently six construction scenarios were developed, and modelled in Simphony. The parameters that were evaluated for each scenario were: production rate (m/shift), project duration, and completion date. Based on the analysis (using simulation) two scenarios were identified to investigate more in depth. Simulation models have been created for the two scenarios (one way and two way tunnelling) to decide on the most suitable construction scenario.

Likhitruangsilp and Ioannou (2004) present a stochastic methodology for evaluating tunnelling performance by using discrete-event simulation. Several tunnelling alternatives were identified, by applying different tunnel excavation and support methods with different geological conditions. Every construction alternative has its own logic of tunnelling operations. In order to evaluate the construction performance each alternative needs to be analyzed separately. Using the STROBOSCOPE simulation system data about the probability distribution of tunnel advance rate and tunnelling unit cost were obtained for all defined construction alternatives. The objective of the simulation models was to estimate the distribution of the advance rate for each possible combination of construction methods and geologic conditions. With this information the optimal excavation and support policies for the tunnelling construction project could be determined.

The relevance of the work described in this section to my research is gaining understanding regarding the use of simulation for evaluating different construction alternatives. It is shown that simulation is an effective tool to model and analyze different alternatives. The work gives an idea about how simulation modelling can be used in the analysis of construction processes, and what the benefits are of using simulation.

Productivity of tunnelling construction

Ruwanpura et al. (2000) describes the experiences of implementing a special purpose tunnelling simulation template based on tunnelling operations performed at the City of Edmonton for shielded tunnel boring machines. A special purpose simulation template named Simphony tunnel template was developed, with the purpose to predict the productivity of tunnelling and evaluate the cost and duration of various options. The tunnel template was developed for a number of reasons, namely:

- To predict the tunnel advance rate, which depends on various factors such as: length of the tunnel, muck car capacity, train speed, dirt volume and removal method and soil conditions
- Balancing the construction cycles at tunnel face and shaft and it optimizes the use of TBM, crane and trains;
- Predict the cost, schedule, cash flows and resource utilization based on the simulation analysis.

In order to identify the critical input parameters the template has been tested. The tests shown that the following parameters are critical in predicting the productivity of tunnelling:

- Type of soil;
- Penetration rate of boring;
- Liner installation time;
- Swell factor of soil;
- The capacity and number of muck cars;
- Train speed.

The dirt removal times at the shaft however has been found to been non critical. The capacity of the muck cars in contrast has been found to be the most critical factor. It was concluded that the developed simulation templates allowed the engineers of the project to test the validity of their planning construction operations. The output of the model (tunnel advance rate, resource utilization, and wait times) helped the engineers to evaluate alternative options.

Obeidat et al. (2006) analyzed the productivity of tunnel construction using the road-header excavation method. In order to analyze the productivity and determine the proper probability distribution for its various activities, a simulation model is presented using MicroCYCLONE and EZStrobe. Road-header excavation method is getting more and more popular, because it is capable to excavate precisely in soft to medium strength rock without weakening the surrounding rock. The tunnel construction using road-header involves three main processes, namely excavation, dirt handling, and tunnel support. The activities that are distinguished and described more in depth are: the excavation process, removal of dirt for the tunnel face, scaling and the installation of mechanical bolts, and installation of initial support. The validation of the developed models, one using MicroCYCLONE and the other using EZStrobe, showed that both models were robust in representing the real world application. Subsequently a sensitivity analysis was conducted to check the sensitivity of the developed model to any changes in the inputs or outputs. Finally the advance rate is predicted based on the developed simulation model. Obeidat et al. (2006) concludes that the prediction of productivity and bit consumption is of importance for proper time and resource scheduling, and hence estimating the budget of tunnelling projects. The prediction of road-header performance, including instantaneous cutting rate, bit consumption rate and machine utilization rate, is stated to be very important to profitability of tunnel projects, and has to be done before the actual construction project starts.

AbouRizk et al. (1997) discusses the use of computer simulation (SLAM II) in the analysis of productivity of a tunnel operation. In this study the main objective was to estimate the productivity (meters per shift) of tunnelling construction operations given that it was necessary to work in different conditions as initially was agreed upon regarding the project, as a result of an excessive amount of water infiltration. Two specific goals were described for the simulation study:

- Estimation of the productivity that could be achieved given the changed conditions;

- Provide a comparison of the estimated productivity under the changed conditions with the productivity that could be achieved if the changed conditions wouldn't have been encountered.

The main differences between the two situations involved:

- Use of smaller capacity muck cars
- Additional handling of materials
- The use of a truck at ground level for disposal of muck brought up through the shaft from the tunnel below.

In this work (AbouRizk et al., 1997), using simulation software SLAM II these factors were simulated and analyzed, and it was concluded that computer based simulation can be used for comparing the productivities of construction operations achieved under different site conditions.

The relevance of the work described in this section to my research is gaining understanding regarding the use of simulation for determining the productivity of tunnelling. Various reasons and goals of the simulation studies were described, and various tunnelling variables were identified to be critical in predicting the productivity of tunnelling.

Analysis of tunnel advance rate

Touran and Asai (1987) predicted the tunnel advance rate regarding the construction of a tunnel. Different simulation models are developed to analyze the affect of various variables on the tunnel advance rate. The reason that this is so important is because the project duration, equipment capacity, power requirements, and total costs are all directly related to the tunnel advance rate. It was stated that simulating the process of tunnel advancement can help plan and control the project more efficiently.

Touran and Asai (1987) stated that the main problem in long tunnels with small diameter is the logistics. Logistics include several activities, namely the transfer of excavated material from the tunnel face to the shaft area, vertical material handling at the shaft, the transfer of tunnel support system to the tunnel face, installing the support system, switching trains, moving forward and backward in the tunnel. What reduces the tunnel advance rate is the complex interaction between all these activities, and not the power and capacity of the TBM (Touran and Asai, 1987). Several variables affecting the tunnel advance rate were identified in this work (Touran and Asai, 1987). In order to investigate the impact of each important factor on the tunnel advance rate, simulation models for the tunnel were developed. The following input data for the simulation models were analyzed:

- TBM penetration rate: the length of the tunnel that the machine can excavate in one hour assuming no waiting or down-time.
- Muck train and material handling data: it is economical to use as large muck car as possible because it reduces the time required for dumping the material and hence reduces the overall length of the train.
- Tunnel lining: erection time of the lining segments

The relative importance of the variables affecting the tunnel advance rate was also studied using sensitivity analysis. The following variables were identified as being critical factors affecting the tunnel advance rate:

- Number of muck trains;
- Train travel time;
- TBM penetration rate;
- Type of rock;
- Rock stand-up time.

Several sensitivity analysis studies were performed on these critical factors to investigate the affect on the tunnel advance rate. Using the CYCLONE simulation models it was shown that the tunnel advance rate was a function of the complex interaction between TBM, muck handling system, tunnel-lining operation, rock competence, and tunnel diameter. The impact of these factors on the tunnel advance rate was also quantified.

The relevance of the work described in this section to my research is that various tunnelling variables were identified to be critical regarding the tunnel advance rate of tunnelling construction projects. These tunnelling variables should be modelled accurately in the simulation study of this research.

Project completion time

Ahuja and Nandakumar (1985) developed a simulation model to forecast the project completion time. Using a computer model the dynamic variables affecting activity duration were analyzed. It was stated that the reliability of project forecast can be enhanced by conducting an analysis to determine the variation in activity durations caused by dynamic variables. In order to obtain more reliable forecasts of project duration a simulation model can be developed that is able to simulate the expected occurrence of the uncertainty variable, analyze and quantify their impact and use this information to estimate the activity duration (Ahuja and Nandakumar, 1985).

The reliability of activity duration estimates, project completion forecasts, and effectiveness of corrective measures, all depend on the incorporation of the impact of uncertainty variables (Ahuja and Nandakumar, 1985). Through literature survey and field experience the significant variables affecting activity duration were identified. The significant uncertainty variables are:

- Learning curve: productivity increases with experience and practice;
- Weather conditions;
- Crew absenteeism;
- Space congestion;
- Regulatory requirements;
- Design changes and rework;
- Economic activity level;
- Labour unrest;
- Specific uncertainty variables.

To determine the impact of these variables on the activity durations, and simulate the project environment, historical data was used. A computer model, called PRODUF, was developed to simulate the impact of the uncertain variables and incorporate their combined impact in activity duration estimates so that more reliable project completion forecasts can be obtained (Ahuja and Nandakumar, 1985).

The relevance of this work to my research is gaining understanding regarding the uncertainty variables affecting project completion time of tunnelling projects. Not only tunnelling variables such as identified in previous described research work are relevant, also these uncertainty variables are important regarding the productivity of tunnelling. In the deterministic model these uncertainty variables will be represented by efficiency factors.

3.3 Summary

This chapter discussed the process of building a simulation model, as well as existing simulation modelling work in the area of tunnelling construction. Different aspects of building a simulation model were described, such as the design stages of building a simulation model, validating the model, conducting sensitivity analyses, and simulation software tools used especially for modelling construction operations. Particular attention was given to EZstrobe simulation software, since it is used in this research. Subsequently, a literature review was performed regarding existing simulation models of tunnelling construction. Simulation in tunnelling construction has been used for various objectives, and had many contributions. In this chapter a literature review was provided regarding the use of simulation for analysis of tunnelling construction projects.

4. Deterministic model for productivity of tunnelling

In this chapter a deterministic model of tunnelling construction using different excavation methods and materials handling systems is described. Essentially three different forms of the model are developed based on three case studies: Laval metro tunnel (in Montreal, Quebec, Canada), Bathurst & Langstaff sewer tunnel (in Vaughan, Ontario, Canada) and Parramatta rail link tunnel (Sydney, Australia). The chapter starts with a brief description of the tunnelling construction processes of the tunnelling case studies that are modelled deterministically. A distinction is made between the excavation and primary support of the tunnelling process, and the horizontal and vertical materials handling systems. Subsequently, the deterministic model is described. Covering, the input variables of the deterministic and simulation model, the factors affecting productivity of tunnelling construction, the efficiency factors and the cycle time and productivity equations. The chapter ends with a description of the assumptions regarding the deterministic model.

4.1 Tunnelling construction processes

4.1.1 Excavation and primary support

In the deterministic model the main focus will be on tunnelling construction using different excavation methods and materials handling systems. The case studies cover the different excavation methods used in tunnelling construction nowadays, such as drill & blast, road header and TBM excavation. In the Laval metro tunnel project both drill and blast and road header was used to excavate the tunnel. In the Bathurst & Langstaff sewer tunnel project and Parramatta rail link tunnel project, TBM was used to excavate the tunnel. Primary support systems used in these case studies, vary from the installation of rock bolts and wire mesh (Laval metro tunnel, Parramatta rail link tunnel), to the installation of pre-cast lining segments by TBM (Bathurst & Langstaff tunnel).

4.1.2 Horizontal and vertical materials handling systems

Rail-mounted system

The rail-mounted materials handling system was used in the Bathurst & Langstaff sewer tunnel project. Two distinctive processes can be distinguished, namely:

- Removal of muck from the face of the tunnel;
- Transporting lining materials (and rail tracks) to the face of the tunnel;

The removal of the muck consists of five major processes: manoeuvring trains at face of the tunnel, loading muck into cars, transferring muck from face of the tunnel to shaft, unloading muck from cars at the shaft of the tunnel, and returning empty muck car to the face of the tunnel. The transportation of the lining materials and rail tracks from the shaft to the face of the tunnel consists essentially of the following processes: loading lining materials and rail tracks in cars at the shaft of the tunnel, transporting liner materials to the face of the tunnel, unloading the liner material and returning of empty car to the shaft.

Rubber-mounted system

The rubber-mounted materials handling system was used in the Laval metro tunnel project. The processes involved using rubber-mounted systems are similar as the processes involved in using the rail-mounted system. The main difference is that it is not necessary to extend rail tracks as excavation proceeds, hence the process of transporting rail tracks from shaft to face of the tunnel is not involved using this materials handling system. A practical difference between the two systems is that trucks are able to move easier and with greater flexibility through the tunnel, whilst in the case of rail-mounted systems the movement of trains are governed by track layout inside of the tunnel. Also it is not possible to use two trains simultaneously on the same track, so switch systems (e.g. Californian-switch) inside of the tunnel (often at the shaft and somewhere in between the face and shaft of the tunnel) have to be installed for the trains to be able to pass each other. In addition, trucks (depending on available space inside of the tunnel) have fewer restrictions regarding movement inside of the tunnel.

Belt-conveyor

The materials handling system using a belt-conveyor is often used in combination with one of the other materials handling systems. The belt-conveyor is essentially used to transport muck from the face of the tunnel to the shaft. As the tunnel is excavated by TBM, muck is directly loaded on the belt-conveyor and transported outside of the tunnel. The transportation of materials (lining material and rail tracks) or personnel throughout the tunnel is usually done by trains or trucks. The processes involved with this system are: excavation by TBM, loading and transporting muck on belt-conveyor to ground level where it is dumped at some place outside of the tunnel. The belt-conveyor in combination with rubber-mounted system was used as materials handling system in the Parramatta rail link tunnel project.

Vertical materials handling system

The vertical materials handling involves essentially the following processes: loading muck on hoisting system at the shaft of the tunnel, hoisting muck from shaft to ground level, unload muck at ground level, loading materials on system, transferring materials from ground level to shaft, and unload material at ground level. In the case studies of Bathurst & Langstaff sewer tunnel and Parramatta rail tunnel, cranes were used at the shaft of the tunnel as the vertical materials handling system. The Laval metro tunnel did not have a vertical shaft. Trucks were able to transport materials directly from face of excavated tunnel to soil disposal area outside of the tunnel.

4.2 Deterministic model

Deterministic models are mathematical models in which the outcomes are determined through known relationships among states and events, without room for random variation. In comparison, stochastic models (e.g. simulation models) use ranges of values for variables in the form of probability distributions. In this research the deterministic models are developed in order to gain better understanding of the tunnelling construction processes, and to identify the tunnelling construction variables that are import for the simulation study. Regression analysis will be applied to show the relation between length of the tunnel and cycle time and tunnel advance rate of the construction process. By comparing the outputs of the deterministic model with the outputs of the actual case studies, and by performing a sensitivity analysis on the tunnelling variables effecting productivity, conclusions can be drawn regarding the validity and credibility of the model.

Dubey et al. (2006) has developed a deterministic model to calculate the productivity in linear ft/hr of Horizontal directional drilling process (HDD). In this research the bore length is divided into equal small lengths (l) to facilitate the calculation of the cycle time. In the excavation process the cycle time for each equal segment will be different. By decreasing the length of these segments, and assume them very small in comparison of the total bore length, it is assumed that the cycle time does not change with the length.

In the calculation of the cycle time of the materials handling processes in tunnelling construction projects, the excavation length can also be divided into small lengths (l) compared with the total length of the tunnel (L) to facilitate the calculation of the cycle time and subsequently the productivity. In figure 2 a schematic representation of the tunnel profile is provided. However, unlike HDD technology, the cycle time of materials handling system used in the construction process will change as excavation proceeds. The cycle time of the materials handling process increases, because the distance between the face and shaft of the tunnel increases as excavation proceeds. This leads to longer transfer times regarding the transportation of muck and material (for primary support) throughout the tunnel.

4.2.1 Input variables of deterministic model

From the literature study and interviews with experts, the main processes and variables used in tunnelling construction projects are identified. An overview of all input variables (resources and activities) used to develop the cycle time and productivity equations, and simulate the tunnelling construction process, is provided in appendix I. These input variables are categorized in 'general tunnelling variables', 'rail-mounted system', 'rubber-mounted systems', 'belt-conveyor' and 'vertical materials handling'.

In the category 'general tunnelling variables' mainly the resources and activities involved in the excavation and primary support process are described. The categories 'rail-mounted systems', 'rubber-mounted systems', 'belt-conveyor' and 'vertical materials handling' describe the main variables of the different materials handling systems used in the construction of tunnels. With these input variables the tunnelling construction processes using different excavation methods and materials handling systems can be simulated, and cycle time and productivity equations developed. These cycle time equations will be used subsequently to calculate the productivity (tunnel advance rate) with the deterministic model. In order to compare productivity and cost of tunnelling construction also cost variables are included in the simulation models. The cost variables that are relevant are: equipment cost ($/hr) and labour cost ($/hr).

4.2.2 Tunnelling productivity factors

In the calculation of the tunnel advance rate, the important influence factors of tunnelling construction are included. The following factors, determined from literature review, are assessed based on the opinions of experts in the field of tunnelling construction (table 1):

Productivity factor	Explanation	Weights
Operator's experience	Learning curve: years of experience, technical know-how of personnel	0,17
Soil / geologic condition	Type, plasticity and moisture content	0,23
Job and management condition	E.g. good communication lines, organized	0,16

	back-up system, availability of resources, skilled labour, etc.	
Site condition	Accessibility of site (urban or remote area)	0,14
Tunnel alignment	Shape of tunnel	0,11
Machine condition	Amount of meters excavated	0,13
Shift type	Day vs. nightshift	0,06

Table 1. Tunnelling construction productivity factors

From data collected from nine interviews with tunnelling construction experts the importance of each factor compared to each other was determined as seen in table 1. In order to assign relative weights to each productivity factor, a paired comparison analysis is performed. Paired comparison analysis is considered to be a good way of weighing up the relative importance of different factors. It is useful where priorities are not clear, or are competing in importance, and there is no objective data to base it on. It is determined qualitatively which factor is most important compared to each other, and based on this information a quantitative weight is assigned to each factor.

Based on paired comparison analysis it is determined which factors are equal or of greater importance to each other. A score is attributed based on equal importance (score 1) to extreme importance (score 5), of one factor over another. This results in relative weights per productivity factor as described in table 1. It is shown that the most important influence factor effecting productivity of tunnelling construction is 'soil/geologic condition'. On the other hand, the factor 'shift type' is considered to be less important in comparison with the other productivity factors.

4.2.3 Efficiency factors

Beside the productivity influence factors, also efficiency factors are included in the productivity equation to calculate the advance rate of tunnelling. The efficiency factors indicate the amount of time loss of activities, involved in the construction process, due to unforeseen circumstances. For example an efficiency of 50% indicates that the time duration to perform certain activities was twice as expected. These efficiency factors are included to replace certain input variables, such as 'downtime system', 'machine delays', 'maintenance time' and 'repair time'. A generalization is made regarding these variables, because it is not practical to use such detailed variables based on subjective data, obtained by interviewing experts. Efficiency factors are applied concerning the excavation processes (U_1), the primary support processes (U_2), the materials handling processes (U_3) and the minor processes (U_4).

4.3 Cycle Time and Productivity equations

The deterministic model is developed to calculate the productivity in linear m/hr, for drill & blast and road header excavation using a rubber-mounted materials handling system, as well as TBM tunnelling, using rail-mounted and belt-conveyor materials handling systems.

The bore length of the tunnel is divided in into equal small length (l) to facilitate cycle time calculation (see figure 1). The cycle time of each segment will be different. The cycle time of the materials handling process will increase with each subsequent section j of the tunnel that is excavated, because of the increasing distance between the face and shaft of the tunnel as excavation proceeds. This results in longer transportation times regarding the materials handling processes throughout the tunnel.

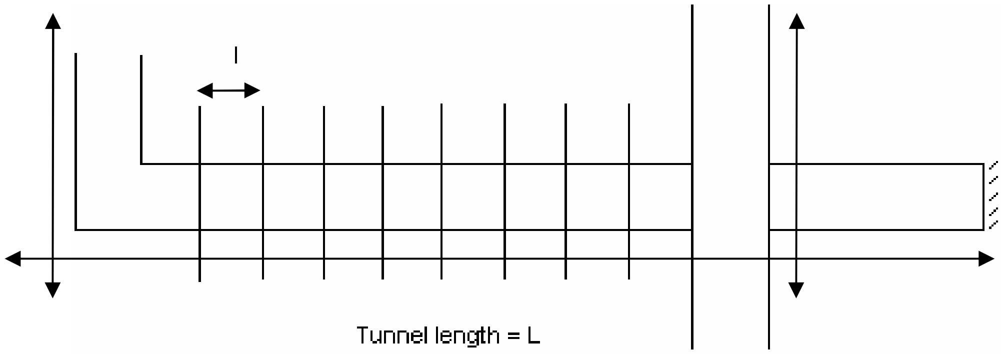

Figure 1. Schematic drawing showing the tunnel profile

4.3.1 Cycle Time Calculation

The total cycle time of the construction process is divided into distinctive cycle times: cycle time of excavation processes, cycle time of primary support processes, cycle time of horizontal materials handling processes, cycle time of vertical materials handling processes, and cycle time of minor processes.

1. Cycle time of excavation processes

Drill and blast excavation

Excavation using the drill and blast method consists of three main activities;

- Drilling holes in the face of the tunnel in which the explosives will be placed (T_{dr}).
- Loading the explosives in the holes (T_{le}).
- Blasting and ventilation (T_{bv}). After the explosives are detonated, the tunnel is ventilated in order to get rid of the dust and gases produced by the explosion.

So $\mathbf{CT_{exc}}$: cycle time of excavation processes (in min)

$$\mathbf{CT_{exc}} = T_{dr} + T_{le} + T_{bv} \qquad (1)$$

After these activities are executed; the face of the tunnel is blasted and ventilation has cleared the air, a certain volume of soil is ready to be transported outside the tunnel to the soil disposal area.

Road header and TBM excavation

Excavation using the road header or TBM method consists of excavating the tunnel and contemporary loading soil in the trucks via a belt-conveyor system integrated in the excavators. Excavation of the face of the tunnel is not a continuous process. It only takes place when there is a truck or train ready at the face of the tunnel to get filled with the muck produced by the road header or TBM.

In order to calculate the time duration of the activity 'excavation and loading soil' (modelled using variable T_{lm}), the productivity of the road header (m^3/hr) is determined (P_{exc}). This is calculated by multiplying the penetration rate of the road header or TBM (modelled using variable A in m/hr) by the surface area of the face of the tunnel (S), and the swell factor of the soil (W). It is assumed that the penetration rate (A) is inversely proportional to the cross section area of the tunnel (S). The relationship between both variables is constant. If the surface area of the face of the tunnel increases with a certain rate, it is assumed that the penetration rate decreases with the same rate.

So $\mathbf{P_{exc}}$: productivity of the road header (in m^3/hr)

$$\mathbf{P_{exc}}\,(m^3/hr) = A \times S \times W$$

Where,

A is the penetration rate of road header or TBM (in m/hr)

S is the surface area face of the tunnel (m^2)

W is the swell factor of the soil

Road header and rubber-mounted materials handling system

The loading time duration of the trucks (T_{lm} in min) is calculated by dividing the capacity of the trucks (V_{truck} in m^3) with the productivity of the road header (P_{exc} in m^3/hr).

So $\mathbf{T_{lm}}$: time duration of excavation and loading trucks/trains by road header (in min)

$$T_{lm} = \left(\frac{V_{truck} x 60}{P_{exc}} \right)$$

Where,

P_{exc} is the productivity of the road header or TBM (in m^3 /hr)

V_{truck} is the capacity of the truck (in m^3)

The cycle time of excavation and loading of trucks is calculated by summing the loading time duration of the trucks (T_{lm}) over the total number of runs (*n*) necessary to dispose the soil generated by excavating tunnel section j of length L_j.

So **CT_{exc}**: cycle time of excavation and loading truck by road header (in min)

$$\mathbf{CT_{exc}} = \sum_{i=1}^{n} T_{lm} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where,

n is number of runs to transport the excavated soil

TBM and rail-mounted materials handling system

The loading time duration of the trains (T_{lm} in min) is calculated by dividing the excavated volume of soil per cycle (V_{muck} in m^3) with the productivity of the TBM (P_{exc} in m^3/hr). The excavated volume of soil is determined by multiplying the excavated length of section j (L_j) (same as stroke length TBM) with the swell factor of soil (S) and cross section area of the tunnel (W).

$$V_{muck}\,(m^3) = L_j \times S \times W$$

Where,

L_j is length tunnel of section j (in m)

So **T_{lm}**: time duration of excavation and loading trucks/trains by TBM (in min)

$$T_{lm} = \left(\frac{V_{muck} x60}{P_{exc}} \right)$$

Where,

V_{muck} is the volume of soil excavated per excavation cycle (in m^3)

The cycle time of excavation and loading of trucks is calculated by summing the loading time duration of the train (T_{lm}) over the total number of runs (*n*) necessary to dispose the soil generated by excavating tunnel section j of length L_j.

So **CT_{exc}**: cycle time of excavation and loading truck by road header (in min)

$$\mathbf{CT_{exc}} = \sum_{i=1}^{n} T_{lm} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

TBM and belt-conveyor materials handling system

The cycle time of the excavation process per cycle is calculated using equation 4. The volume of muck excavated each excavation cycle (V_{muck}), is divided by the productivity of the TBM (P_{exc}). The total volume of soil excavated per stroke length of the TBM is determined by multiplying the excavated length (L_j) with the swell factor of the soil (W) and cross section area of the tunnel (S).

$$V_{muck}\,(m^3) = L_j \times S \times W$$

So $\mathbf{CT_{exc}}$ is: cycle time of excavation process (in min)

$$CT_{exc} = \left(\frac{V_{muck} x 60}{P_{exc}} \right) \text{..............................} \quad (4)$$

2. Cycle time of primary support processes

Primary support may consist of installing rock bolts and wire mesh along the excavated surface of the tunnel, depending on the ground conditions on site, as well as installing single pass liners of pre-cast concrete segments by TBM. The cycle time duration of the primary support processes are calculated using equation 5, by dividing the excavated tunnel length (modelled by L_j) by the primary support advance rate (B).

So $\mathbf{CT_{ps}}$: cycle time of primary support (in min)

$$CT_{ps} = \left(\frac{L_j x 60}{B} \right) \text{..............................} \quad (5)$$

Where,

B is the advance rate of the primary support processes (m/hr)

L_j is length tunnel of section j (m)

3. Cycle time of horizontal materials handling processes

The cycle time (CT_{truck}) consists of two components, namely time to dispose the muck from the face of the tunnel (P_m), and time to transport lining material to the face of the tunnel (P_l). In this paragraph a distinction is made regarding the excavation methods and accompanying materials handling systems. The total cycle time of the horizontal materials handling system is calculated using equation 12.

Drill & blast, road header and rubber-mounted materials handling system

The disposal of the muck consists of five major processes: manoeuvring trucks at face of the tunnel (T_{mt}), loading muck into trucks (T_{lm}), transporting muck from face of the tunnel to soil disposal area (T_s), unloading muck from trucks (T_{um}), and returning empty truck towards the face of the tunnel (T_{sb}). The transportation of the lining materials from the shaft to the face of the tunnel consists essentially of the following processes: transporting the lining material to the face of the tunnel (T_s), and unloading the lining material (T_{ul}).

$CT_{horz, j}$: cycle time of horizontal materials handling system (in min)

$$\mathbf{CT_{truck} = P_m + P_l}$$

- Time to dispose the muck: $P_m = \sum_{i=1}^{n} CT_{mi}$ ……………………………………… (6)

$$CT_{mi} = T_{mt} + \mathbf{T_{lm}} + T_s + T_{um} + T_{sb}$$

For the tunnel excavation by road header the duration of the activity loading muck into trucks (**T_{lm}**) is 0, as it is performed simultaneously with excavation and is already considered in the cycle time of the excavation processes (CT_{exc}).

- Time to transport lining material: $P_l = \sum_{i=1}^{n} CT_{l_i}$ ………………………………… (7)

$$CT_{li} = T_s + T_{ul}$$

Where,

CT_{mi}, and CT_{li} are respectively time to dispose the muck, and time to transport lining material (in min)

T_{mt} is time to manoeuvre truck or train at face tunnel (in min)

T_{lm} is loading time muck into truck (in min);

T_s is time to transport muck, and time to transport lining material (in min)

T_{sb} is transfer time empty trucks (in min)

T_{um} is unloading time muck (in min)

T_{ul} is unloading time lining material (in min)

The loading time duration of the trucks (T_{lm} in min) of the tunnel excavated by drill and blast is calculated by dividing the capacity of the trucks (V_{truck} in m^3) with the productivity of the loader (P_{loader} in m^3/hr), described in equation 8.

So $\mathbf{T_{lm}}$: time duration of loading trucks by loader (in min)

$$T_{lm} = \left(\frac{V_{truck} x60}{P_{loader}} \right) \text{.........................} (8)$$

Where,

P_{loader} is the productivity of the loader (in m^3 /hr)

The number of runs to transport the excavated soil (n) and number of runs to transport the lining material (m) are determined. The number of runs *n* is calculated by dividing the volume of excavated soil per cycle (V_m) with the capacity of the trucks (V_{truck}). The volume of excavated soil is calculated by multiplying excavated length of section j (L_j) with the cross section area of the tunnel (S) and the swell factor of the soil (W). The number of runs to transport the lining material is calculated by dividing the amount of lining material per cycle by the amount of lining material per truck.

So ***n***: number of runs to dispose the excavated soil

$$V_{\text{muck}} = L_j \; x \; S \; x \; W;$$

$$n = \left(\frac{V_{\text{muck}}}{V_{truck}} \right)$$

So ***m***: number of runs to transport the lining material

$$m = \left(\frac{Amount\ of\ lining\ material}{Amount\ of\ lining\ material\ per\ truck/train} \right)$$

TBM and rail-mounted materials handling system

The disposal of the muck consists of three major processes: manoeuvring trains at face of the tunnel (T_{mt}) and transporting muck from face to the shaft of the tunnel (T_s). The transportation of the lining materials and rail tracks from the shaft to the face of the tunnel consists essentially of the following processes: transporting the lining material to the face of the tunnel (T_s), and unloading the lining material (T_{ul}).

So $\mathbf{CT_{horz,}}$ j: cycle time of horizontal materials handling system

$$\mathbf{CT_{horz,\,j} = P_m + P_l}$$

- Time to dispose the muck: $P_m = \sum_{i=1}^{n} CT_{mi}$ .... (9)

$$CT_{mi} = T_{mt} + T_s$$

- Time to transport lining material: $Pl = \sum_{i=1}^{m} CT_{li}$ .... (10)

$$CT_{li} = T_s + T_{ul}$$

The number of runs to transport the excavated soil (*n*) and number of runs to transport the lining material (*m*) is assumed to be 1. Each excavation cycle exactly one train is loaded with the excavated soil. The trains consist of several muck cars and material cars.

The transportation times (T_s and T_{sb}) is calculated using equation 11. The distance between the face of the tunnel and soil disposal area (consisting of the length of the excavated tunnel from section 1 until section k (L_j) and the distance between the tunnel and soil disposal area (L_{sd})) is divided by the speed of the trucks or trains (v_{truck}).

So $\mathbf{T_s = T_{sb}}$: time duration of transportation of muck and lining material (in min)

$$T_s = T_{sb} = \left(\frac{\sum_{j=1}^{k} L_j + L_{sd}}{v_{truck}} \right) \qquad (11)$$

Where,
L_j is length tunnel of section j (in m)
L_{sd} is distance between the tunnel and the disposal area outside of the tunnel (in m)
v_{truck} is speed trucks (km/hr)

So $\mathbf{CT_{horz,\,j}}$ is: cycle time of horizontal materials handling (in min)

$$\mathbf{CT_{horz,\,j}} = \sum_{i=1}^{n} CT_{mi} + \sum_{i=1}^{m} CT_{li} \qquad (12)$$

4. Cycle time of vertical materials handling processes

The cycle time (CT_{vert}) of the vertical materials handling consists of two components, namely time to dispose the muck from the undercut area of the shaft of the tunnel to ground level (P_m) and time to transport lining material from ground level to the undercut area of the shaft (P_l). The cycle time of the vertical materials handling system is calculated by equation 16. The vertical materials handling applies only for rail mounted materials handling system, in tunnelling projects with a shaft and a crane system.

Each construction cycle one train, consisting of several muck cars (*n*) and material cars (*m*), arrives at the shaft of the tunnel. One by one the muck cars get loaded on the crane system (T_{lm}), transported to ground level (T_s), emptied (T_{um}) and transported back to the undercut area of the shaft of the tunnel (T_{sb}). Subsequently, the lining segments are loaded (T_{ll}) and transported one by one on the material cars at the shaft of the tunnel (T_s). Once the lining materials are loaded, the train is ready to travel back to the face of the tunnel.

So **CT_{vert}:** cycle time of vertical materials handling system (in min)

$$\mathbf{CT_{vert,\,j} = P_m + P_l}$$

- Time to dispose the muck: $P_m = \sum_{i=1}^{n} CT_{mi}$ .... (13)

$$CT_{mi} = T_{lm} + T_s + T_{um} + T_{sb}$$

- Time to transport lining material: $Pl = \sum_{i=1}^{m} CT_{l_i}$ .... (14)

$$CT_{li} = T_{ll} + T_s + T_{sb}$$

Where,

CT_{mi}, and CT_{li} are respectively time to dispose the muck, and time to transport lining material in the vertical materials handling system (in min)

T_{lm} is loading time muck on hoisting system (min)

T_s is transport time duration of muck cars, lining material and rail tracks (min)

T_{sb} is transfer time empty system (min)

T_{um} is unloading time muck at ground level (min)

T_{ll} is loading time lining material on hoisting system (min)

The transportation times (T_s and T_{sb}) are calculated using equation 15. The distance between the undercut area of the shaft and ground level (L_{shaft}) is divided by the speed of the vertical materials handling system (V_{vert}).

So **$T_s = T_{sb}$**: time duration of transportation of muck cars and lining material (in min)

$$T_s = T_{sb} = \left(\frac{L_{shaft}}{v_{vert}} \right) \text{...} \quad (15)$$

Where,

L_{shaft} is total depth shaft (m)

V_{vert} is speed vertical hoisting system (km/hr)

So $\mathbf{CT_{vert,\,j}}$ is: cycle time of vertical materials handling system (in min)

$$\mathbf{CT_{vert,\,j}} = \sum_{i=1}^{n} CT_{mi} + \sum_{i=1}^{m} CT_{li} \quad \text{.......................} \ (16)$$

Where,

n is the number of muck cars per train

m is number of runs to load lining materials on cars

5. Cycle time of minor time factors

Besides the major activities of tunnelling construction, such as excavation, materials handling processes and installation of primary support, there are also 'minor' activities involved in the construction of tunnels. These time factors are also included in the cycle time calculation and productivity equation. CT_{min} consists of time factors, such as placing road header or drill jumbo at face tunnel, displacing road header or drill jumbo, start-up TBM, reset TBM, scaling (manual or mechanical), surveying, extending services (air and water lines) and rail tracks. The cycle time of the minor time factors using drill and blast and road header excavation method are calculated by equation 17 and 18. Equation 19 described the minor time factors of TBM excavation.

- Time to place road header or drill jumbo at face tunnel (min) = T_{pl}
- Time to displace road header or drill jumbo from face tunnel (min) = T_{dp}
- Time to scale (mechanically and manually) the tunnel (min) = T_{sc}
- Time to survey the tunnel (min) = T_{sv}
- Time to start-up TBM (min) = T_{st}
- Time to reset TBM (min) = T_{re}
- Time to extend services (air and water lines) and rail tracks (min) = T_{ext}

So $\mathbf{CT_{min}}$: cycle time of the drill and blast excavation (in min)

$$\mathbf{CT_{min}} = T_{pl} + T_{dp} + T_{sc} + T_{sv} \quad \text{.................................} \ (17)$$

For the road header excavation method, the tunnelling construction process is slightly different. It is not necessary to perform mechanical or manual scaling, hence T_{sc} is 0.

So $\mathbf{CT_{min}}$: cycle time of road header excavation method (in min)

$$\mathbf{CT_{min}} = T_{pl} + T_{dp} + T_{sv} \quad \text{..} \ (18)$$

So $\mathbf{CT_{min}}$: cycle time of TBM excavation method (in min)

$$\mathbf{CT_{min}} = T_{st} + T_{re} + T_{ext.} \quad \text{.......................................} \ (19)$$

4.3.2 Productivity Calculation

The influence factors affecting productivity of tunnelling (in percentage) are:

- Operator's experience: f_1
- Soil condition: f_2
- Job and management condition: f_3
- Site condition: f_4
- Tunnel alignment: f_5
- Machine condition: f_6
- Shift type: f_7

In the ideal situation none of these factors will affect the productivity of the tunnelling construction project negatively, and the value 1 is given to these factors. All factors are assumed to have the same weight relative to each other.

The efficiency factors (in percentage) are:

- Efficiency excavation process: U_1
- Efficiency lining process: U_2
- Efficiency materials handling system: U_3
- Efficiency minor processes (time factors): U_4

Tunnel advance rate (Lm/hr)

$$= \left(f_1 \text{ x } f_2 \text{ x } f_3 \text{ x } f_4 \text{ x } f_5 \text{ x } f_6 \text{ x } f_7\right) \text{ x } \left(\frac{60 \text{ x } L_j}{CT_{exc} \text{ x } u_1 + CT_{ps} \text{ x } u_2 + CT_{mh} \text{ x } u_3 + CT_{\min} \text{ x } u_4} \right) \text{.... (20)}$$

$$CT_{mh} = \sum_{j=1}^{k} CT_{horz,j} + \sum_{j=1}^{k} CT_{vert,j}$$

Where,

L_j is length tunnel of section j (m)

CT_{exc} is cycle time of the excavation process (in min)

CT_{mh} is cycle time of the horizontal and vertical materials handling processes (in min)

CT_{ps} is the cycle time of the primary support processes (in min)

$CT_{horz,\,j}$ is cycle time horizontal materials handling of section j (in min)

$CT_{vert,\,j}$ is cycle time vertical materials handling of section j (in min)

CT_{min} is the cycle time of the minor time factors of tunnelling process (in min)

$\sum_{j=1}^{k} CT_{vert,j}$ and $\sum_{j=1}^{k} CT_{horz,j}$ are respectively the sum of cycle times of the vertical and the horizontal materials handling of section j=1 until section k

4.3.3 Assumptions of deterministic model

- The deterministic model represents the real world tunnelling construction system accurately as long as one truck is in use in the materials handling system. As soon as multiple trucks are put into use, it is assumed that the trucks travel simultaneously towards the face of the tunnel, get loaded one by one, travel in formation towards the soil disposal area where the trucks are emptied, before travelling back towards the face of the tunnel all together. In the real world tunnelling construction process the materials handling system does not behave like that. The movement of the trucks is much more flexible. As one truck is being loaded at the face of the tunnel, another is emptied at the soil disposal area and another one is travelling towards the face of the tunnel.

- An assumption is also made regarding the determination of the number of runs of the disposal of the excavated soil (n) and the number of runs of transport of the lining material (m). The number of runs n or m is assumed to be an integer.

- The deterministic model represents the real world tunnelling construction system accurately as long as one train is in use in the materials handling system. In the actual tunnel project 1 to 3 trains were used based on the excavated length of the tunnel. There was a switch installed somewhere in between the face and shaft of the excavated tunnel for the trains to be able to pass each other, and at the shaft of the tunnel there was space for two trains to be serviced. As tunnel excavation proceeded multiple trains were put into use primarily to decrease the travelling time duration inside of the tunnel, each construction cycle. Assuming multiple trains are in use, the time duration to transport lining material from the shaft to the face of the tunnel is assumed to be 0. As soon as multiple trains are used, this time factor is assumed to be non critical, because this particular activity is performed parallel with other construction activities. Because of the confined space inside of the tunnel, only one train at a time could travel on the main rail track.

- The cycle time of the vertical materials handling is only applicable for tunnelling construction projects that use a shaft and a crane system to transport the muck cars to ground level and lining material to the undercut area of the shaft.

4.4 Summary

In this chapter a deterministic model is presented describing the behaviour of tunnelling construction using different systems to deal with the issues of excavation and materials handling in tunnelling. The chapter starts with a brief description of the specific tunnelling processes of the tunnelling case studies. Also, the model's variables, the productivity factors and efficiency factors of the model are described. Subsequently, the cycle time and productivity equations are presented. In order to calculate the total cycle time, four distinctive cycle times are distinguished, namely: the cycle times of the excavation processes, the primary support processes, the materials handling processes and minor processes. The chapter ends with the description of the assumptions regarding the deterministic model.

Using the deterministic model the tunnel advance rate (in Lm/hr) of different kinds of tunnelling construction projects can be determined. The model can be applied to tunnelling projects in which excavation takes place by drill and blast, road header or TBM. Also tunnelling using different materials handling systems (rubber-mounted, rail-mounted and conveyor belt) can be applied to the deterministic model.

5. Application of the deterministic model

In this chapter the deterministic model is applied to the case studies of the Laval metro tunnel project, Bathurst & Langstaff sewer tunnel project and Parramatta rail tunnel project. With regression analysis cycle time and productivity equations are developed. For each case study also a sensitivity analysis is performed to evaluate and identify the relationships between model's variables (resources) and the tunnel advance rate. The chapter ends with the validation of the deterministic model, by comparing the actual productivity with the calculated productivity of the model.

5.1 Laval metro tunnel project

The cycle time (in min) and productivity (in Lm/hr) are calculated applying the deterministic model to the case study of the Laval metro tunnel. The Laval metro tunnel project is an extension of the metro network in Montreal (Canada) to Laval. For the calculation of the cycle time and productivity of the Laval Metro tunnel project, only the rubber-mounted materials handling system in combination with drill & blast and road header excavation method is considered. The Laval metro tunnel was build using two different excavation methods. The drill and blast and the road header excavation method was used for different sections of the tunnel project. The flowcharts of appendix II show the construction processes involved for both excavation methods.

5.1.1 Cycle time and productivity calculation

The cycle time has been calculated for each segment (of length L_j) using the proposed model for collected set of data. The cycle time of the construction process is subdivided into four distinctive cycle times: cycle time of excavation processes (CT_{exc}), cycle time of the primary support processes (CT_{ps}), cycle time of the (horizontal) materials handling processes (CT_{horz}) and the cycle time of the minor processes (CT_{min}). In table 1 and 2 the cycle times, values and a reference to the equations of the deterministic model are described.

CT drill and blast	Equation number	Values (in min)
CT_{exc}	1	200.0
CT_{ps}	5	90.0
$CT_{horz,\ j=1}$	12	211.8
CT_{min}	17	135.0

Table 1. Cycle time calculation, drill and blast excavation

CT road header	Equation number	Values (in min)
CT_{exc}	2	269.9
CT_{ps}	5	90.0
$CT_{horz,\, j=1}$	12	24.7
CT_{min}	18	40.0

Table 2. Cycle time calculation, road header excavation

Determination of efficiency factors (U_1, U_2, U_3 & U_4)

The values of the efficiency factors U_1, U_2, U_4 have all been taken equal to 100% for the Laval metro tunnel project using drill and blast excavation. Reasons for this set of values are the dimensions of the Laval metro tunnel (length of the tunnel), and the availability of (extra) loaders, and other equipment (e.g. scissor lifts, platform trucks) used during construction. However U_3 is set to 90% due to efficiency loss in the materials handling system. It was stated that there was not much loss of efficiency due to breakdown of equipment, because equipment was available and could be relatively easily replaced. However, there was no easy replacement possibility for the road header during excavation of this type. Because of the cost of the machine there was only one machine available on site. So for this method of excavation, due to breakdown or other problems of the road header, the efficiency factor U_1 is set to 90%.

Determination of factors (f_1 until f_7)

In this study the value of the productivity factors have all been taken equal to 1, because it is assumed that all conditions were ideal. In the ideal situation none of these factors will affect the productivity of the tunnelling construction project negatively. However, values of these factors totally depend upon the project and vary from 0 to 1.

Once the cycle times of the construction processes, the length of tunnel segment L_j, and the values of the efficiency and productivity factors are determined, the tunnel advance rate (in Lm/hr) can be calculated using the productivity equations 20, for both drill and blast and road header excavation. A calculation of the tunnel advance rate for tunnel segment j=1 of the tunnel is provided:

$$\text{Tunnel adv. rate (Lm/hr)} = \left(f_1 x f_2 x f_3 x f_4 x f_5 x f_6 x f_7\right) x \left(\frac{60 x L_j}{CT_{exc} x u_1 + CT_{ps} x u_2 + CT_{horz,j} x u_3 + CT_{min} x u_4} \right)$$

- *Drill and blast*

$$\text{Tunnel advance rate (Lm/hr)} = \left(\frac{60 \, x \, 3,0}{200,0 + 90,0 + 211,8x(1/0,9) + 135,0} \right) = 0.273 \text{ Lm/hr}$$

- *Road header*

Tunnel advance rate (Lm/hr) $= \left(\dfrac{60 \text{ x } 3{,}0}{269{,}9 * (1/0{,}9) + 90{,}0 + 24{,}7x(1/0{,}9) + 40{,}0} \right)$ **=**0.394 Lm/hr

Regression analysis is a statistical tool for the investigation of relationships between variables. In this research regression analysis is applied to show the relation between the length of the tunnel and respectively the cycle time and productivity of the construction process. The total cycle time and the productivity can be determined by equations 21 and 22 (excavation by drill and blast), and equations 23 and 24 (excavation by road header), which have been developed by regression analysis. Figure 1 and figure 2 show the regression analysis of collected data for the cycle time calculations of the tunnel excavated by drill and blast (fig 1), and the tunnel excavated by road header (fig 2). The relationship between tunnel length (L) and the productivity (Lm/hr) for both excavation methods is shown in figure 3.

- *Drill & blast:* Cycle time (min) = 0,0347**L** + 656,8...............................(21)
  Tunnel advance rate (Lm/hr) = -0,00001**L** + 0,274.....(22)
- *Road header:* Cycle time (min) = 0,0293**L** + 454,29.............................(23)
  Tunnel advance rate (Lm/hr) = -0,00002**L** + 0,3959.....(24)

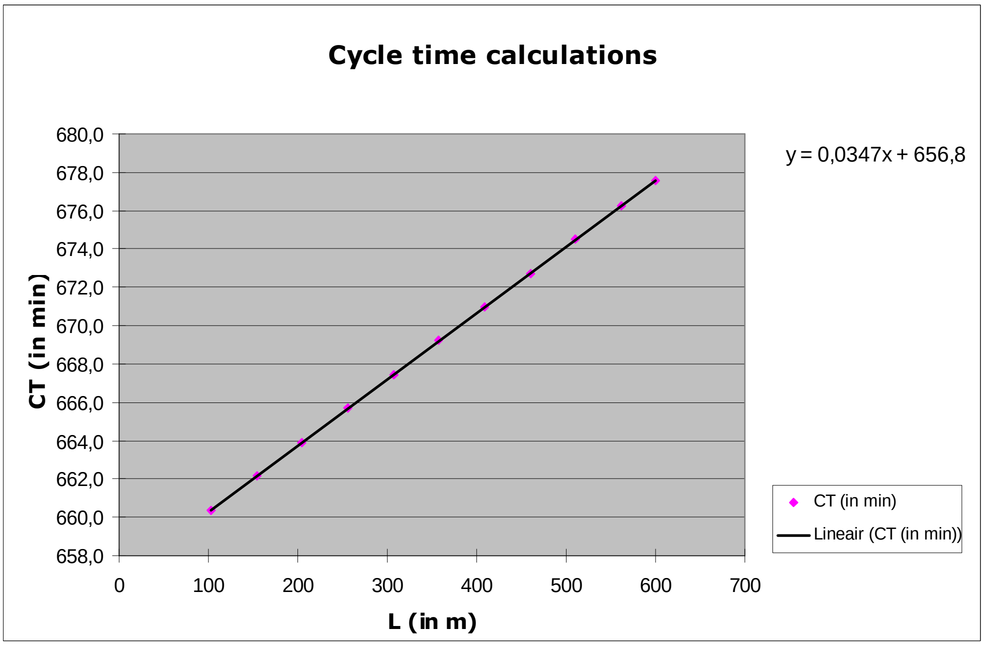

Figure 1. Linear regression for the cycle time calculations using drill and blast: Laval metro tunnel

As already expected, the graphs (fig 1 and fig 2) make clear that there is a (linear) relationship between the distance (L) from the face of the tunnel to the disposal area outside of the tunnel, and the total cycle time (CT) of the construction processes. The increasing cycle time over distance can be completely attributed to the cycle time of the materials handling processes operating during construction. Bigger distance (L) means longer travel times of the trucks to dispose the muck from the face of the tunnel, and to transfer materials for primary support to the face of the tunnel. However, figure 3 shows that although the total cycle time of the construction processes increases as excavation proceeds (and L increases), this does not have an significant impact on the productivity (Lm/hr) of the tunnel construction project. The reason that the increasing cycle time of the materials handling process (CT_{horz}) does not have a huge impact on the productivity is that it is not a significant part of the total cycle time of the construction process.

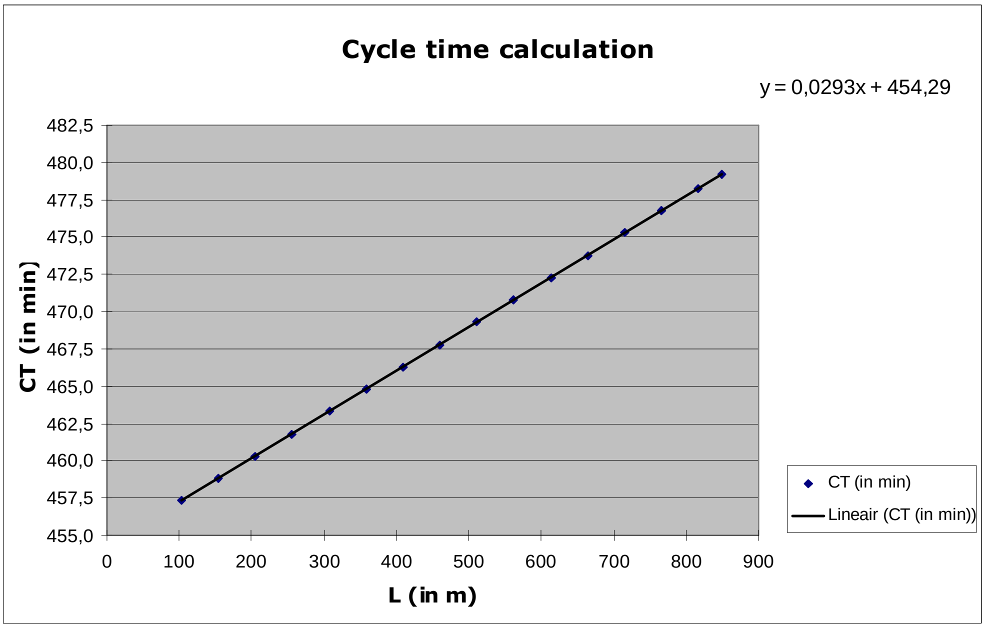

Figure 2. Linear regression for the cycle time calculations using road header: Laval metro tunnel

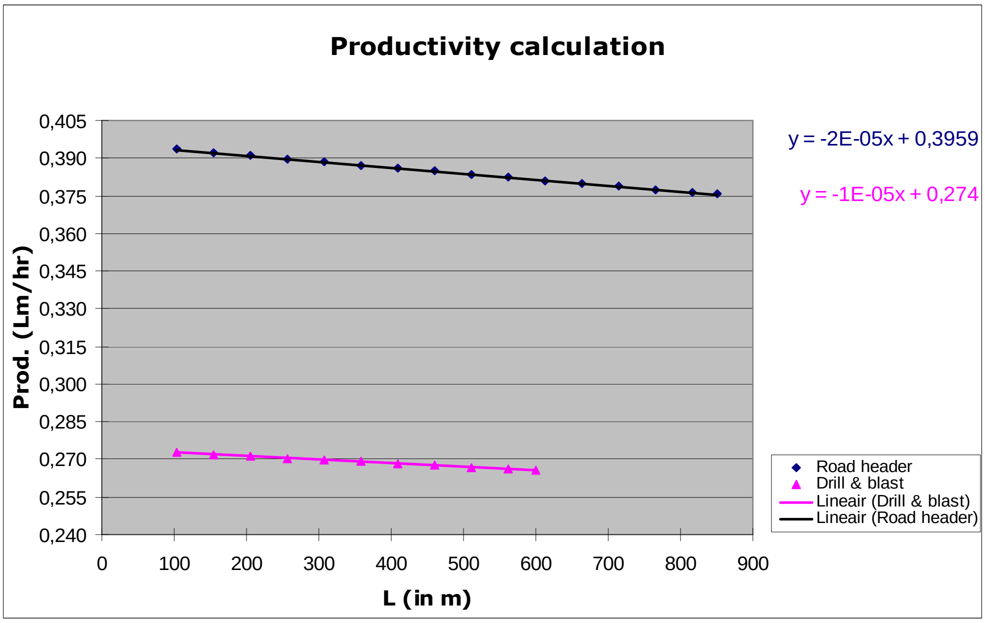

Figure 3. Linear regression for the productivity calculation

5.1.2 Sensitivity analysis

Managers are continually attempting to evaluate the impact of their decisions on the existing state of the production system and its productive output. They want to know what will happen if the level or setting of one of the controllable variables is changed. Sensitivity analysis is done by selecting an important factor, and changing the value of this factor while the other factors have fixed values. By performing the sensitivity analysis the affect of each individual variable on the tunnel advance rate (Lm/hr) is shown. This information is important for a variety of reasons: (a) evaluating the applicability of the model, (b) determining parameters for which it is important to have more accurate values, and (c) understanding the behaviour of the system being modelled.

The variables that are relevant regarding the deterministic model of the Laval metro tunnel project are listed in table 3. Also the actual values of the variables (collected from the tunnelling expert) are described.

Model variables	**Symbol**	**Value**
Distance between tunnel and soil disposal area (m)	L_{sd}	100
Excavation length per cycle (Lm/cycle)	Lj	3,0
Penetration rate road header (Lm/hr)	A	0,67
Number of trucks	N	3
Capacity of trucks (m^3)	V_{truck}	11
Speed of trucks (km/hr)	v_{truck}	25
Number of loaders	L	1
Productivity of loader (m^3/hr)	P_{loader}	60
Number of road headers	R	1
Productivity of road header (m^3/hr)	P_{exc}	31,1
Advance rate primary support (m/hr)	B	2,0
Swell factor of soil	S	1,4
Cross section of tunnel excavated by drill and blast (m^2)	W	44,1
Cross section of tunnel excavated by road header (m^2)	W	37,0
Efficiency factor excavation processes (road header excv. in %)	U_1	90
Efficiency factor excavation processes (drill and blast excv. in %)	U_1	100
Efficiency factor primary support processes (%)	U_2	100
Efficiency factor materials handling processes (%)	U_3	90
Efficiency factor minor processes (%)	U_4	100

Table 3. Tunnelling construction variables and their values of the Laval metro tunnel project

Laval metro tunnel project: Drill and Blast excavation

In figure 4 the graph is presented showing the relationship between the variables of the deterministic model and the tunnel advance rate of the tunnel excavated by drill and blast. As the values of the variables increase in percentage, the tunnel advance rate increases. A value of 0% on the x-axis indicates the actual state of the tunnelling construction system; the state in which the variables have values as described in table 3. Hence, x-values below 0% represent decreasing values of these variables compared to the actual state and vice versa.

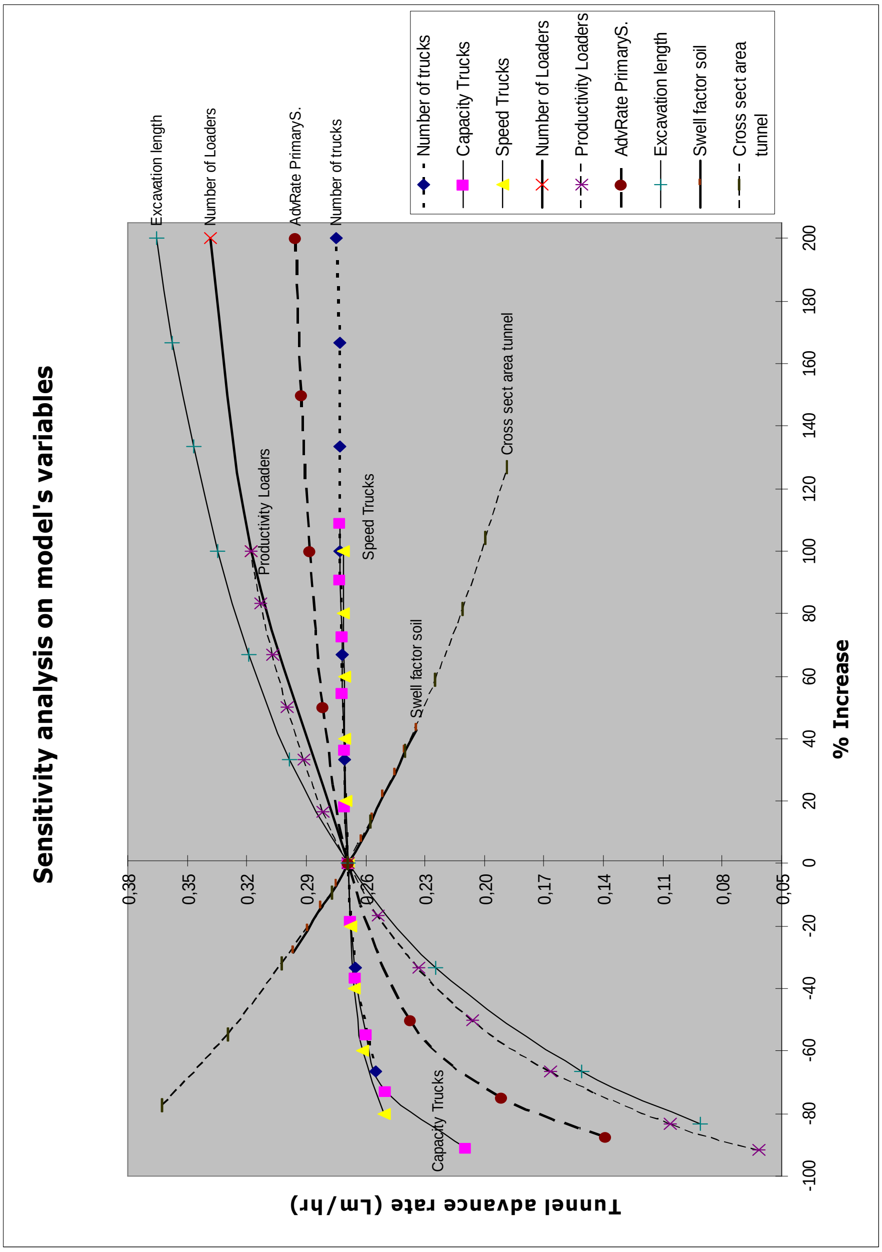

Figure 4. Sensitivity analysis of deterministic model's variables of drill and blast excavation

The graph shows that the variables 'excavation length', 'productivity of the loaders', and 'number of loaders', have the biggest impact on the tunnel advance rate. On the other hand the impact of the variables 'number of trucks' and 'speed of trucks', on productivity is less significant. The graph also shows the variables that have a negative impact on the tunnel advance rate. These variables are 'swell factor of soil' and 'cross section area of tunnel'. In appendix III the sensitivity analysis of each single variable is described in depth, as well as the efficiency factors of the deterministic model.

Laval metro tunnel project: Road header excavation

In figure 5 the graph is presented showing the relationship between the variables of the deterministic model and the tunnel advance rate, of the tunnel excavated by road header.

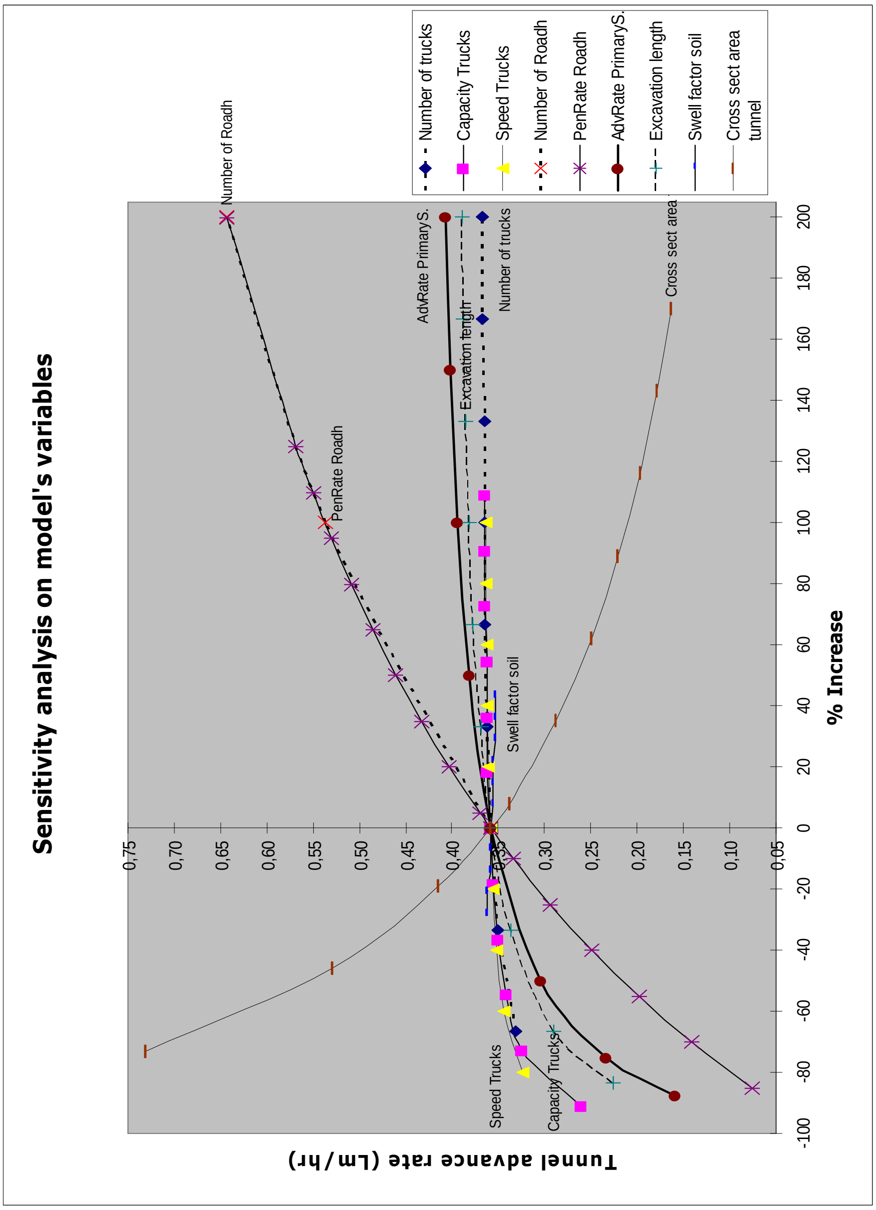

Figure 5. Sensitivity analysis of deterministic model's variables of road header excavation

The graph shows that the variables, 'number of road headers' and 'penetration rate of road header', have the biggest impact on the tunnel advance rate. On the other hand the impact of the variables 'number of trucks' and 'speed of trucks', on productivity is less significant. The graph also shows the variables that have a negative impact on the tunnel advance rate. These variables are 'swell factor of soil' and 'cross section area of tunnel'. In appendix III the sensitivity analysis of each single variable is described in depth, as well as the efficiency factors of the deterministic model.

5.2 Bathurst & Langstaff sewer tunnel project

The cycle time (in min) and productivity (in Lm/hr) are calculated applying the deterministic model to the case study of the Bathurst & Langstaff sewer tunnel project. The Bathurst & Langstaff sewer tunnel was constructed in Vaughan, Ontario, Canada. Three tunnel drives were being completed on the project, two for the Bathurst Sewer and one for the Langstaff Sewer. The tunnels of this project were excavated using TBM and a rail-mounted materials handling system was used. At the shaft of the tunnel a crane was placed to perform the vertical materials handling. The tunnels were each 2500 meters long, and situated at a depth of on average 24.0 meters. In appendix II the flowchart is presented of the construction processes involved in the Bathurst & Langstaff sewer tunnel project.

5.2.1 Cycle time and productivity calculation

The cycle time has been calculated for each segment (of length L_j) using the proposed model for collected set of data. The cycle time of the construction process is subdivided into five distinctive cycle times: cycle time of the excavation processes (CT_{exc}), cycle time of the primary support processes (CT_{ps}), cycle time of the horizontal materials handling processes (CT_{horz}), cycle time of the vertical materials handling processes (CT_{vert}), and the cycle time of the minor processes (CT_{min}). In table 4 the cycle times, values and a reference to the equations of the deterministic model are described.

Cycle times	Equation number	Values (in min)
CT_{exc}	3	12.0
CT_{ps}	5	12.0
$CT_{horz,\ j=1}$	12	2.5
CT_{vert}	16	22.1
CT_{min}	19	7.7

Table 4. Cycle time calculation, Bathurst and Langstaff tunnel

Determination of efficiency factors (U_1, U_2, U_3 & U_4)

The values of the efficiency factors U_1, U_2, U_3 & U_4 for the Bathurst & Langstaff sewer tunnel project are: U_1=0,85, U_2=0,9 U_3=0,85 & U_4 =1. Main reasons for this set of values are the dimensions of tunnel, and the availability of (extra) trains, rails and other equipment used during construction. It was stated by the expert that there was loss of efficiency due to breakdown of equipment (during excavation the TBM often encounters mechanical or other problems, affecting the penetration rate) or derailing of trains inside the tunnel. Also, the fact that the tunnel length was relatively long (2500 m), and the space inside the tunnel very confined (diameter tunnel 3.25 meters), made it more difficult to deal with breakdown and replacement of equipment.

Determination of factors (f_1 until f_7)

In this study the value of the productivity factors have all been taken equal to 1, because it is assumed that all conditions were ideal. In the ideal situation none of these factors will affect the productivity of the tunnelling construction project negatively. However, values of these factors totally depend upon the project and people involved in the project and vary from 0 to 1.

Once the cycle times of the construction processes, the length of tunnel segment L_j, and the values of the efficiency and productivity factors are determined, the productivity (in Lm/hr) can be calculated using the productivity equation 20. A calculation of the productivity for tunnel segment j=1 of the tunnel is provided:

$$\text{Tunnel adv rate (Lm/hr)} = \left(f_1 \text{ x } f_2 \text{ x } f_3 \text{ x } f_4 \text{ x } f_5 \text{ x } f_6 \text{ x } f_7\right) \text{ x } \left(\frac{60 \text{ x } L_j}{CT_{exc} \text{ x } u_1 + CT_{mh} \text{ x } u_3 + CT_{\min} \text{ x } u_4}\right)$$

$$CT_{mh} = \sum_{j=1}^{k} CT_{horz,j} + \sum_{j=1}^{k} CT_{vert,j} = 2.5 + 22.1 = 24.6 \text{ min}$$

$$\text{Tunnel adv. rate (Lm/hr)} = \left(\frac{60 \text{ x } 1{,}2}{12{,}0x(1/0{,}85) + 24{,}6x(1/0{,}85) + 7{,}7}\right) = 1.42 \text{ Lm/hr}$$

Regression analysis is a statistical tool for the investigation of relationships between variables. In this research regression analysis is applied to show the relation between the length of the tunnel and respectively the cycle time and productivity of the construction process. The total cycle time and the productivity are calculated by equations 25 and 26, which have been developed by regression analysis. Figure 6 shows the regression analysis of collected data for the cycle time calculations of the tunnelling construction process. The relationship between tunnel length (L) and the productivity (Lm/hr) is shown in figure 7.

$$\text{Cycle time (min)} = 0{,}0071\mathbf{L} + 50{,}764 \quad (25)$$

$$\text{Tunnel advance rate (Lm/hr)} = -0{,}0001\mathbf{L} + 1{,}3997 \quad (26)$$

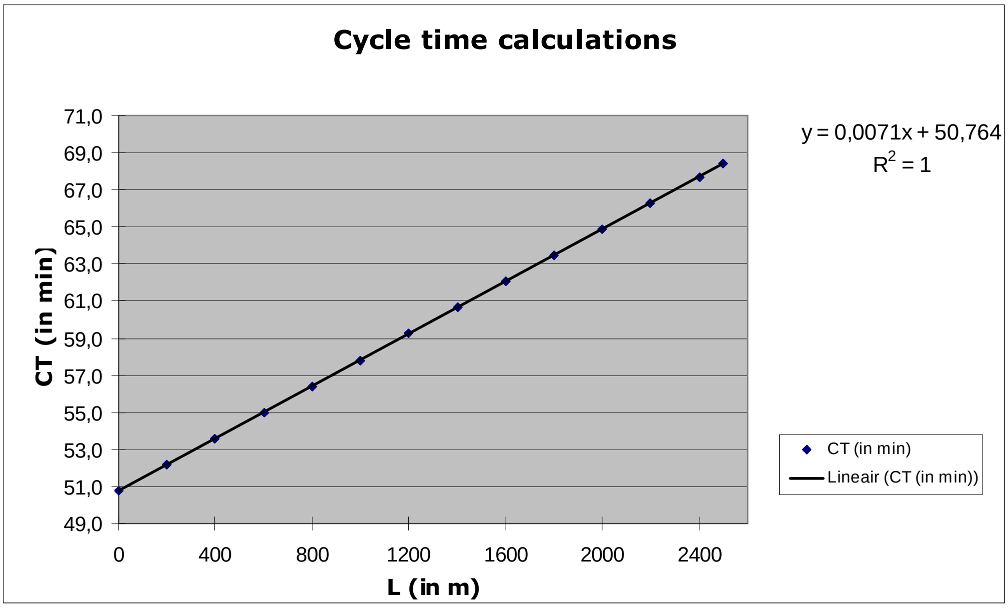

Figure 6. Linear regression for the cycle time calculations

As already expected, the graph (fig 6) makes clear that there is a (linear) relationship between the length of the tunnel (L), and the total cycle time (CT) of the construction processes. The increasing cycle time over distance can be completely attributed to the cycle time of the materials handling processes operating during construction. As excavation proceeds and distance between face and the shaft of the tunnel (L) increases, also the transfer times increase of the trucks to dispose the muck from the face of the tunnel, and to transfer materials for primary support to the face of the tunnel. Figure 7 shows that as excavation proceeds and the excavated tunnel length L increases, the productivity (Lm/hr) of the tunnel construction project decreases significantly. The reason that increasing cycle time of the materials handling process (CT_{horz}) has such a big impact on the productivity is that it is a significant part of the total cycle time.

As shown in the graphs and equations (25 and 26), the horizontal materials handling processes have a significant impact on the productivity. Therefore, it is important to minimize the transfer times of the trains inside the tunnel. In order to decrease the transfer times in each construction cycle, switch systems are installed at the shaft and, as excavation proceeds, somewhere in between the face and the shaft of the tunnel, so that multiple trains can be put into service simultaneously. Switch systems are necessary because there is only space for one travelling train at a time inside the tunnel. It is assumed in the deterministic model that as soon as multiply trains are working simultaneously during construction, the time duration of transporting empty train and lining material towards the face of the tunnel is 0, as it becomes a non critical time factor.

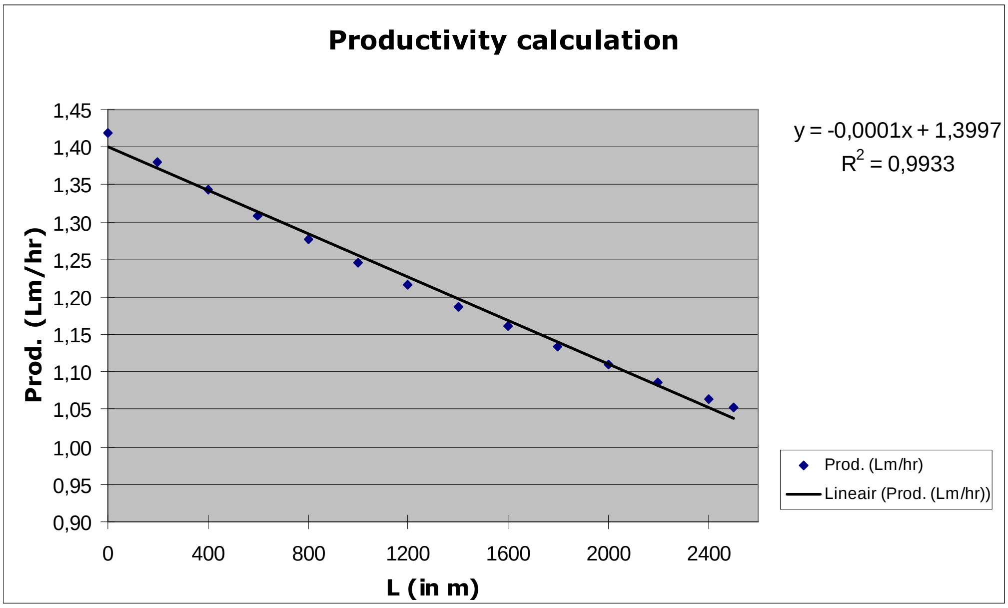

Figure 7. Linear regression for the productivity calculation

5.2.2 Sensitivity analysis

Sensitivity analysis is done by selecting an important factor, and changing the value of this factor while the other factors have fixed values. By performing the sensitivity analysis the affect of each individual variable on the tunnel advance rate (Lm/hr) is shown.

The variables that are relevant regarding the deterministic model of the Bathurst & Langstaff sewer tunnel project are listed in table 5. Also the actual values of the variables (collected from expert) are described.

Model variables	Symbol	Value
Penetration rate TBM (Lm/hr)	A	6,0
Productivity TBM (m^3/hr)	P_{exc}	50,8
Stoke length TBM (m)	L_j	1,2
Number of trains	N	1-3
Capacity of trains (m^3)	V_{train}	18,0
Number of muck cars (4,5 m^3 each) per locomotive	n.a.	4
Number of material cars per locomotive	n.a.	2
Speed of trains (km/hr)	V_{train}	10
Number of cranes	C	1
Height of shaft tunnel (m)	L_{shaft}	24,0
Speed of vertical materials handling system (empty) (km/hr)	$v_{vert,\ e}$	46,0
Speed of vertical materials handling system (loaded) (km/hr)	$v_{vert,\ l}$	16,0
Advance rate primary support (m/hr)	B	6,0
Swell factor of soil	S	1,2
Cross section area tunnel (m^2)	W	8,3
Efficiency factor excavation processes (%)	U_1	85
Efficiency factor primary support processes (%)	U_2	90
Efficiency factor materials handling processes (%)	U_3	85
Efficiency factor minor processes (%)	U_4	100

Table 5. Tunnelling construction variables and their values of the Bathurst & Langstaff tunnel

In figure 8 the graph is presented showing the relationship between the variables of the deterministic model and the tunnel advance rate. The graph shows the impact on productivity of the variables relative to each other. As the values of the variables increase in percentage, the tunnel advance rate increases. A value of 0% on the x-axis indicates the actual state of the tunnelling construction system; the state in which the variables have values as described in table 5. So, x-values below 0% represent decreasing values of these variables, compared to the actual state. X-values above 0% represent increasing values of the variables compared to the actual state of the system.

The graph shows that the variables, 'number of cranes', 'stroke length TBM', and 'penetration rate of TBM', have the biggest impact on the tunnel advance rate. On the other hand the impact of the variable 'number of trains', on productivity is less significant. The graph also shows the variables that have a negative impact on the tunnel advance rate. These variables are 'number of muck cars' and 'height shaft'. In appendix V the sensitivity analysis of each single variable is described in depth, as well as the efficiency factors of the deterministic model.

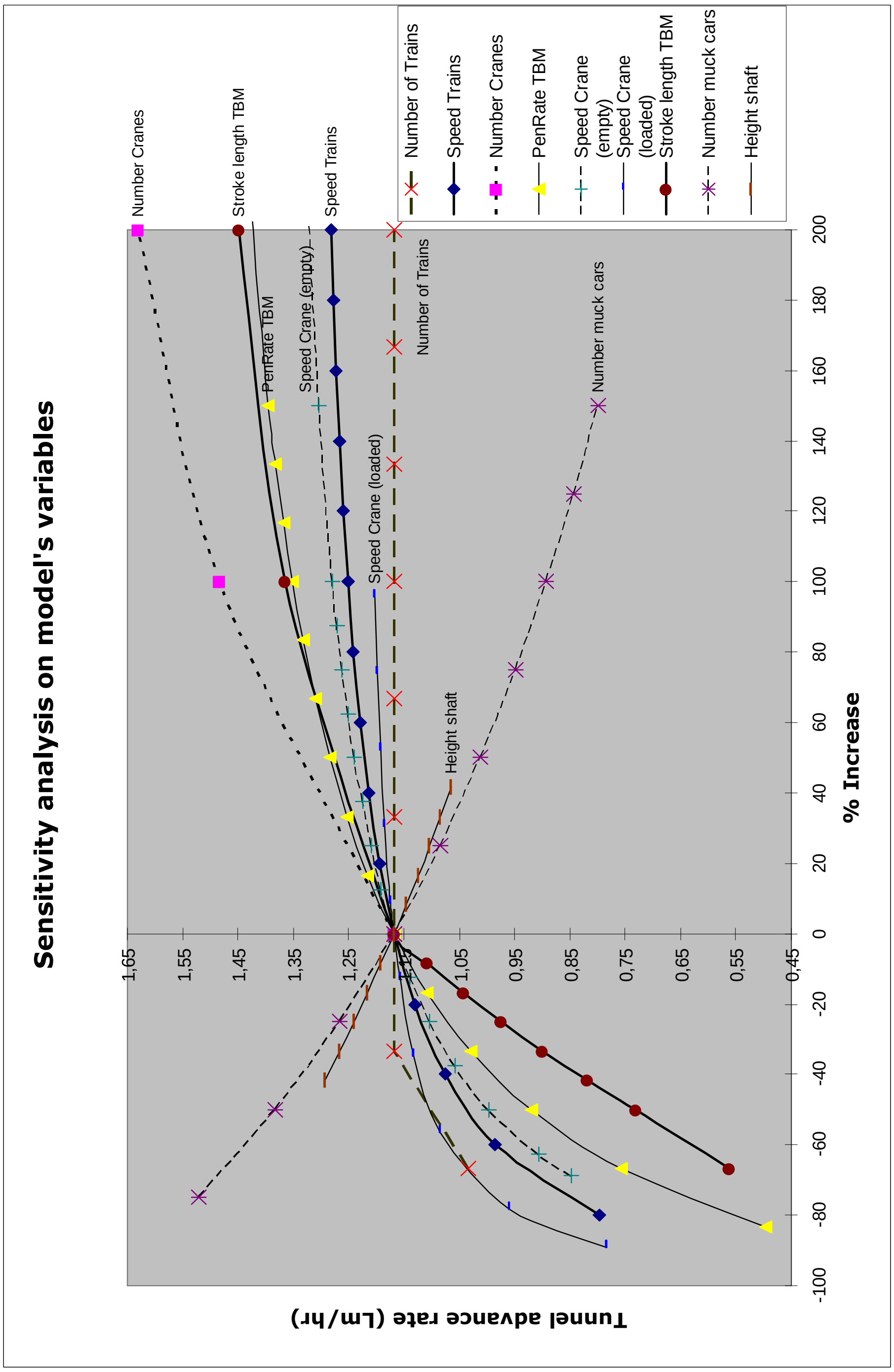

Figure 8. Sensitivity analysis of deterministic model's variables

5.3 Parramatta rail link tunnel project

The cycle time (min) and productivity (Lm/hr) is calculated applying the deterministic model to the case study of the Parramatta rail link tunnel project. The Parramatta rail link tunnel was constructed in Sydney, Australia. The Parramatta rail link is a railway line in the northern suburbs of Sydney, Australia, which connects the suburbs of Epping on the Northern line to Chatswood on the North Shore line. The tunnels of this project were excavated using TBM and a belt-conveyor was used as the main materials handling system. The tunnels were each respectively 6700 and 5300 meters long, and located from 15 to 60 meters below ground elevation. In appendix II the flowchart is presented of the construction processes involved in the Parramatta rail link tunnel project.

5.3.1 Cycle time and productivity calculation

The cycle time has been calculated for each segment (of length L_j) using the proposed model for collected set of data. The cycle time of the construction process is subdivided into four distinctive cycle times: cycle time of excavation processes (CT_{exc}), cycle time of the primary support processes (CT_{ps}), cycle time of the materials handling processes (CT_{mh}), and the cycle time of the minor processes (CT_{min}). In table 6 the cycle times, values and a reference to the equations of the deterministic model are described.

Cycle times	**Equation number**	**Values (in min)**
CT_{exc}	4	15.0
CT_{ps}	5	15.0
CT_{min}	19	1.5

Table 6. Cycle time calculation, Bathurst and Langstaff tunnel

Determination of efficiency factors (U_1, U_2 & U_4)

The values of the efficiency factors U_1, U_2 & U_4 for the Parramatta rail link tunnel project are: U_1=0.8, U_2=0.9 and U_4 =1. Main reasons for this set of values are the dimensions of tunnel, and the availability of (extra) trucks, belt-conveyors and other equipment used during construction. It was stated by the expert that there was loss of efficiency due to breakdown of equipment (during excavation the TBM often encounters mechanical or other types of problems, affecting the penetration rate) or damage of the belt-conveyor inside the tunnel. Also the fact that the tunnel length was relatively long (6700 m) and the space inside the tunnel confined (diameter tunnel 7.27 meters), made it more difficult to deal with breakdown and replacement of equipment.

Determination of factors (f_1 until f_7)

In this study the value of the productivity factors have all been taken equal to 1, because it is assumed that all conditions were ideal. In the ideal situation none of these factors will affect the productivity of the tunnelling construction project negatively. However, values of these factors totally depend upon the project and people involved and vary from 0 to 1.

Once the cycle times of the construction processes, the length of tunnel segment L_j, and the values of the efficiency and productivity factors are determined, the productivity (in Lm/hr) can be calculated using the productivity equation 20. A calculation of the productivity for tunnel segment j=1 of the tunnel is provided:

Tunnel advance rate (Lm/hr)

$$= \left(f_1 x\, f_2 x\, f_3 x\, f_4 x\, f_5 x\, f_6 x\, f_7\right) x \left(\frac{60\, x\, L_j}{CT_{exc} x\, u_1 + CT_{ps} x\, u_2 + CT_{\min} x\, u_4} \right) = \left(\frac{60\, x\, 1.5}{15.0x(1/0.8) + 15.0x(1/0.9) + 1.5} \right) =$$

2.44 Lm/hr

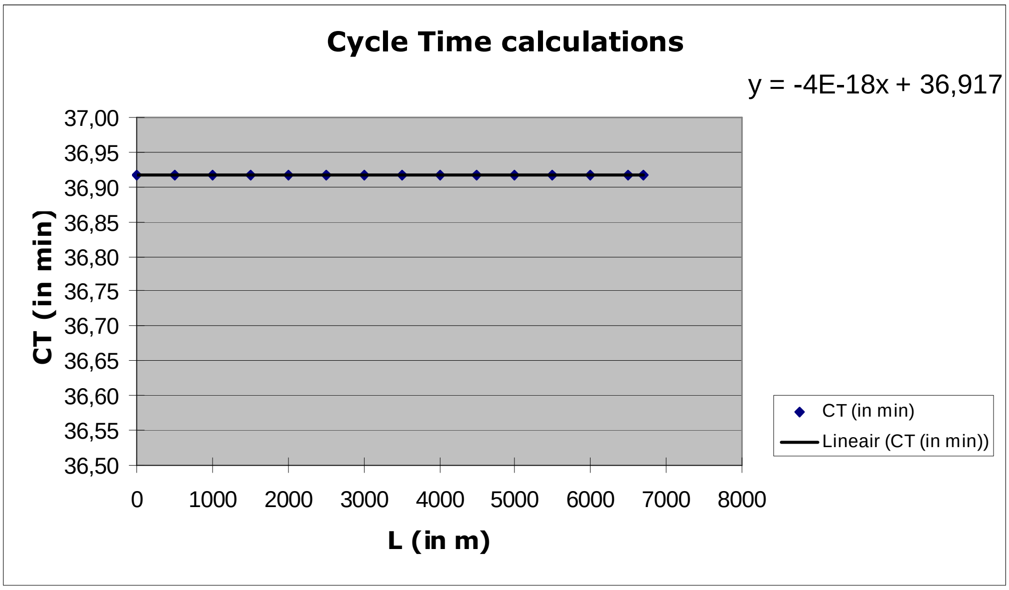

Figure 9. Linear regression for the cycle time calculations

Regression analysis is a statistical tool for the investigation of relationships between variables. In this research regression analysis is applied to show the relation between the length of the tunnel and respectively the cycle time and productivity of the construction process. The total cycle time and the productivity are calculated by equations 27 and 28, which have been developed by regression analysis. Figure 9 shows the regression analysis of collected data for the cycle time calculations of the tunnelling construction process. The relationship between tunnel length (L) and the productivity (Lm/hr) is shown in figure 10.

Cycle time (min) = -4E-18**L** + 36,917.............................. (27)

Tunnel advance rate (Lm/hr) = -5E-19**L** + 2,4379.......... (28)

The graph (figure 9) makes clear that there is absolutely no significant relationship between the length of the tunnel (L), and the total cycle time (CT) of the construction processes for this type of tunnelling. The main reason that there is no relationship is that the materials handling processes (horizontal and vertical) are considered to be non critical time factors. Excavated soil gets disposed by the belt-conveyor continuously; while excavation takes place, the tunnel is lined and all other minor activities are taken place. Primary support material is supplied once every three or four cycles, because there was sufficient space to have it in stock for more than one cycle at the face of the tunnel. Loading these materials from ground level to the truck at the shaft of the tunnel, and transferring them subsequently to the face of the tunnel is done while excavation or lining takes place. Therefore, these processes are considered to be non critical in calculating the cycle time of the tunnelling construction process. Logically, the same (non-existing) relationship is shown in figure 10. As excavation proceeds and distance between the face and shaft of the tunnel increases, the productivity (Lm/hr) remains constant.

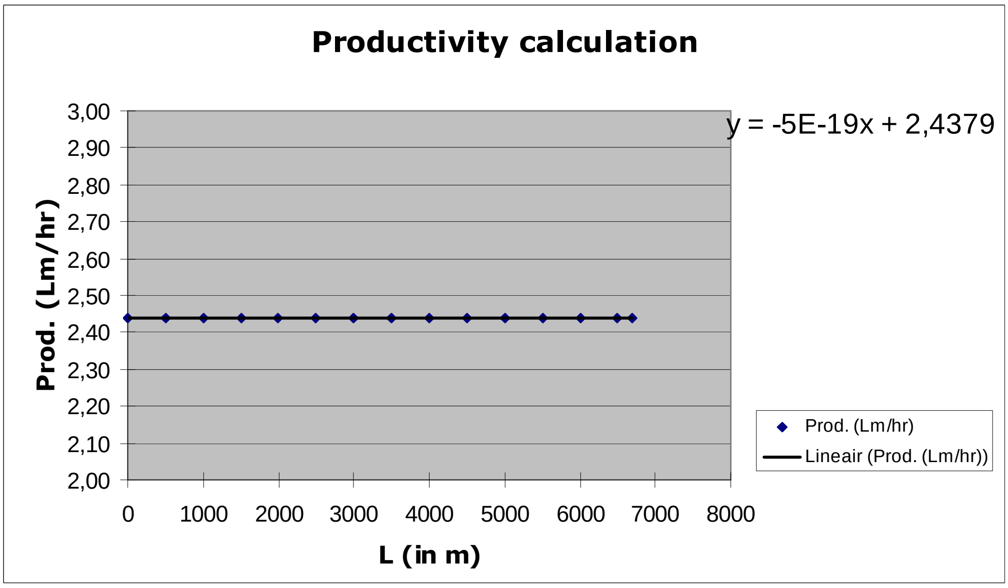

Figure 10. Linear regression for the productivity calculation

5.3.3 Sensitivity analysis

Sensitivity analysis is done by selecting an important factor, and changing the value of this factor while the other factors have fixed values. By performing the sensitivity analysis the affect of each separate variable on the tunnel advance rate (Lm/hr) is shown.

The variables that are relevant regarding the deterministic model of the Parramatta rail link tunnel project are listed in table 7. Also the actual values of the variables (collected from expert) are described.

Model variables	**Symbol**	**Value**
Penetration rate TBM (Lm/hr)	A	6,0
Productivity of TBM (m^3/hr)	P_{exc}	423,3
Stoke length TBM (m)	L_j	1,5
Advance rate primary support (m/hr)	B	6,0
Swell factor of soil	S	1,7
Cross section of face tunnel (m^2)	W	41,5
Efficiency factor excavation processes (%)	U_1	80
Efficiency factor primary support processes (%)	U_2	90
Efficiency factor minor processes (%)	U_4	100

Table 7. Tunnelling construction variables and their values of the Parramatta rail link tunnel

In figure 11 the graph is presented showing the relationship between the variables of the deterministic model and the tunnel advance rate. The graph shows the impact on productivity of the variables relative to each other. As the values of the variables increase in percentage, the tunnel advance rate increases. A value of 0% on the x-axis indicates the actual state of the tunnelling construction system; the state in which the variables have values as described in table 7. So, x-values below 0% represent decreasing values of these variables, compared to the actual state. X-values above 0% represent increasing values of the variables compared to the actual state of the system.

The graph shows that the variables, ‘penetration rate TBM’, and ‘primary support advance rate’, have the biggest impact on the tunnel advance rate. On the other hand the impact of the variable ‘stroke length TBM’’ on productivity is less significant. In appendix VI the sensitivity analysis of each single variable is described, as well as the efficiency factors of the deterministic model.

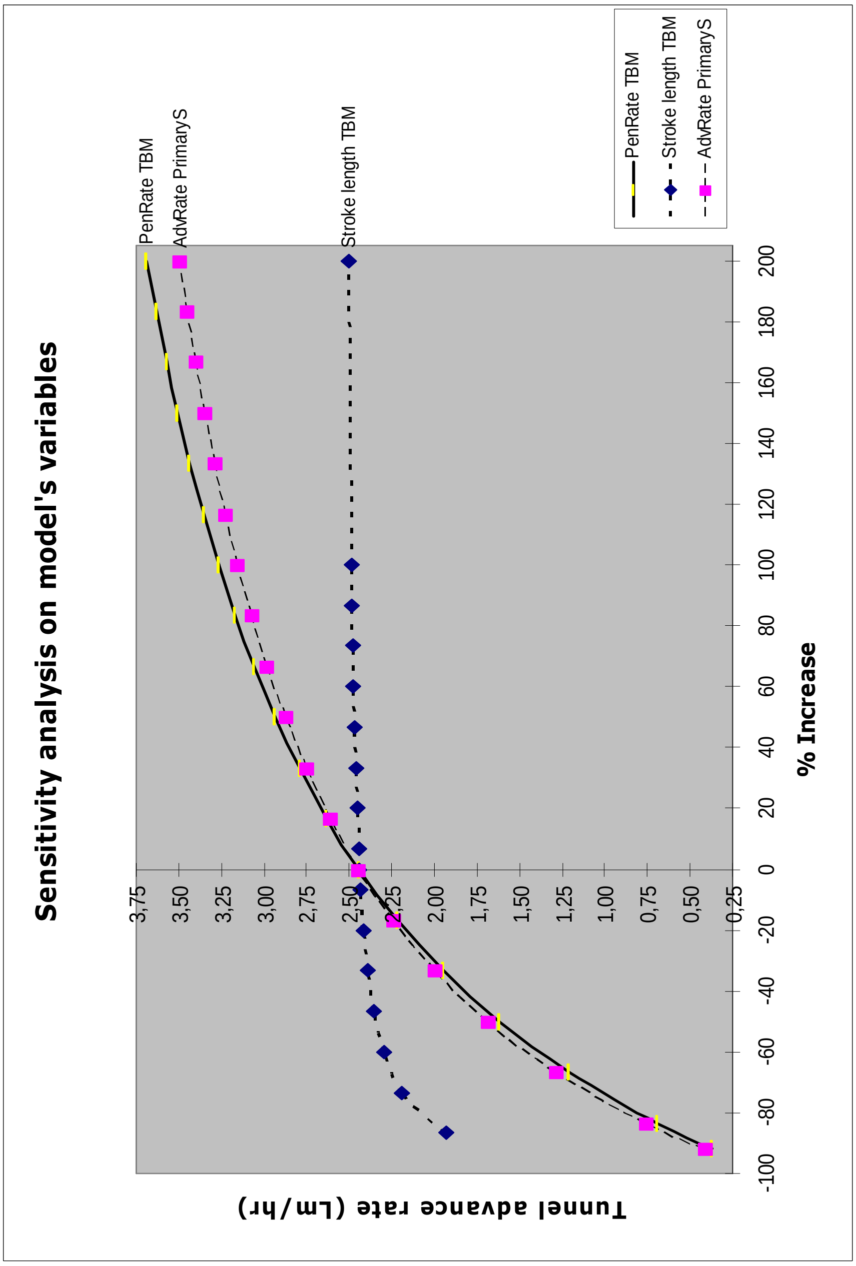

Figure 11. Sensitivity analysis of deterministic model’s variables

5.4 Validation of deterministic model

The validation of the deterministic productivity model is done by comparing the calculated productivity (in terms of tunnel advance rate) with the actual productivity, per case study. It was determined that the actual productivity per case study, is very close to the productivity calculated by the deterministic model.

The average tunnel advance rate of the Laval metro tunnel, excavated by drill and blast, calculated using the deterministic model is 0,269 Lm/hr. The tunnel advance rate of the tunnel excavated by road header is on average 0,384 Lm/hr. While in actual, the average tunnel advance rate was respectively 0,295 Lm/hr (drill and blast) and 0,306 Lm/hr (road header). Hence, the percentage of validity is 91% (drill and blast) and 80% (road header). The average tunnel advance rate of the Bathurst & Langstaff sewer tunnel calculated using the deterministic model is 1.217 Lm/hr. While in actual, the average tunnel advance rate was 1.07 Lm/h. Hence, the percentage of validity is 88%. The average tunnel advance rate of the Parramatta rail link tunnel calculated using the deterministic model is 2.44 Lm/hr. While in actual, the average tunnel advance rate was on average between 2.0 and 2.5 Lm/h. Hence, the percentage of validity is between 82% and 98%. Therefore, for all three case studies, it is concluded in the researcher's belief, that the designated deterministic model is robust and can be used to determine the productivity of tunnelling construction projects, using different excavation methods and materials handling systems.

5.5 Summary

In this chapter the deterministic model was applied to the case studies of the Laval metro tunnel, Bathurst & Langstaff sewer tunnel and Parramatta rail link tunnel. With regression analysis cycle time and productivity equations were developed. For each case study also a sensitivity analysis was performed to evaluate the impact of tunnelling variables on the productivity. The affect of the following variables on the tunnel advance rate was assessed: number, capacity and speed of trains and trucks; number of muck and material cars per train; TBM and road header penetration rate; stroke length of TBM; number and capacity of loaders; number of road headers; number of cranes; and speed of crane system. Furthermore, the affect of the advance rate of primary support; swell factor of soil; cross section area of tunnel; excavated length per cycle; height of vertical shaft; and efficiency factors on the tunnel advance rate was investigated.

These variables all have an impact on the productivity of tunnelling construction. It is important to model the variables that have a significant impact on the tunnel advance rate with greater care, by obtaining more accurate values for these variables. Using the deterministic model it is shown that the tunnel advance rate is a function of the complex interaction between the excavation processes (drill and blast, TBM or road header), the materials handling processes, the primary support processes, minor (supporting) processes, ground conditions and tunnel dimensions.

6. Simulation modelling of tunnelling construction

In this chapter the simulation models of the Laval metro tunnel project are explained. The simulation models describe the construction operations involved in the excavation of the tunnel by drill and blast, as well as by road header. This chapter starts with descriptions of the simulation models. Subsequently, the application of the models to the case study is described. Regression analysis will be performed to develop cycle time and productivity equations. Subsequently, sensitivity analysis is performed to evaluate and identify the relationships between tunnelling variables (resources) and the tunnel advance rate. Cost information is added into the analysis of the simulation model, in order to assess different combinations of resources and determine the 'best' resource combination for the Laval metro tunnel project, based on productivity and cost. Using simulation, also a comparison is made between the road header and drill and blast excavation methods. Finally, by comparing the outputs of the simulation model with the outputs of the actual case study, conclusions are drawn regarding the validity of the models.

6.1 Simulation modelling

In the previous chapter a deterministic model was developed, described and applied to the case studies. Deterministic models are mathematical models in which the outcomes are determined through known relationships among states and events, without room for random variation. In practice this means that only average time durations of activities, and average productivity figures of resources are considered. Also sensitivity analysis was performed on the model to instigate the relationships between the variables (e.g. resources) and the productivity of tunnelling.

In this chapter two tunnelling simulation models will be described of the Laval metro tunnel project. The behaviour of time durations of activities and productivity of equipment are described by means of a stochastic model. Stochastic models (e.g. simulation models) use ranges of values for variables in the form of probability distributions. Simulation can be used as a decision-making tool for construction managers, to evaluate the impact of certain management decisions regarding tunnelling construction, such as in resource management or excavation method to use.

Triangular distributions are used in this simulation study to describe the time durations of activities. This type of probability distribution is used in the simulation models because of the method of data collection. As to the value of the distributions, it is based on minimum, maximum and most probable knowledge of the interviewed construction managers of the field. If the most likely outcome is known, together with the smallest and biggest value, a triangular distribution can be used to model the time duration of activities.

In appendix IX an example is given of the output generated by EZstrobe for the Laval metro tunnel excavated by road header. EZstrobe generated all kinds of information regarding separate resources (queues) and activities. It also displays the input parameters with its values and shows different kind of statistical data, such as utilization rate of queues (in %), time durations of activities and average durations, standard deviation, minimum and maximum values. However, the type of data that is of interest needs to be defined. In this particular case the following information was subtracted from the simulation model: the cycle time (CT), tunnel advance rate (ProdRate), total cost per construction cycle (TtlCst), hourly cost per construction cycle (HourlyCst), cost per meter excavation (UnitCst) and cost per volume soil excavation (UnitCstVol). For a detailed description of the EZstrobe simulation tool, Martinez (2001) may be consulted.

6.2 Description of Laval metro tunnel simulation model

The simulation models of the Laval metro tunnel project are described in this paragraph. In order to develop the models, different construction cycles were separated so that possible modelling mistakes could be detected more easily. The process of the development of the models was iterative. The construction cycles were modelled and tested separately from each other. Only after producing reasonable results it was included and linked to the other cycles. The flowcharts representing the construction processes regarding the Laval metro tunnel is shown in appendix II. This includes the section of the tunnel excavated by drill and blast, as well as the section excavated by road header.

The Laval metro tunnel project is an extension of the metro network in Montreal (Canada) to Laval, and is one of the largest construction projects that the region has seen in recent years. It is estimated that approximately 50.000 passengers will use the tunnel each day, and that the project will remove 3.000 vehicles per day from the road system.

6.2.1 Tunnel section excavated by drill and blast

The simulation model of the Laval metro tunnel construction of the tunnel section excavated by drill and blast is shown in figure 1a and figure 1b. In figure 1a the excavation and soil disposal cycles are modelled. In figure 1b the scaling, primary support, surveying and extending services cycles are depicted. The activities and resources of the simulation model are described in table 1. In appendix VII an elaborated description of the simulation model is provided.

Nr.	Model activity	Activity description
1	Placing drill jumbo	Placing the drill jumbos at the face of the tunnel from its starting position
2	Drilling	Drilling holes at the face of the tunnel by drill jumbos
3	Displacing drill jumbo	Drill jumbo gets displaced from the face of the tunnel to its starting position
4	Repair	Repairing the drill jumbo
5	Loading explosives	Placing the explosives in the holes at the heading of the tunnel, with the use of platform trucks
6	Blasting and ventilation	Blasting and ventilating the tunnel
7	Manoeuvre truck	Manoeuvring the trucks at the face of the tunnel
8	Load soil	Loading soil in the trucks by a loader
9	Transfer soil	Transporting the soil towards the soil disposal area by trucks
10	Unload soil	Unloading the soil from the trucks at the soil disposal area
11	Return empty truck	Empty truck returns to its starting position
12	Stop soil disposal	Soil disposal cycle is finished
13	Mechanical scaling	Scaling mechanically along the surface area of the excavated tunnel with an excavator
14	Manual scaling	Scaling the excavated tunnel manually with the use of platform trucks
15	Transfer lining material	Transporting lining materials (rock bolts and wire mesh) towards the face of the tunnel
16	Unload lining material	Unloading the lining material at the heading of the tunnel
17	Return empty material truck	Returning of material truck towards its starting position
18	lining tunnel	Lining of the tunnel with the use of drill jumbo to drill holes for the installation of rock bolts, and platform trucks
19	Surveying tunnel	Surveying the face of the tunnel to evaluate its position, and determine the position of the holes to be drilled in next construction cycle
20	Extending services	Extending the air and water lines inside the tunnel

Table 1. Tunnelling construction activities of Laval metro tunnel, excavated by drill & blast

Laval metro tunnel project: drill and blast excavation

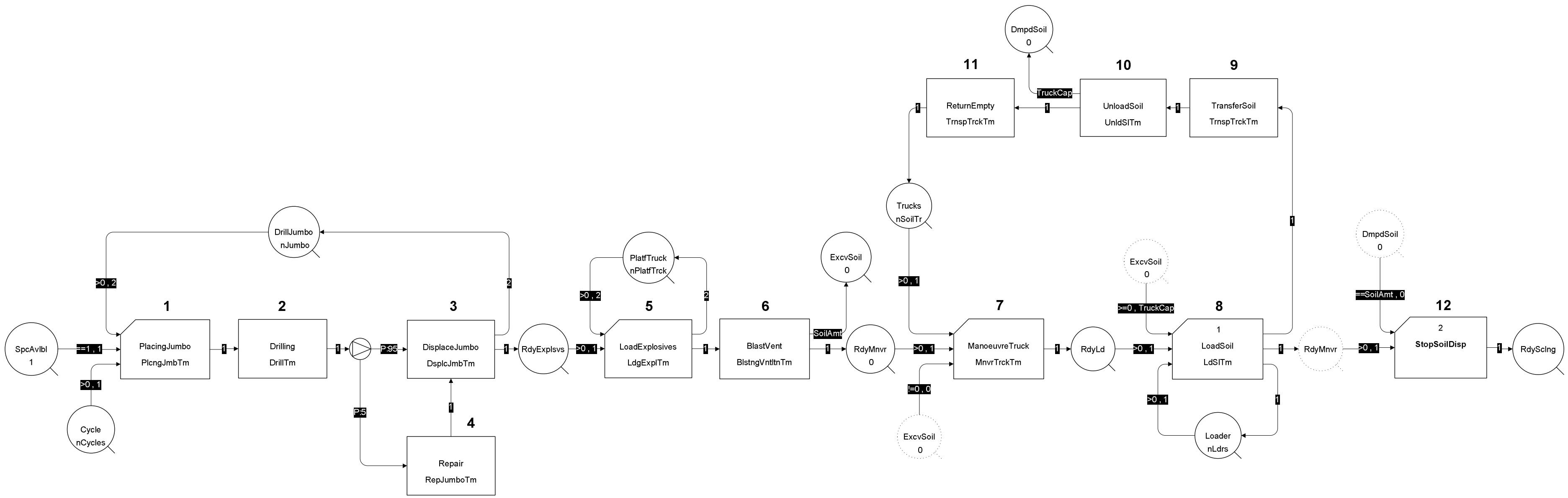

Figure 1a. EZstrobe simulation model of the Laval metro tunnel project, excavated by drill and blast

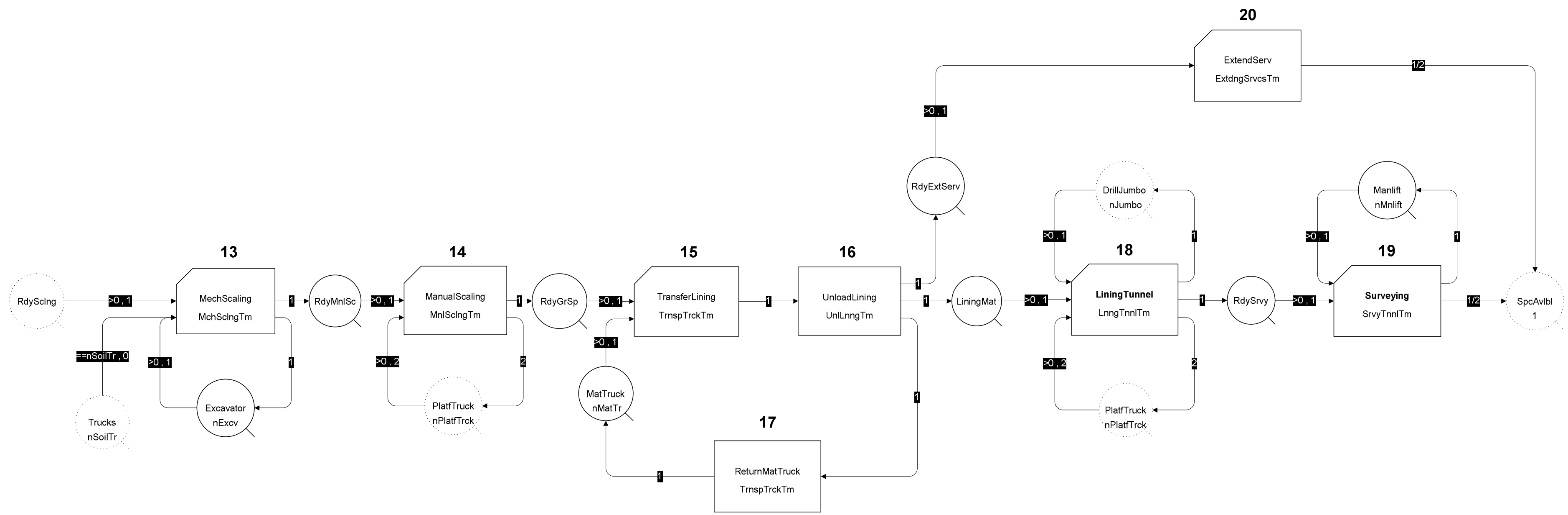

Figure 1b. EZstrobe simulation model of the Laval metro tunnel project, excavated by drill and blast

6.2.2 Tunnel section excavated by road header

The simulation model of the Laval metro tunnel project, of the tunnel section excavated by road header is presented in figure 2a and figure 2b. In figure 2a the excavation, soil disposal and maintenance cycles are modelled. In figure 2b the primary support, surveying and extending services cycles are presented. The activities and resources of the simulation model are described in table 2. In the appendix VII an elaborated description of the simulation model is provided.

Nr.	Model activity	Activity description
1	Relocating Road header	Placing the road header at the face of the tunnel from its starting position
2	Manoeuvre truck	Manoeuvring the trucks at the face of the tunnel
3	Excavate and load trucks	Excavating and simultaneously loading trucks with soil excavated by the road header
4	Repair	Repairing the road header
5	Transfer soil	Transporting the soil towards the soil disposal area by truck
6	Unload soil	Unloading the soil from the trucks at the soil disposal area
7	Return empty truck	Empty truck returns to its starting position
8	Stop soil disposal	Soil disposal cycle is finished
9	Displacing road header	Road header gets displaced from the face of the tunnel to its starting position
10	Maintenance	Performing maintenance on road header
11	Transfer lining material	Transporting lining materials (rock bolts and wire mesh) towards the face of the tunnel
12	Unload lining material	Unloading the lining material at the heading of the tunnel
13	Return empty material truck	Returning of material truck towards its starting position
14	lining tunnel	Lining of the tunnel with the use of drill jumbo to drill holes for the installation of rock bolts, and platform trucks
15	Surveying tunnel	Surveying the face of the tunnel to evaluate the position of the tunnel and determine the holes to be drilled in next construction cycle
16	Extending services	Extending the air and water lines inside the tunnel

Table 2. Tunnelling construction activities of Laval metro tunnel, excavated by road header

Laval metro tunnel project: road header excavation

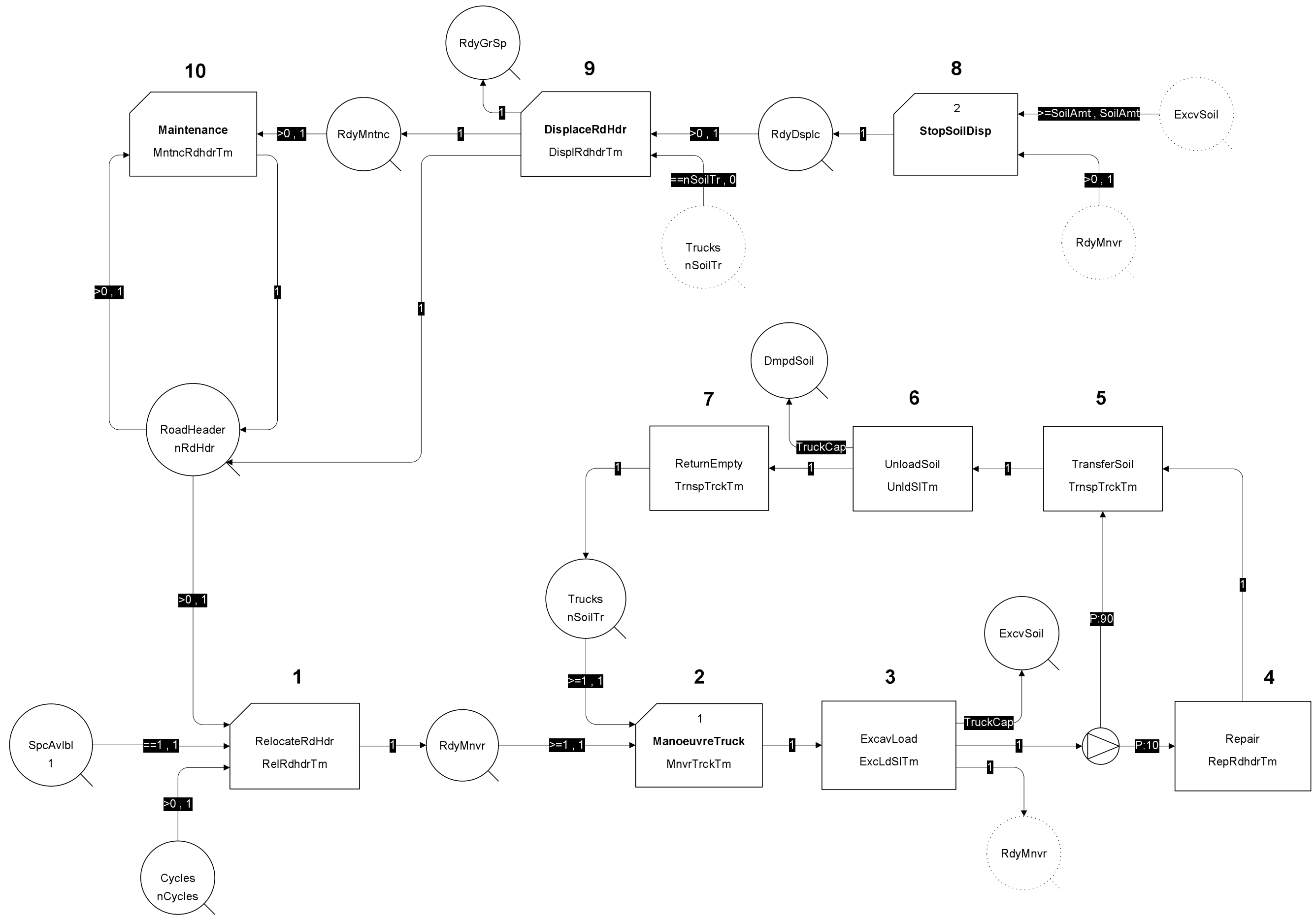

Figure 2a. EZstrobe simulation model of the Laval metro tunnel project, excavated by road header

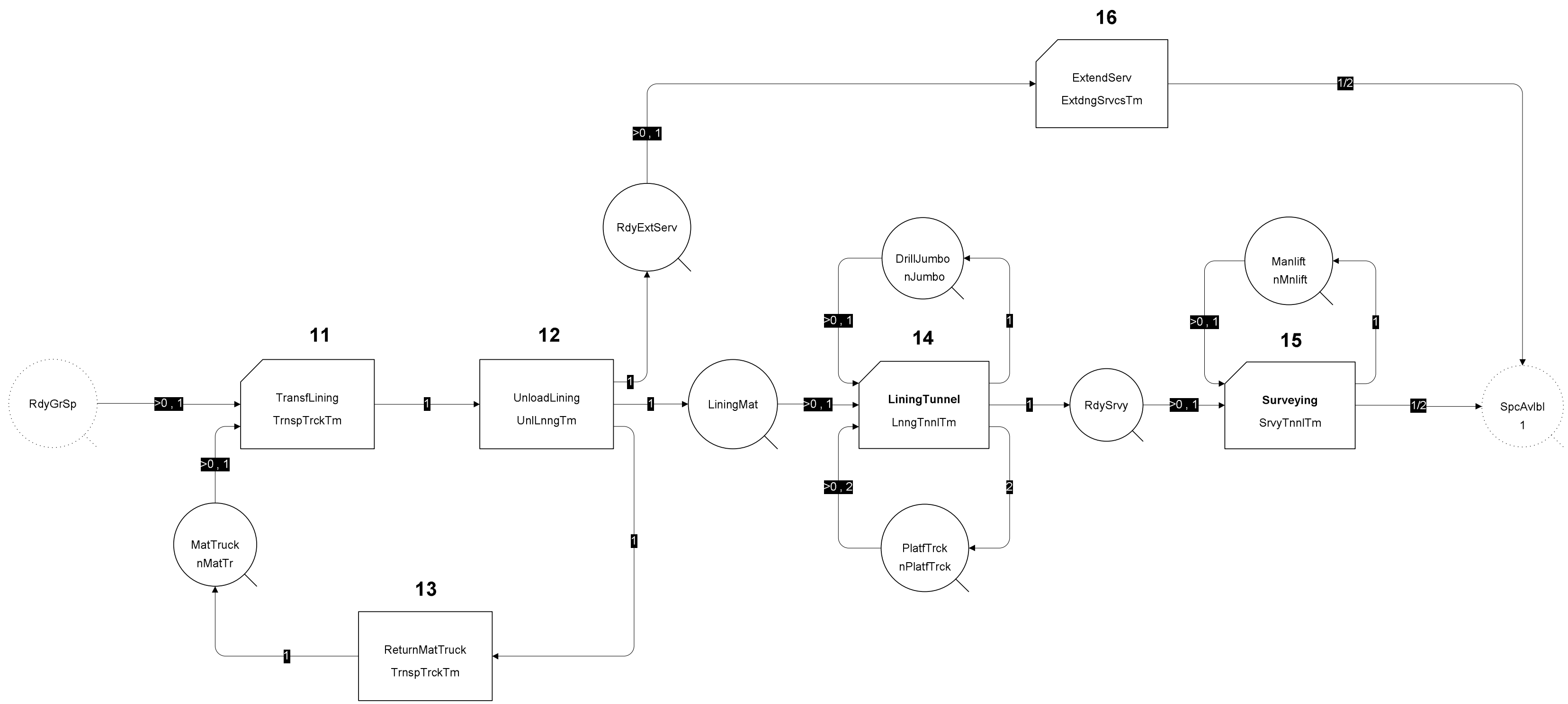

Figure 2b. EZstrobe simulation model of the Laval metro tunnel project, excavated by road header

6.3 Application of simulation model

Applying the simulation model to the Laval metro tunnel project, the cycle time (in min) and productivity (in Lm/hr) are determined. A comparison is made between actual productivity and productivity determined by simulation, to assess the validity of the simulation models. In appendix VIII the variables and equations used to develop the simulation models are described. The Laval metro tunnel was built using two different excavation methods; the drill and blast and the road header excavation methods was used for different sections of the tunnel project. The flowcharts of appendix II show the construction processes involved regarding the excavation method that was used.

6.3.1 Cycle time calculations

Regression analysis is a statistical tool for the investigation of the relationships between variables. In this research regression analysis is applied to show the relation between the length of the tunnel and respectively the cycle time and productivity of the construction process. Figure 3 shows the regression analysis of collected data for the cycle time calculations of the tunnel section excavated by drill and blast, and the tunnel section excavated by road header. The relationship between tunnel length (L) and the productivity (in terms of tunnel advance rate in Lm/hr) is showed in figure 4.

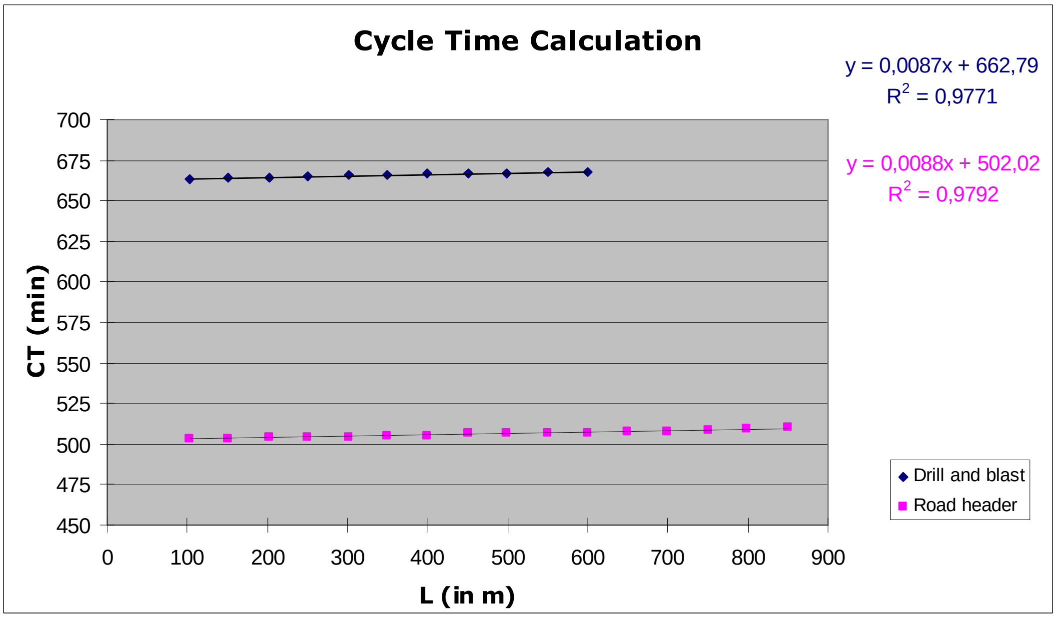

Figure 3. Cycle time calculations of Laval metro tunnel project

The graph of figure 3 makes clear that there is a (linear) relationship between the distance (L) from the face of the tunnel to the disposal area outside of the tunnel, and the total cycle time (CT) of the construction processes. It may be expected that the cycle time increases over distance. The increasing cycle time over distance can be completely attributed to the cycle time of the materials handling processes operating during construction. Bigger distance (L) means longer travel times of the trucks to dispose the muck from the face of the tunnel, and to transfer materials (for primary support) to the face of the tunnel. However, the length of the tunnel is relatively not big enough, for the transportation time durations of the trucks, to make a significant impact on the total cycle time of the construction cycle. The increasing time durations of the transportation activities are an insignificant part of the total cycle time of the construction process.

6.3.2 Productivity calculations

The tunnel advance rates (in Lm/hr) of the construction processes for both the tunnel section excavated by drill and blast, as well as the tunnel section excavated by road header, are calculated using equation 1. The tunnel advance rate is a function of the excavated length of tunnel section j (L_j), and the total cycle time of the construction processes performed in one construction cycle (CT_{cp}).

Productivity (Lm/hr):

$$\text{Tunnel advance rate} = \left(\frac{60 \text{ x } \mathrm{L}_{\mathrm{j}}}{CT_{cp}} \right) \text{..........} \quad (1)$$

Where,

L_j is the excavated length of tunnel of section j (in m)

CT_{cp} is the total cycle time of the construction processes (in min)

The graph of figure 4 shows that there is a (linear) relationship between the distance from the face of the tunnel to the disposal area outside of the tunnel (L) and the productivity (in terms of tunnel advance rate) of the construction processes. However, the increasing time duration of the transportation activities, does not have a significant impact on the total cycle time, and hence on the tunnel advance rate of the construction processes.

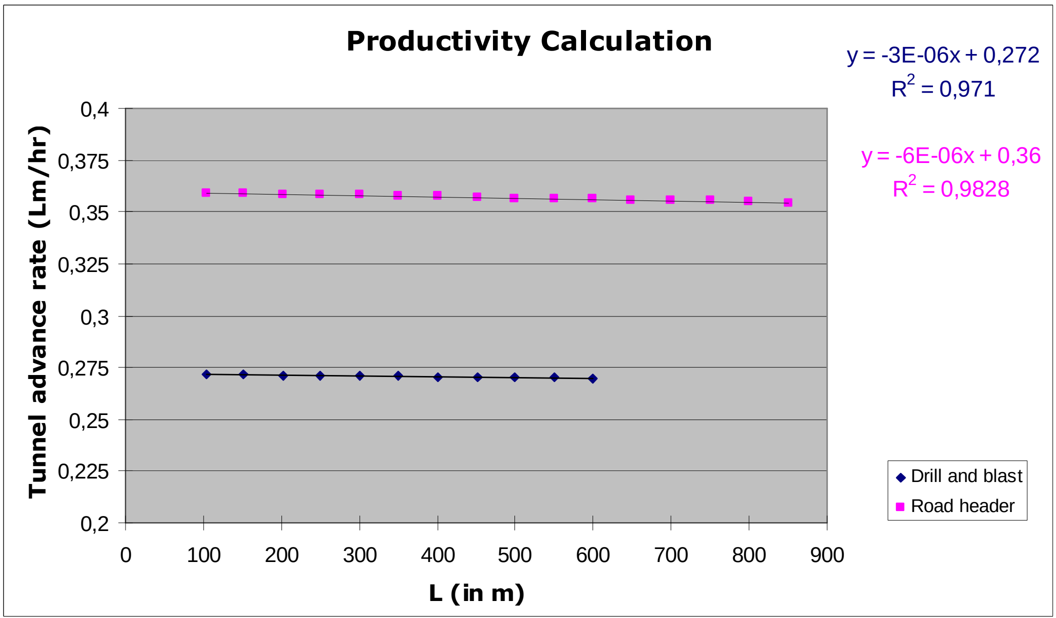

Figure 4. Productivity Calculation of Laval metro tunnel project

In the graphs of figure 3 and 4, the cycle time and productivity equations with their R^2 value, determined by regression analysis, are described for both simulation models. The value of R^2 indicates the proportion of variability in a set of data that is accounted for the statistical model. It provides a measure of how well future outcomes are likely to be predicted by the model. Values of R^2 nearby 1 mean that there is a significant relationship between the variables. Hence, the equations determined by linear regression analysis are good predictors for the calculations of cycle time and productivity (in terms of tunnel advance rate) for the Laval metro tunnel construction project. The cycle time and the productivity can be determined by equations 2 and 3 (excavation by drill and blast), and equations 4 and 5 (excavation by road header), developed by regression analysis.

- *Drill & blast:* Cycle time (min) = 0,0087**L** + 662,79.............................. (2)

  Tunnel advance rate (Lm/hr) = -0,000003**L** + 0,272…. (3)

The average tunnel advance rate of the section of the tunnel excavated by drill and blast, determined by the simulation model is 0.271 Lm/hr. In the actual project the average tunnel advance rate was 0.295 Lm/hr. Hence, the percentage of validity is 92%.

- *Road header:* Cycle time (min) = 0,0088**L** + 502,02............................... (4)

  Tunnel advance rate (Lm/hr) = -0,000006**L** + 0,36........ (5)

The average tunnel advance rate of the section of the tunnel excavated by road header, determined by the simulation model is 0.357 Lm/hr. In the actual project the average tunnel advance rate was 0.306 Lm/hr. Hence, the percentage of validity is 86%.

6.4 Sensitivity analysis

By performing the sensitivity analysis the affect of each individual variable on the tunnel advance rate (Lm/hr) is shown. Also the impact on the tunnel advance rate of the variables compared to each other may be assessed. A sensitivity analysis is performed on the tunnel excavated both by drill and blast and road header. In appendix X the sensitivity analysis of each single variable of the simulation models are described in depth.

6.4.1 Drill and blast excavation

Figure 5 shows the sensitivity analysis of the Laval metro tunnel project, for the tunnel section excavated by drill and blast. A value of 0% on the x-axis indicates the actual state of the tunnelling construction system; the state in which the variables have values as described in table 1 to table 4 of appendix VIII. So, x-values below 0% represent decreasing values of these variables, compared to the actual state. X-values above 0% represent increasing values of the variables compared to the actual state of the system.

The graph shows that the variables ‘excavation length’, ‘productivity of the loaders’, and ‘number of loaders’, have the biggest impact on the tunnel advance rate. On the other hand the impact of the variable ‘number of trucks’ on the productivity is less significant. The graph also shows the variables that have a negative impact on the tunnel advance rate. These variables are ‘swell factor of soil’ and ‘cross section area of tunnel’.

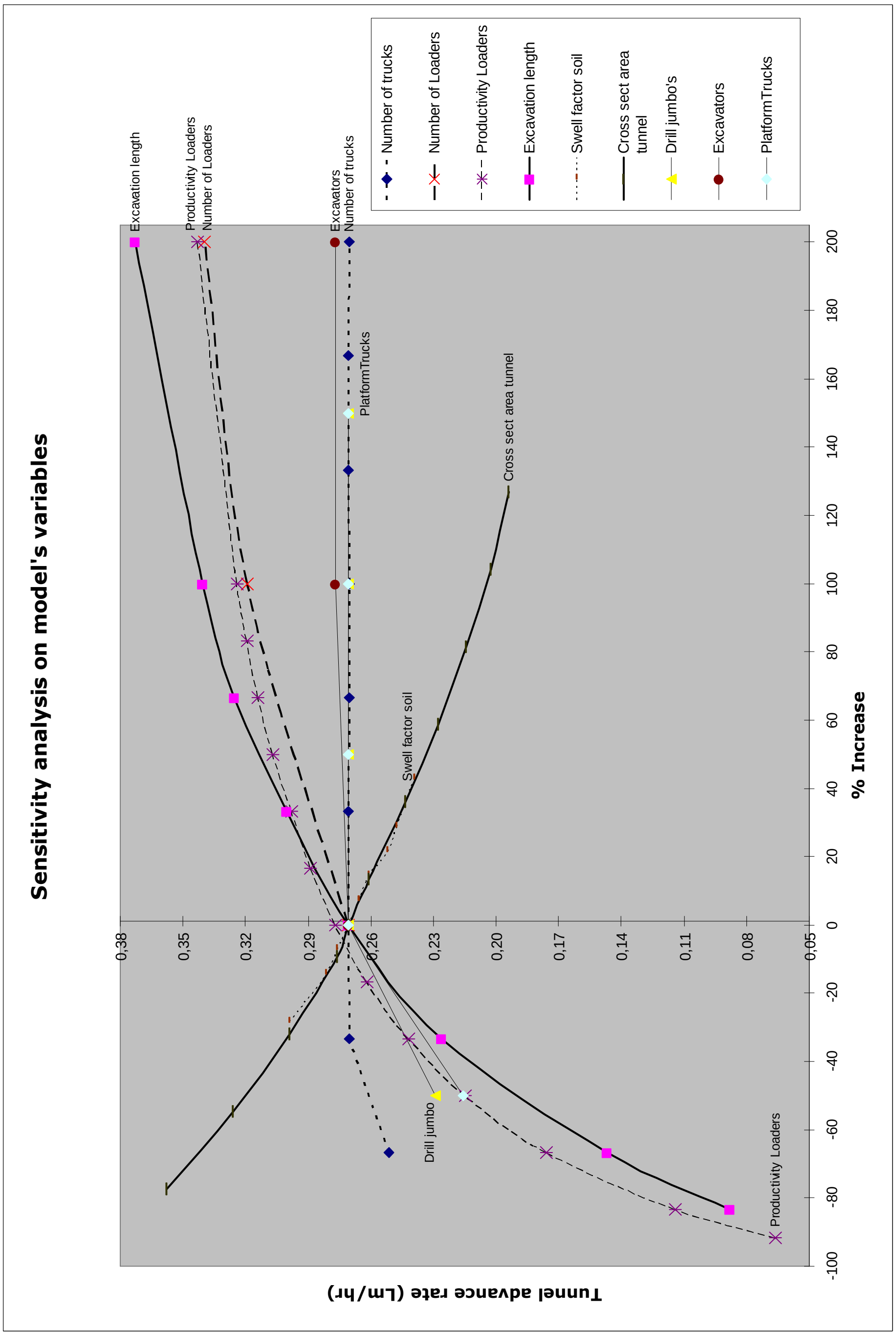

Figure 5. Sensitivity analysis of Laval metro tunnel project excavated by drill and blast

6.4.2 Road header excavation

Figure 6 shows the sensitivity analysis of the Laval metro tunnel project, for the tunnel section excavated by road header.

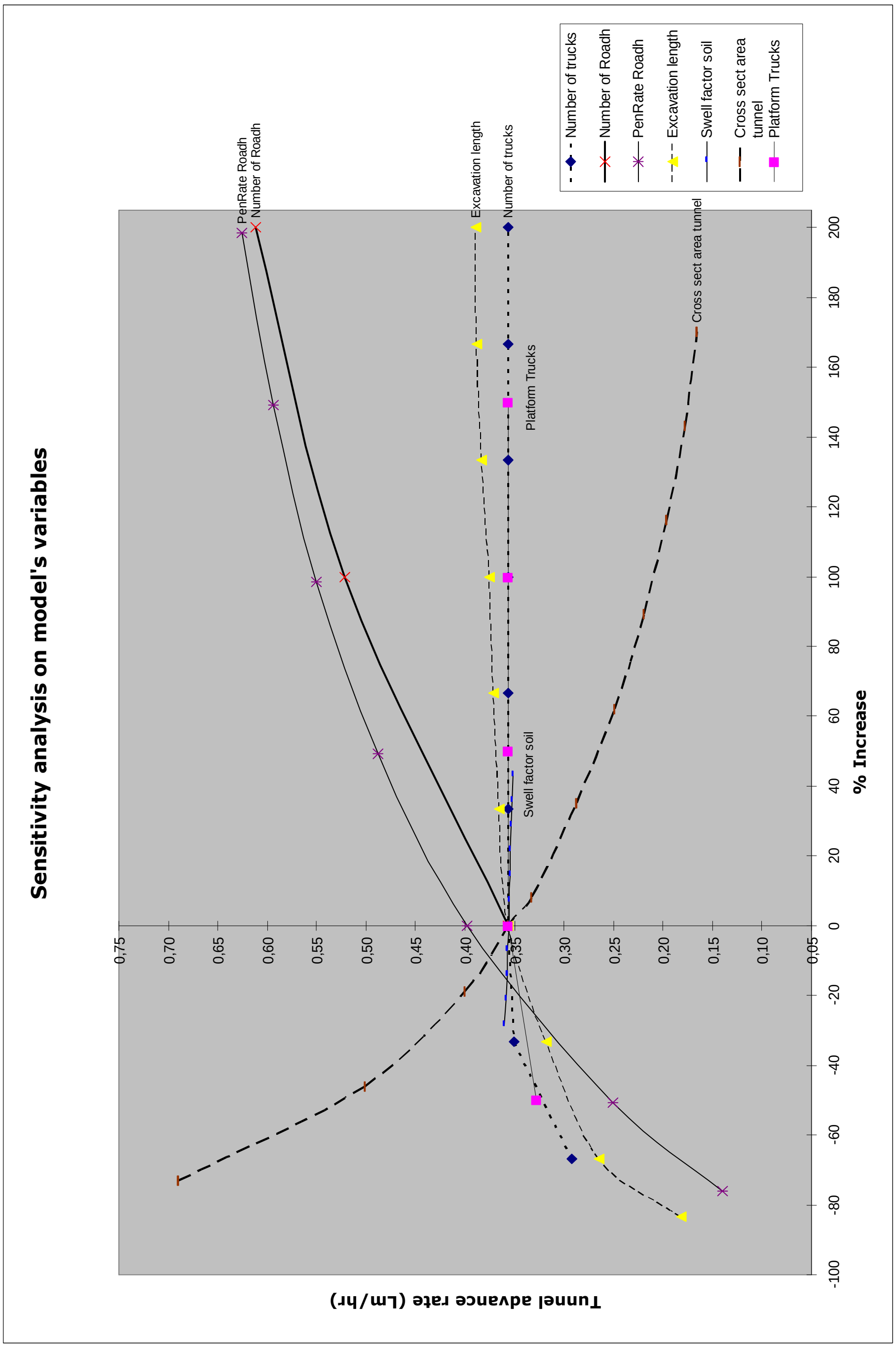

Figure 6. Sensitivity analysis of Laval metro tunnel project excavated by road header

The graph shows that the variables 'penetration rate of road header', and 'number of road headers', have the biggest impact on the tunnel advance rate. On the other hand the impact of the variables 'number of trucks' and 'number of platform trucks', on productivity is less significant. The graph also shows the variables that have a negative impact on the tunnel advance rate. These variables are 'swell factor of soil' and 'cross section area of tunnel'.

6.5 Productivity and cost analysis

In the sensitivity analysis of the previous paragraph the affect of single variables on the productivity (in terms of tunnel advance rate) was assessed. In this paragraph different combination of resources of the Laval metro tunnel construction are assessed based on productivity (Lm/hr) and cost ($/Lm). The 'best' solution is determined using the decision index method.

6.5.1 Tunnelling resources

Only the resources that were found to have an impact on the model's output are used to conduct sensitivity analysis, by assessing different resource combinations based on productivity (tunnel advance rate: Lm/hr) and cost (unit rate: $/Lm). In tables 3 and 4 the resources are described that are important in the construction process. These resources are considered to be critical based on the sensitivity analysis. Changing these variables has an impact on the tunnel advance rate and cost of the construction process. A distinction is made between the tunnel section excavated by drill and blast, and the tunnel section excavated by road header. In this work, average cost figures were used from (construction) cost data literature (RS Means, 2006 edition) to determine the cost (US $/hr) of the various resources used in tunnelling construction.

Resources	Cost/hr ($)	Variation range
Road headers	450	1-2
Soil Trucks	80	1-5
Platform trucks	80	1-2

Table 3. Estimated cost and variation range of resources, road header excavation

Resources	Cost/hr ($)	Variation range
Drill jumbos	150	1-2
Soil Trucks	80	1-3
Loaders	95	1-2
Excavators (backhoe)	100	1-2
Platform trucks	80	1-2

Table 4. Estimated cost and variation range of resources, drill and blast excavation

Besides these resources, other resources were used during construction of the Laval metro tunnel. Regarding labour, nine workers were working each construction cycle to perform the various activities. For both the tunnel excavated by drill and blast as well as the tunnel excavated by road header, a man-lift is used to perform surveying, a material truck is used to transport lining material towards the face of the tunnel, and a drill jumbo to install the rock bolts during the lining processes. However, in the case of the Laval metro tunnel project, these resources are assumed to be non critical. Changing these resources does not effect the time duration of the activities and hence the productivity of the construction project. Nevertheless, the costs (US $/hr) of these resources are considered in the cost calculation (see table 5).

Resources	Cost/hr ($)	Number of resources
Labour	50	9
Man-lift	20	1
Material truck	80	1
Drill jumbo (in road header excavation)	150	1

Table 5. Estimated cost of non critical resources

6.5.2 Productivity and cost analysis

The cost of excavating one linear meter of tunnel (unit cost in $/Lm) is calculated by the simulation model using equation 6. The unit cost is a function of the total time duration of the construction processes performed in one construction cycle (CT_{cp}), the excavated length of tunnel section j (L_j), and the total hourly cost of resources (C_{res}) used in the construction processes. The hourly cost of resources is calculated by multiplying the number of resources by its cost ($/hr) per resource type. The sum of the hourly cost per resource type is the total hourly cost of resources (C_{res}).

Cost of excavating one linear meter of tunnel ($/Lm):

$$\text{Unit cost} = \left(\frac{C_{res} x CT_{cp}}{\mathrm{L_j}} \right) \text{.................................} \quad (6)$$

Where,

CT_{cp} is the total cycle time of the construction processes (in hr)

C_{res} is the total hourly cost of all resources used in one construction cycle ($/hr)

L_j is the excavated length of tunnel of section j (in m)

Road header excavation

Table 1 of appendix XI shows the associated cost and productivity of each combination of resources for the section of the Laval metro tunnel excavated by road header. Three major resources (road headers, soil trucks and platform trucks) are changed according to the variation range described in table 3, to determine the most economical and productive resource combinations.

Figure 7 shows the feasible solutions graph for the Laval metro tunnel excavated by road header. Each resource combination has a value for the productivity and a value for cost. In figure 1 of appendix XI, all resource combinations are considered. In figure 7, the solutions represented by a line with positive slope were not considered, as these are solutions with high cost and low productivity. The solutions represented by bold lines are the most efficient solutions. The less efficient solutions are represented by thin lines. For example, the resource combination of two road headers, five trucks and two platform trucks (2,5,2) has the same productivity as resource combination (2,4,2), but a higher cost. Therefore, resource combination (2,5,2) is less efficient than combination (2,4,2). Any solution line that intersects the line of solution combination (2,4,2) can be considered less efficient, as they represent combinations with lower productivity and higher cost. However, the solution lines of resource combinations (2,2,2) and (2,3,2) have lower cost and lower productivity compared to combination (2,4,2) and therefore are more efficient. Hence, the most efficient solutions for the Laval metro tunnel excavated by road header are resource combinations (2,2,2), (2,3,2) and (2,4,2). The best solution is one of them.

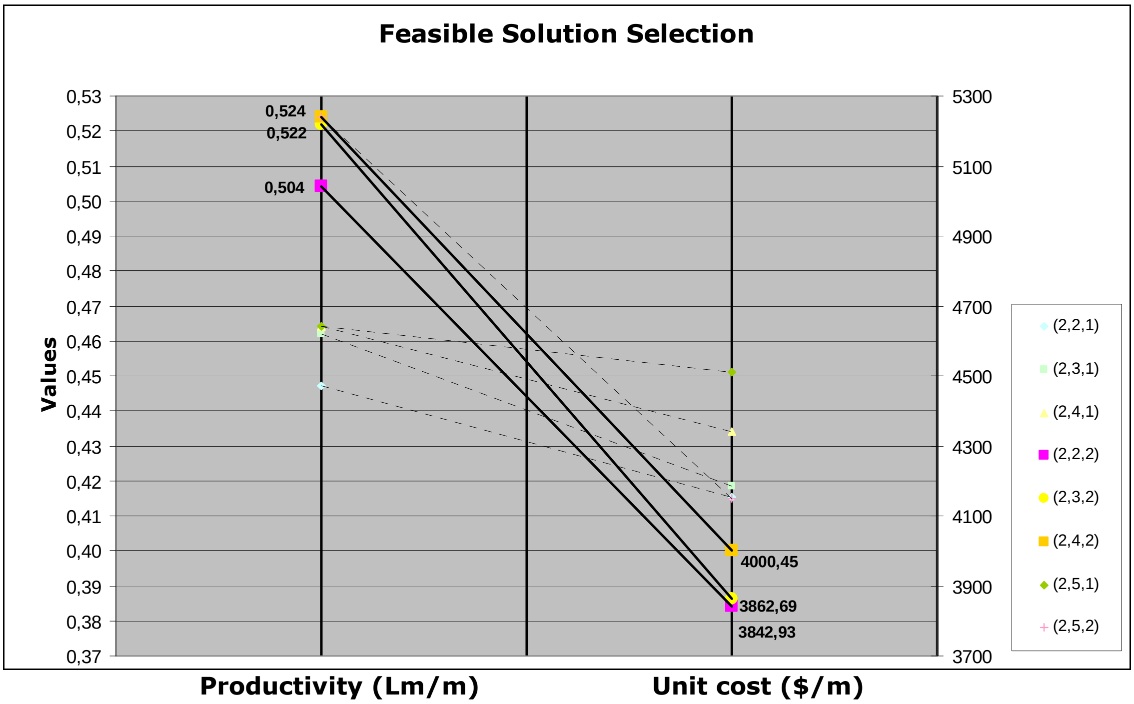

Figure 7. Feasible solutions graph for Laval metro tunnel excavated by road header

In table 1 and 2 of appendix XI the efficiency ratio is determined of the various resource combinations for both simulation models. The efficiency ratio of each combination is calculated by dividing its productivity by its cost. It is showed that the same resource combinations as described above have the biggest efficiency ratio.

Figure 8 shows the unit cost and productivity (tunnel advance rate) graph of the Laval metro tunnel excavated by road header. Each point in the graph represents a unique resource combination.

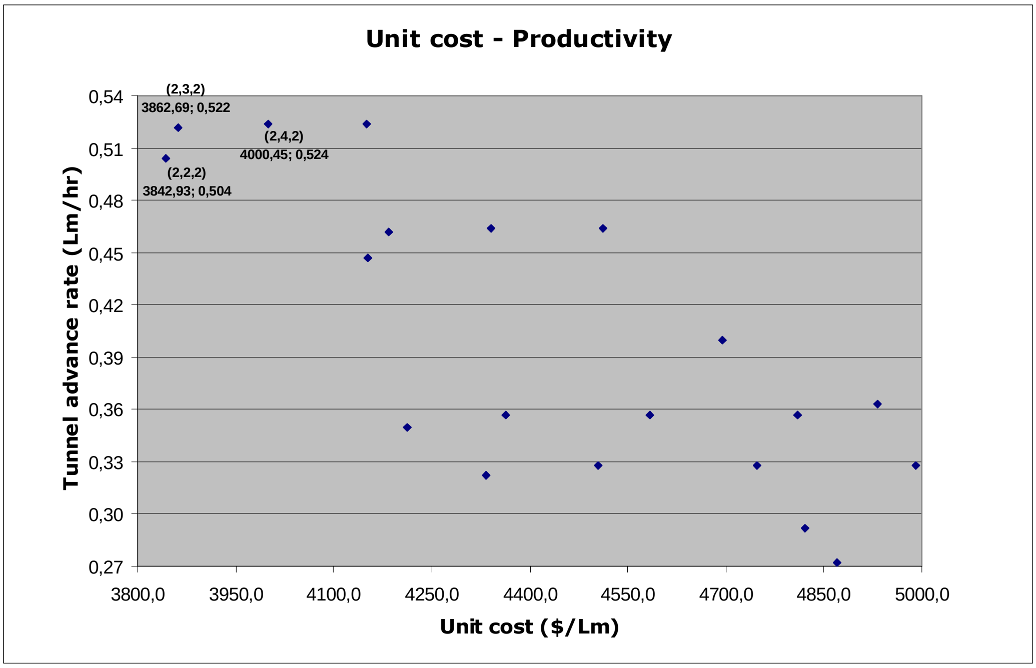

Figure 8. Unit cost – productivity graph Laval metro tunnel, road header excavation

In the case of the Laval metro tunnel project, the sub-optimal recourse combination regarding the section of the tunnel excavated by road header, for cost minimization is: two road headers, two soil trucks and two platform trucks. Resulting in a tunnel advance rate of 0,504 Lm/hr and a unit rate of 3842.93 $/Lm. However, if productivity maximization is pursued, the sub-optimal resource combination is: two road headers, four soil trucks and two platform trucks. This combination leads to higher cost (4000.45 $/Lm), but also a higher tunnel advance rate: 0,524 Lm/hr.

Drill and blast excavation

Table 2 of appendix XI shows the associated cost and productivity of each combination of resources for the section of the Laval metro tunnel excavated by drill and blast. Five major resources (drill jumbos, soil trucks, loaders, excavators and platform trucks) were changed according to the variation range described in table 4, to determine the most economical and productive resource combinations. The variation range per resource type is determined based on the sensitivity analysis on single variables as performed and described in previous paragraph of this chapter.

Figure 9 shows the unit cost and productivity (tunnel advance rate) graph of the Laval metro tunnel excavated by drill and blast. Each point in the graph represents a unique resource combination.

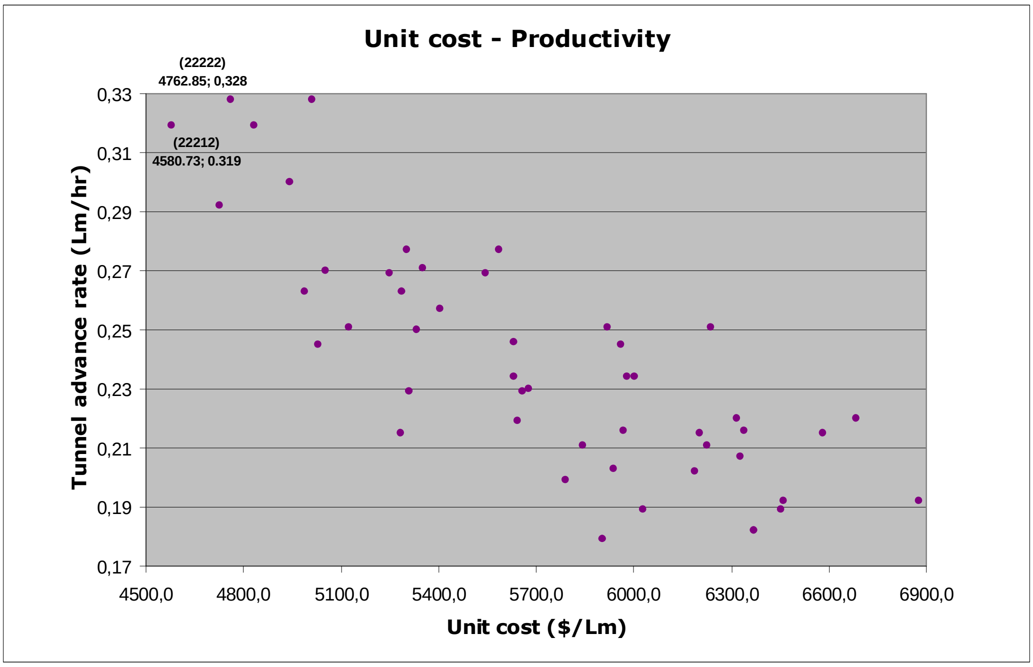

Figure 9. Unit cost – productivity graph Laval metro tunnel, drill and blast excavation

In the case of the Laval metro tunnel project, the sub-optimal recourse combination regarding the section of the tunnel excavated by drill and blast, for cost minimization is: two drill jumbos, two soil trucks, two loaders, one excavator and two platform trucks (combination 2,2,2,1,2). Resulting in a tunnel advance rate of 0,319 Lm/hr and a unit rate of 4580.73 $/Lm. However, if productivity (tunnel advance rate) maximization is pursued, the sub-optimal resource combination is: two drill jumbos, two soil trucks, two loaders, two excavator and two platform trucks (combination 2,2,2,2,2). This combination leads to higher cost per linear meter excavation (4762.85 $/Lm), but also a higher productivity: 0,328 Lm/hr.

6.5.3 Determination of best solution

In multi-objective problems where decisions are made based on productivity and cost, the best solution may not be the one that guarantees minimum cost or maximum productivity. Zayed and Halpin (2001) describe a method (decision index method) to determine the best solution from a cost and productivity point of interest. This method assesses the difference between unit costs, and difference in productivity of the feasible solutions. If the cost difference is less than the productivity difference referenced to the lowest cost solution, this solution is better than the lowest cost solution and vice versa. With this method, both cost and productivity are optimized.

In order to determine the best solution in the feasible set of solutions of the Laval metro tunnel excavated by road header, first of all the most efficient resource combinations have to be selected. Than for each solution, the unit cost is divided by the productivity. In order to compare these feasible solutions to the lowest cost solution, these results are divided by the result for the lowest cost solution. This results in the decision index. If the result for any solution is less than 1, this means that the solution is better than the lowest cost solution. The solution that has the lowest index value should be selected.

In table 6 the decision index method is applied for the tunnel section excavated by road header. Table 7 describes the application of the method for the tunnel section excavated by drill and blast.

Resources Combinations	**Cost (dollars/Lm)**	**Productivity (Lm/hr)**	**Cost/productivity**	**Index**
(2,2,2)	3842.93	0,504	3842.93/0,504=7609,76	1.0
(2,3,2)	3862.69	0,522	3862.69/0,522=7399,79	0,9724<1
(2,4,2)	4000,45	0,524	4000,45/0,524=7634,45	1,0032>1

Table 6. Determine best solution out of feasible solutions for Laval metro tunnel, road header excavation

According to the decision index method, the best resource combination for the tunnel excavated by road header is: two road headers, three soil trucks and two platform trucks (2,3,2).

Resources Combinations	**Cost (dollars/Lm)**	**Productivity (Lm/hr)**	**Cost/productivity**	**Index**
(2,2,2,1,2)	4580.73	0,319	4580.73/0,319=14359,66	1.0
(2,2,2,2,2)	4762.85	0,328	4762.85/0,328=14520,88	1,1011>1

Table 7. Determine best solution out of feasible solutions for Laval metro tunnel, drill and blast excavation

The best resource combination for the tunnel excavated by drill and blast, according to the decision index method is: two drill jumbos, two soil trucks, two loaders, one excavator and two platform trucks (2,2,2,1,2).

6.6 Comparison of excavation methods

In the previous paragraph, the section of tunnel excavated by road header and drill and blast were discussed and considered separately from each other. In this paragraph a comparison will be made between the two excavation methods based on productivity and cost. The comparison is made assuming a tunnel with same tunnel dimensions (cross section area and tunnel length) and soil properties is excavated by both methods.

Figure 10 shows the relationship between the length of tunnel (L) and productivity (in terms of tunnel advance rate). The productivity can be determined by equation 7 (excavation by drill and blast), and equation 8 (excavation by road header), which have been developed by regression analysis.

- *Drill & blast:* Tunnel advance rate (Lm/hr) = -0,000003**L** + 0,27........ (7)
- *Road header:* Tunnel advance rate (Lm/hr) = -0,000005**L** + 0,3142..... (8)

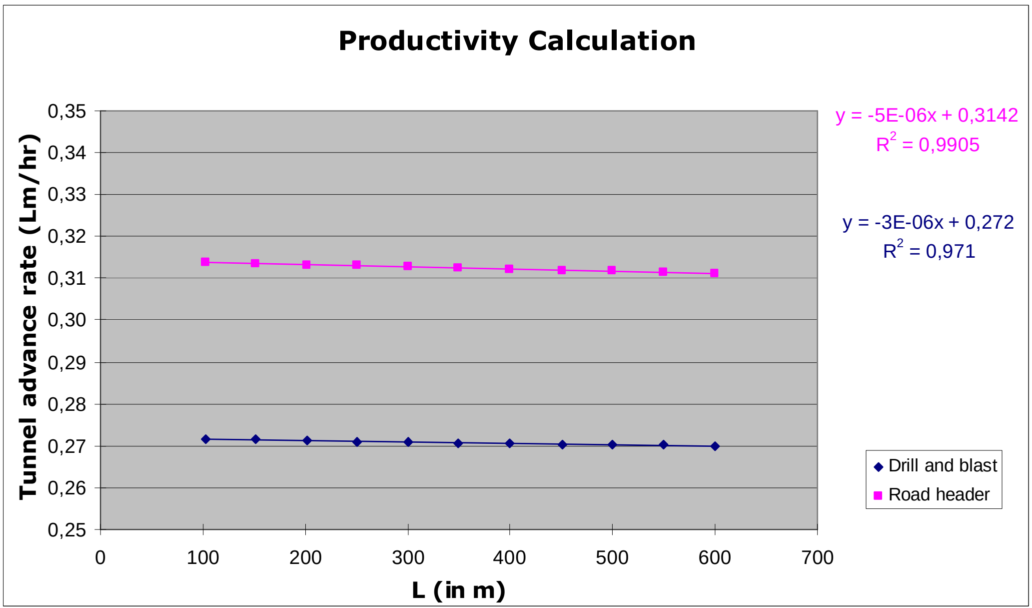

Figure 10. Productivity calculation of drill and blast and road header excavation

Figure 10 and the accompanying equations show that higher productivity is achieved by excavation of the tunnel using the road header excavation method. The average tunnel advance rate of the section of the tunnel excavated by drill and blast, determined by the simulation model is 0.271 Lm/hr. The average tunnel advance rate of the section of the tunnel excavated by road header is 0.312 Lm/hr. These productivity figures are determined assuming same resource allocation as in the actual tunnelling project.

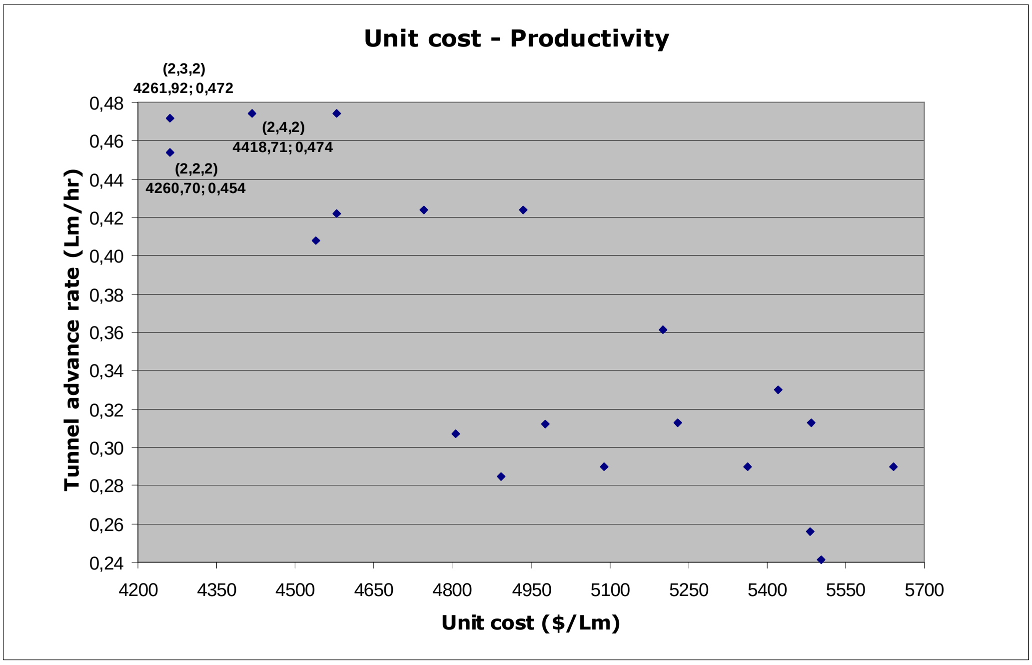

Figure 11. Unit cost-productivity graph of tunnel excavated by road header

In table 3 of appendix XI the table describing each resource combination with its productivity and unit cost is presented. The unit cost and productivity graph of the tunnel excavated by drill and blast is shown in figure 9 of this chapter. In figure 11 the unit cost and productivity (tunnel advance rate) graph of the tunnel excavated by road header is shown. Each point in the graph represents a unique resource combination. The graph shows that three resource combinations are most efficient. Applying the decision index method, as described in the previous paragraph, it is determined that resource combination (2,3,2) is the 'best' solution.

In table 8 for both excavation methods the tunnel advance rate and unit cost related to actual resource allocation, and tunnel advance rate and unit cost related to best resource combination are described.

Excavation	Actual adv. rate (Lm/hr)	Actual unit cost ($/Lm)	'best' adv. rate (Lm/hr)	'best' unit cost ($/Lm)
Drill and blast	0,271	5350,20	0,319	4580,73
Road header	0,312	4976,90	0,472	4261,92

Table 8. Comparison of excavation methods

The table shows that excavation by the road header method results in higher productivity and lower unit cost, compared to excavation by drill and blast.

6.7 Validation of simulation models

The validation of the simulation model is done by comparing the calculated productivity with the actual productivity of the project on the field. Besides the actual productivity, it is also compared with the calculated productivity of the deterministic model. The average tunnel advance rate of the Laval metro tunnel, excavated by drill and blast, calculated by the simulation model is 0.271 Lm/hr. The tunnel advance rate of the tunnel excavated by road header is on average 0,357 Lm/hr. While in actual, the average tunnel advance rate was respectively 0,295 Lm/hr (drill and blast) and 0,306 Lm/hr (road header). Hence, the percentage of validity is 92% (drill and blast) and 86% (road header). Therefore, the designated simulation model is considered to be robust, and can be used to estimate the productivity of tunnelling construction projects of the same kind as the Laval metro tunnel project. Table 9 describes the output of the deterministic and simulation models and their percentage of validity.

Excavation	Actual adv. Rate (Lm/hr)	Deterministic Model(Lm/hr)	Simulation Model (Lm/hr)	Deterministic Validity (%)	Simulation Validity (%)
Drill and blast	0,295	0,269	0,271	91	92
Road header	0,306	0,384	0,356	80	86

Table 9. Deterministic and simulation models outputs

6.8 Summary

In this chapter the simulation model of the Laval metro tunnel was described. With regression analysis cycle time and productivity equations were developed, and sensitivity analysis was performed. The sensitivity analysis showed that the following variables affect the tunnel advance rate of tunnelling construction: number and capacity of trucks; number of road headers; road header penetration rate; number and productivity of loaders, number of drill jumbos, number of platform trucks, and number of excavators. Furthermore, the affect of the swell factor of soil; cross section area of tunnel; and excavated length per cycle, on the tunnel advance rate was investigated.

Using simulation, it is showed that a best allocation of resources can be determined based on productivity (Lm/hr) and cost ($/Lm). Using the decision index method the best solution was determined, by optimizing both productivity and cost. Simulation was also used in order to compare the road header and drill and blast excavation methods based on productivity and cost. It was determined that the road header excavation method achieves higher productivity (in Lm/hr) and a lower unit cost (in $/m) than the drill and blast excavation method.

7. Discussion

In this research deterministic and probabilistic models using simulation are proposed, describing the behaviour of tunnelling construction processes. Different systems to deal with the issues of excavation and materials handling are considered. A comparison between both modelling methods will be described in this chapter, based on the case study of the Laval metro tunnel project. This case study was modelled and analyzed using both modelling approaches. Initially, differences in results regarding the productivity calculations will be assessed. Subsequently, the results of the sensitivity analysis performed for both modelling approaches are described. Finally, the advantages and limitations of both approaches are discussed.

The deterministic model was developed and applied to three case studies, these are: Laval metro tunnel, Bathurst & Langstaff sewer tunnel and the Parramatta rail link tunnel. A sensitivity analysis was performed for each one of the case studies and based on this information, and a comparison between the actual productivity and the calculated productivity, the validity and effectiveness of the model was assessed. In addition, based on the data collected from interviews and the proposed deterministic model, two different simulation models of the Laval metro tunnel were developed using EZstrobe simulation software. A sensitivity analysis was performed to determine the impact of the tunnelling variables on the productivity. Once it was determined that the simulation models produced reasonable results, they were than used to experiment with different resource combinations to evaluate the impact on productivity and cost. Subsequently, a comparison was made between the road header and drill and blast excavation methods. Such information can be used in real projects by the project manager to make decisions as to what excavation method or resources to use.

7.1 Productivity calculation

Figure 1 and figure 2 show the relationship between the tunnel advance rate and length of the Laval metro tunnel, determined by both modelling approaches. Figure 1 compares the productivity calculated by the deterministic and simulation model of the tunnel section excavated by drill and blast. Figure 2 deals with the section of tunnel excavated by road header. The figures show that the average productivity (in terms of tunnel advance rate) determined by both modelling methods are close to each other. In table 1 a summary is shown of the average output of the deterministic and simulation models and their percentage of validity, for the Lava metro tunnel project.

Excavation	Actual adv. Rate (Lm/hr)	Deterministic Model(Lm/hr)	Simulation Model (Lm/hr)	Deterministic Validity (%)	Simulation Validity (%)
Drill and blast	0,295	0,269	0,271	91	92
Road header	0,306	0,384	0,356	80	86

Table 1. Deterministic and simulation models outputs

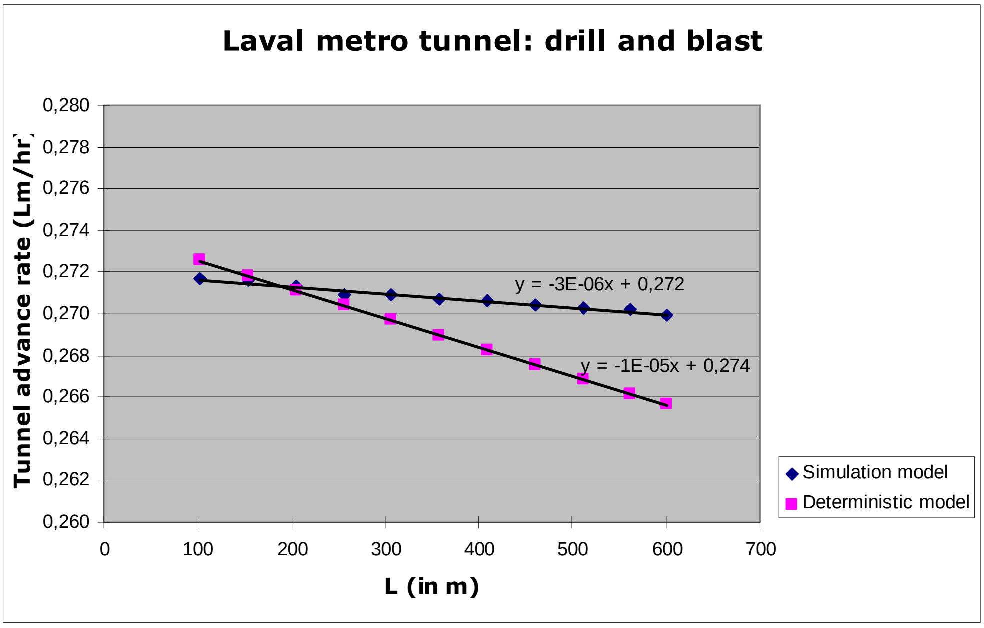

Figure 1. Comparison simulation and deterministic modelling results for Laval tunnel exc. by drill and blast

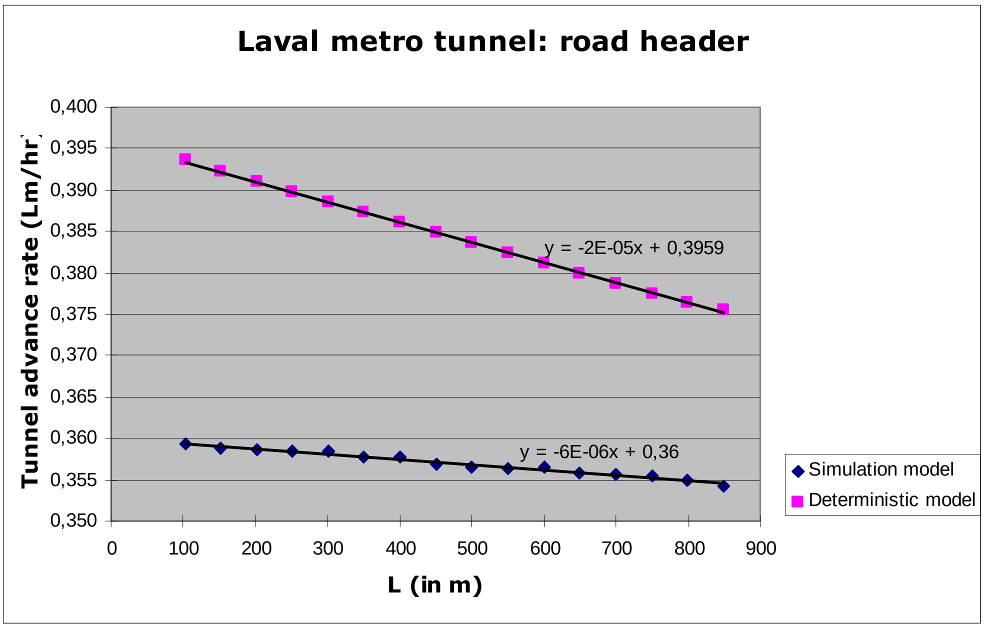

Figure 2. Comparison simulation and deterministic modelling results for Laval tunnel exc. by road header

The productivity equations determined by the deterministic and simulation models are different. There are mainly three reasons for the difference of the productivity equations determined by both modelling approaches.

- The time durations of the activities are modelled differently in both modelling approaches. In the deterministic model the time durations of activities are represented by fixed (average) values, without room for random variation. However, in the simulation models ranges of values for variables in the form of probability distributions are used. In this case the time durations of activities were modelled as (triangular) probability distributions;
- The complex movement of trucks in the materials handling processes is modelled differently in both types of modelling approaches. In contrast to the deterministic model, the simulation models considers queuing theory (mathematical study of waiting lines) to model for example the arrival at the queue of the trucks, this includes the average waiting time of trucks in the queue, and loading times of the trucks by the road header or loaders;
- In the deterministic model efficiency factors are included in the productivity equation. These efficiency factors are included to compensate for certain variables, such as 'downtime system', 'machine delays', 'maintenance time' and 'repair time'. In the simulation models only the increase of the cycle time due to problems with excavation equipment (such as drill jumbo and road header) is considered, and in contrast to the deterministic model, delay due to inefficiency of the materials handling processes, primary support processes and minor processes are not considered. The reason that these inefficiencies are not considered in the simulation models is that the direct causes of inefficiencies in these processes were not clear, and therefore could not be modelled.

7.2 Sensitivity analysis

Sensitivity analysis carried out in both the deterministic model and the simulation models of the Laval metro tunnel has shown the affect of tunnelling variables on the tunnel advance rate of the project. For the section of tunnel excavated by drill and blast the analysis has shown that the variables 'number of loaders', 'capacity of loaders' and 'excavation length' have the biggest impact on the tunnel advance rate. The sensitivity analysis has also shown that the variables 'number of trucks' and 'capacity of trucks' are less significant. Figure 4 in chapter 5 and figure 5 in chapter 6 show the results of the sensitivity analysis related to the Laval metro tunnel excavated by drill and blast.

For the section of tunnel excavated by road header, the sensitivity analysis has shown that the variables 'number of road headers' and 'penetration rate of road header' have the biggest impact on productivity. On the other hand, the variable 'excavation length' is of less importance compared to the drill and blast excavation method. The analysis also showed that the variables 'number of trucks' and 'capacity of trucks' have less significant impact on the tunnel advance rate. Figure 5 of chapter 5 and figure 6 of chapter 6 show the results of the sensitivity analysis related to the Laval metro tunnel excavated by road header.

Based on the results of the analysis, tunnelling construction managers would be able to evaluate the impact of decisions on the existing state of the tunnelling system and its output. It is useful to know what will happen if the magnitude of one of the controllable tunnelling variables is changed. The results of the sensitivity analysis can be used to make decisions regarding scheduling and planning of construction processes and resource allocation of tunnelling construction projects.

7.3 Advantages and limitations of modelling approaches

The advantage of using the proposed deterministic model is that it gives information about the average advance rate of a tunnelling project. The total time duration for the excavation of a tunnel with a certain length can be calculated using the deterministic model. The application of the model for this specific information is easier and less time consuming than the development of a simulation model.

In addition to deterministic models, simulation models using EZstrobe were used in this work to assess resource allocation based on productivity and cost. It is an effective method in order to assess the affect of certain resource combinations on the productivity and cost of the tunnelling project. Simulation is also an effective tool to model, analyze and compare different construction alternatives.

Using EZstrobe software, simulation models have produced graphical representations of the construction operations of the tunnelling project. They give an overview of the total construction processes involved in the project, the sequence of operations and the use of resources. In contrast to the deterministic model, simulation models are effective communication tools that can be used to improve understanding of the construction processes.

8. Conclusions and recommendations

8.1 Conclusions

In this research deterministic and probabilistic models using simulation were presented describing the behaviour of tunnelling construction. Using the deterministic model, several sensitivity analysis studies were performed. The affect of the following variables on the tunnel advance rate was assessed: number, capacity and speed of trains and trucks; number of muck and material cars per train; TBM and road header penetration rate; stroke length of TBM; number and capacity of loaders; number of road headers; number of cranes; and speed of crane system. Furthermore, the affect of the advance rate of primary support; swell factor of soil; cross section area of tunnel; excavated length per cycle; height of vertical shaft; and efficiency factors, on the tunnel advance rate was investigated. These variables all have a significant impact on the productivity of tunnelling construction.

By comparing the calculated productivity (in terms of tunnel advance rate) with the actual productivity of each case study, it was determined that the actual productivity of each case study was close to the productivity calculated by the deterministic model. The percentage of validity of the Laval metro tunnel is respectively 80% (tunnel excavated by road header) and 91% (tunnel excavated by drill and blast). The Bathurst & Langstaff tunnel has a validity percentage of 88%, and the Parramatta tunnel between 81% and 98%. Therefore, it is concluded in the researcher's belief, that the designated deterministic model is robust and can be used to determine the productivity of tunnelling construction projects, using different excavation methods and materials handling systems.

Subsequently, simulation models of the Laval metro tunnel project were developed. Using regression analysis, cycle time and productivity equations were determined, and a sensitivity analysis was performed on the tunnelling variables of the simulation models. The sensitivity analysis showed that the following variables affect the tunnel advance rate of tunnelling construction: number and capacity of trucks; number of road headers; road header penetration rate; number and productivity of loaders, number of drill jumbos, number of platform trucks, and number of excavators. Furthermore, the affect of the swell factor of soil; cross section area of tunnel; and excavated length per cycle, on the tunnel advance rate was investigated.

Using simulation, it is shown that a best allocation of resources can be determined based on productivity (Lm/hr) and cost ($/Lm). For both the tunnel section excavated by drill and blast, as well as the tunnel section excavated by road header, it is shown that multiple combinations of resources are feasible. Using the decision index method the best solution, from a set of feasible solutions was determined by optimizing both productivity and cost. Simulation was also used in order to compare the road header and drill and blast excavation methods based on productivity and cost. The comparison is made assuming a tunnel with certain tunnel dimensions (cross section area and tunnel length) and soil properties is excavated by both methods. The results showed that the road header excavation method achieves higher productivity (in Lm/hr) and a lower unit cost (in $/m) than the drill and blast excavation method. It is shown that simulation is an effective tool to model, analyze and compare different construction alternatives.

By comparing the calculated productivity with the actual productivity of the Laval metro tunnel project, the validity of the models was assessed. The percentage of validity of the Laval metro tunnel simulation models is respectively 86% for the tunnel excavated by road header, and 92% for the tunnel excavated by drill and blast. Therefore, it can be concluded that the developed simulation models are robust and can be used to determine the productivity of tunnelling construction projects of the same kind as the Laval metro tunnel (drill and blast and road header excavation).

Using the deterministic and simulation models it is shown that the tunnel advance rate is a function of the complex interaction between the excavation processes (drill and blast, TBM or road header), the materials handling processes, the primary support processes, ground conditions and tunnel dimensions.

8.2 Recommendations

There are a few recommendations to be made for future research purposes. First of all, the recommendations regarding the deterministic modelling study will be described. Subsequently recommendations regarding the simulation study will be examined, as well as a few general recommendations for future research work.

- The deterministic modelling study has focused primarily on the excavation and materials handling processes of tunnelling construction. Less attention was given to the primary support processes. For future research purposes, these processes may be investigated in greater detail. For example the affect of the resources (such as drill jumbos and platform trucks) used to perform the primary support processes (installation of rock bolts, wire mesh, ring beams, or installation of pre-cast liner segments), on the cycle time duration and tunnel advance rate may be investigated in greater depth.

- Assumptions were made, regarding the materials handling processes of the deterministic model. The deterministic model represents the real world tunnelling construction system accurately as long as one truck or one train is used in the materials handling system. For future research purposes, the materials handling processes concerning the use of multiple trucks or trains in confined tunnels may be modelled with greater care. The complex movement of trucks or trains in real world tunnelling projects may be modelled more accurately.

- Regarding the deterministic modelling, it was assumed that the (influence) factors affecting the productivity all have the same weight when applied to the productivity equations. The value 1 is given to these factors assuming that tunnelling construction in the ideal situation is modelled (hence, none of these factors will affect the productivity of tunnelling construction negatively). These factors are: 'operator's experience', 'soil condition', 'job and management condition', 'site condition', 'tunnel alignment', 'machine condition' and 'shift type'. It may be obvious that some of these factors have a bigger impact on productivity than others. From data collection (nine interviews with tunnelling construction experts) data was gathered concerning the importance of each factor compared to each other. In order to assign relative weights to each productivity factor, a paired comparison analysis was performed. In order to quantify the relative importance of these factors to each other, and assign a valid weight to each individual factor, it is necessary to perform a thorough study and data collection. The impact of these (influence) factors on the productivity equation may also be quantified.

- In the simulation study of the Laval metro tunnel time durations of activities were assumed to be triangular distributed. The minimum, most probable and maximum value of the triangular distribution was decided based on the construction manager's knowledge. For future research purposes, the time durations of the activities may be modelled by probability distributions, based on data collected of actual time durations of activities on site. By collecting a certain amount of time duration figures per activity, a more suitable probability distribution may be assigned to the various operations of tunnelling construction projects.

- Simulation modelling was only applied to the case study of the Laval metro tunnel project. As already mentioned in this research, this project covers the road header and drill and blast excavation methods, in combination with a rubber-mounted materials handling system. Also TBM tunnelling using rail-mounted materials handling system may be simulated and analyzed using EZstrobe. In appendix XII the EZstrobe simulation model of the Bathurst & Langstaff sewer tunnel project is described. For future research purposes, this case study may be used for the analysis of TBM tunnelling construction in combination with rail-mounted materials handling system.

- In this research, the road header and drill and blast excavation methods were compared to each other based on productivity and cost. For future research considerations, also TBM tunnelling may be added in the comparison. The differences between the three excavation methods based on productivity of tunnelling and cost may be analyzed. For future research purposes, the same kind of comparison may also be performed on the materials handling systems that are used in contemporary tunnelling. As described in chapter two of this thesis, the most common materials handling systems are: rubber-mounted system, rail-mounted system and belt-conveyor system. Assuming that a tunnel is excavated by a certain excavation method, by comparing these three materials handling system to each other based on productivity and cost, conclusions may be drawn on the most suitable type of materials handling system to be used under certain circumstances.

- This study focuses primarily on the tunnelling construction processes concerned with the excavation of the horizontal tunnel. No attention is given to the other aspects of tunnelling construction, such as the construction of the vertical shaft of the tunnel, and the final lining of the tunnel to be performed after completion of tunnel excavation. For future research purposes these construction processes also may be investigated and analyzed by means of deterministic or simulation modelling.

- Deterministic and simulation modelling is especially useful to describe and analyze construction projects that consist of repetitive construction cycles. For future research purposes, also other types of repetitive projects, such as: the construction of highways, airport runways, railways, bridges, high-rise buildings, pipelines and mass transit systems, may be modelled and analyzed by means of deterministic or simulation modelling.

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Appendix I: Model's input variables

General tunnelling variables

Resources

- Stroke length TBM (m/cycle)
- Dimensions of tunnel
- Swell factor of soil
- Working hours project (hr/day)
- Amount of lining material needed for lining x meter of tunnel
- Amount of man-hours used in excavation process
- Amount of man-hours used in lining process

Activities

- Excavation: penetration rate (m/hr)
- Primary support of tunnel: advance rate (m/hr)
- Time duration of 'drilling', 'loading explosives' and 'blasting'
- Placement and displacement time road header or drill jumbo
- Startup and reset times of TBM
- Surveying time duration
- Mechanical and manual scaling time duration
- Extending air and water lines time duration

Rail-mounted systems

Resources

- Number of trains
- Number of cars per train
- Capacity of cars (m^3)
- Speed of train (m/s)
- Capacity loaders (m3/hr)
- Amount of man-hours for extend services and rail tracks
- Amount of man-hours used to load muck into cars
- Amount of man-hoursl used to load material into car at shaft

Activities

- Time duration of maneuvring truck or train at face tunnel
- Loading muck into cars: loading times
- Transportation muck to tunnel shaft: transfer times
- Dump muck at shaft of tunnel: unloading times
- Returning empty muck cars to face of tunnel: transfer times
- Loading lining material at shaft: loading times
- Lining material/rail tracks to face tunnel: transfer times
- Deposit liner material/rail tracks at face of tunnel:loading times
- Returning empty material cars to shaft: transfer times
- Extend services and rail tracks: completion times

Figure 1. Input variables general tunnelling variables and rail-mounted system

Rubber-mounted systems

Resources
- Number of trucks
- Capacity of trucks (m^3)
- Speed of trucks (m/s)
- Capacity loaders (m^3/hr)
- Amount of man-hours used to load muck into cars
- Amount of man-hours used to load material into cars at shaft

Activities
- Time duration of maneuvring truck or train at face tunnel
- Loading muck into truck: loading times
- Transportation muck to tunnel shaft: transfer times
- Dump muck at shaft of tunnel: unloading times
- Returning empty trucks to face of tunnel: transfer time
- Loading lining material at shaft: loading times
- Transportation of lining material to face tunnel: transfer times
- Deposit liner material at face of tunnel: loading times
- Returning empty trucks to shaft: transfer times

Belt-conveyor

Resources
- Capacity of belt-conveyor (m^3/hr)
- Speed of belt-conveyor (m/s)
- Length of belt-conveyor (m)
- Amount of man-hours used to load muck on belt-conveyor

Activities
- Loading muck on belt-conveyor: loading times
- Transportation muck to tunnel shaft: transfer times

Figure 2. Input variables rubber-mounted system and belt conveyor

Vertical materials handling

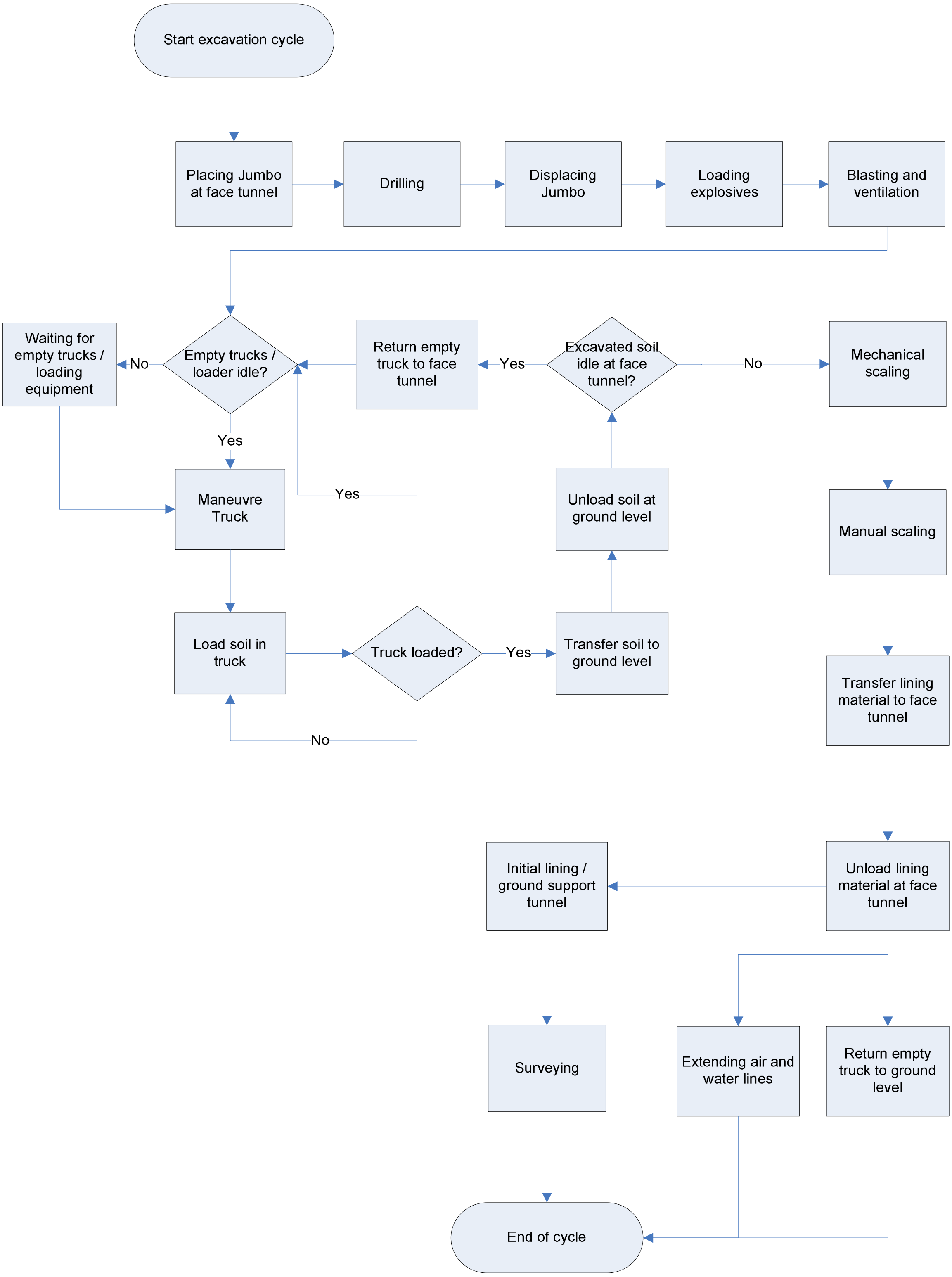
Resources
- Capacity of skip, bucket, crane etc. (m^3)
- Number of cranes
- Capacity Loaders (m^3/hr)
- Height of shaft (m)
- Speed of hoisting system (m/s)
- Amount of man-hours involved at shaft
- Amount of man-hours involved at ground level

Activities
- Loading muck on system: loading time
- Hoisting muck from shaft to ground level: transfer time
- Unload muck at ground level: unloading time
- Loading materials and personnel at ground level: loading time
- Transporting material from ground level to shaft: transfer time
- Unload material at ground level: unload time

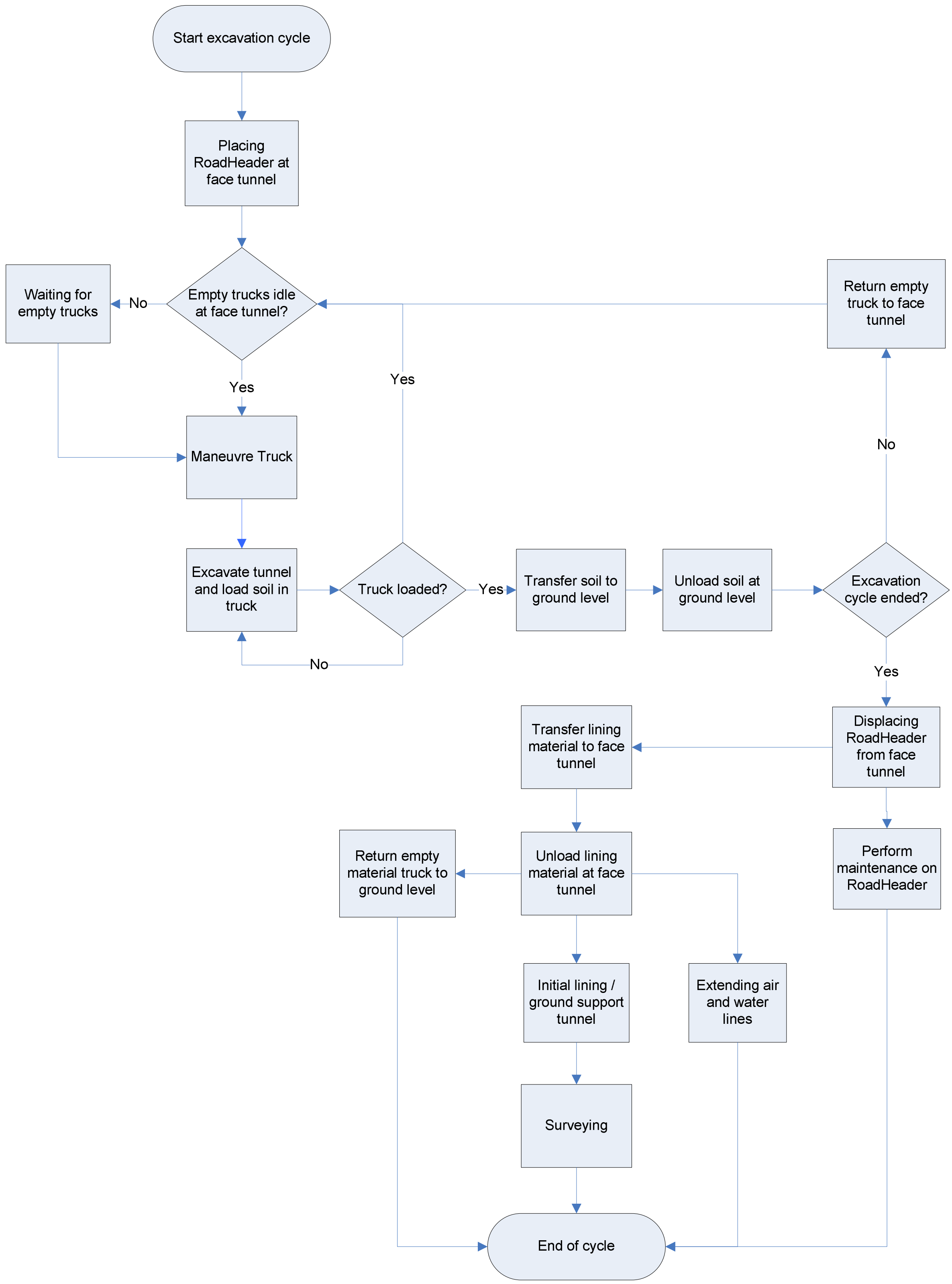
Figure 3. Input variables vertical materials handling

Appendix II: Flowcharts tunnelling projects

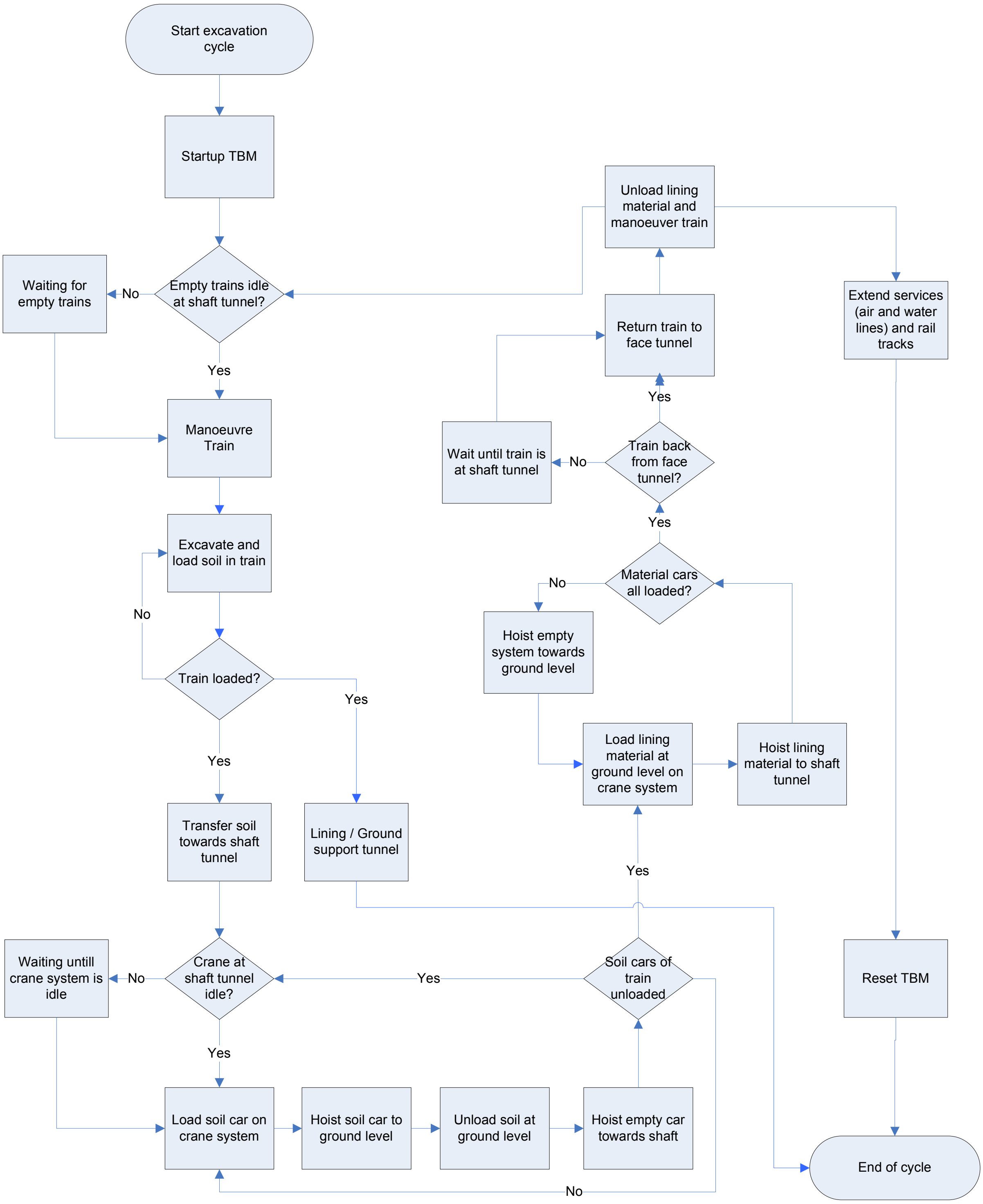
Laval metro tunnel project: drill and blast excavation



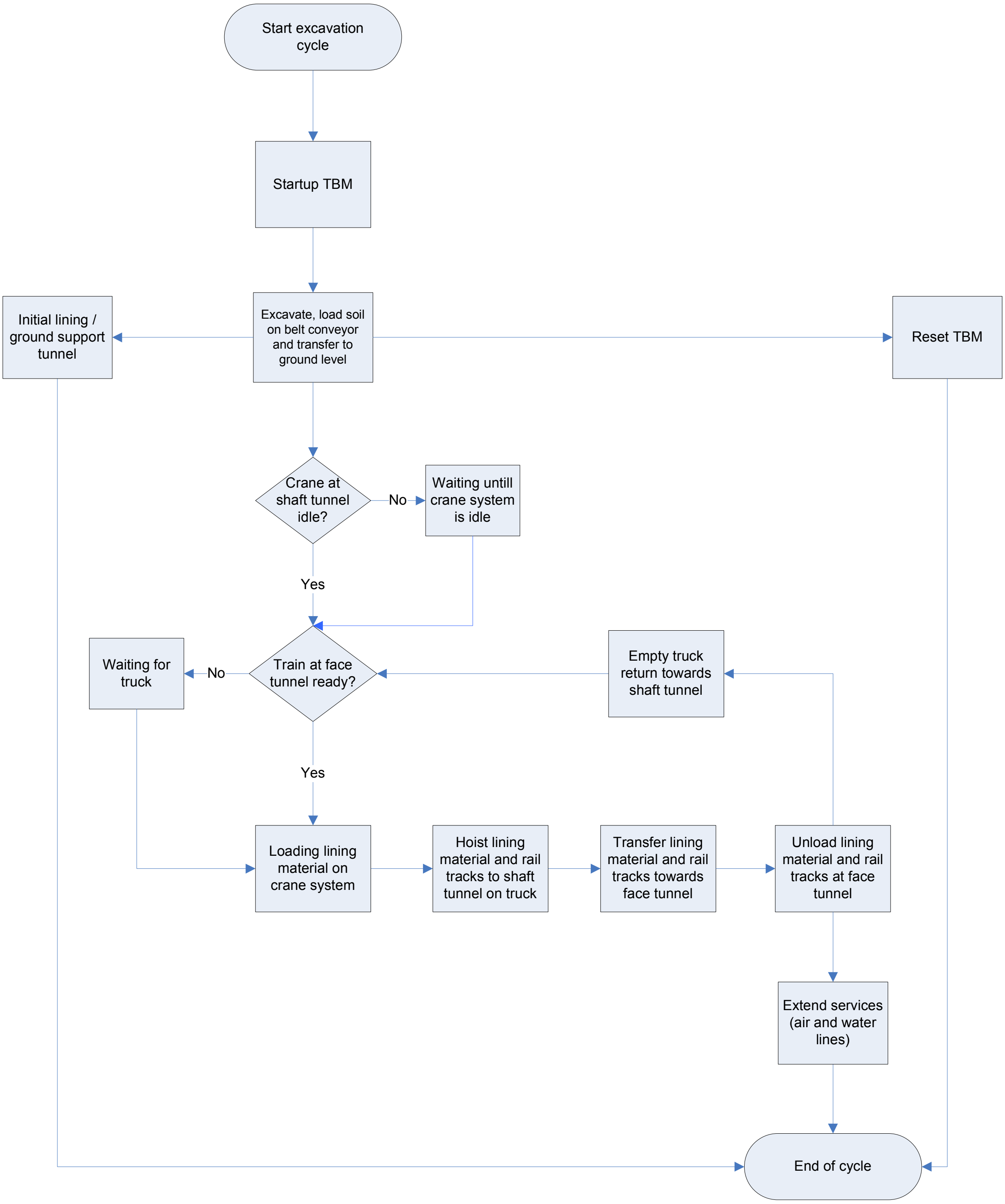
Laval metro tunnel project: Road header excavation



Bathurst & Langstaff sewer tunnel project



Parramatta rail link tunnel project



Appendix III: Sensitivity analysis Laval metro tunnel

Trucks properties

Several simulation runs are performed by changing the number of trucks (capacity of 11 m^3) used to transport the muck from the face of the tunnel to the disposal area outside of the tunnel. The travel time of the trucks depend on the distance (L) between the face of the tunnel and the disposal area. In figure 1 and figure 2 of appendix IV the graphs are presented showing the relationship between the distance (L) and the tunnel advance rate, in relation to the number of trucks. The average tunnel advance rate per option is used to develop the graph showing the relationship between number of trucks and tunnel advance rate (figure 1). The tunnel advance rate increases by increasing the number of trucks until the number of trucks reaches 5 for road header, and 5 for drill and blast excavation.

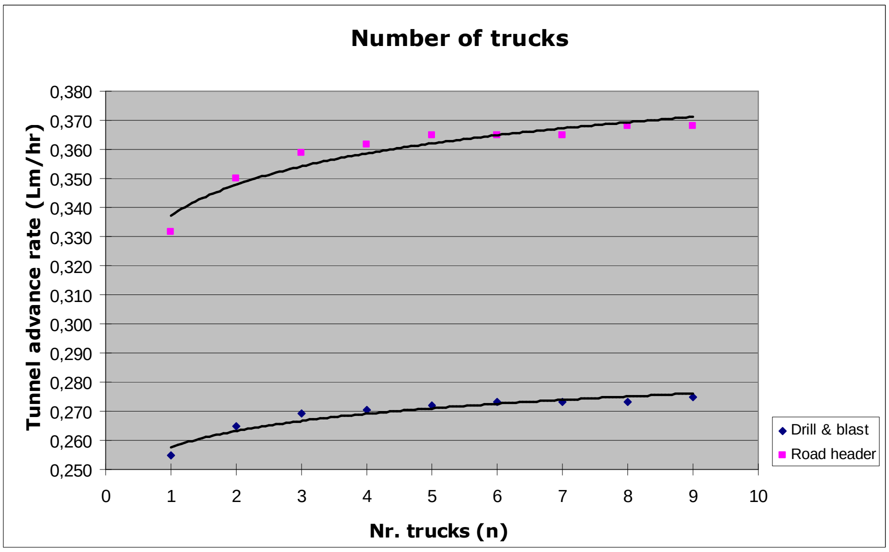


Figure 1. Sensitivity analysis on number of trucks with capacity of 11 m^3

Same type of analysis is also performed on the capacity and the speed of the trucks. In figure 3 and 4 (capacity trucks), and figure 5 and 6 (speed trucks) of appendix IV the graphs are presented showing the relationship between the distance (L) and the tunnel advance rate, in relation to the capacity and speed of the trucks. The average tunnel advance rate per option is used to develop the graph showing the relationship of respectively the capacity of trucks and speed of trucks, and tunnel advance rate (figure 2 and figure 3). The tunnel advance rate increases significantly by increasing the capacity of the trucks until the capacity reaches approximately 11 m^3 for the tunnel excavated by drill and blast. For the tunnel excavated by road header the tunnel advance rate increases significantly by increasing the capacity of the trucks until it reaches approximately 13 m^3.

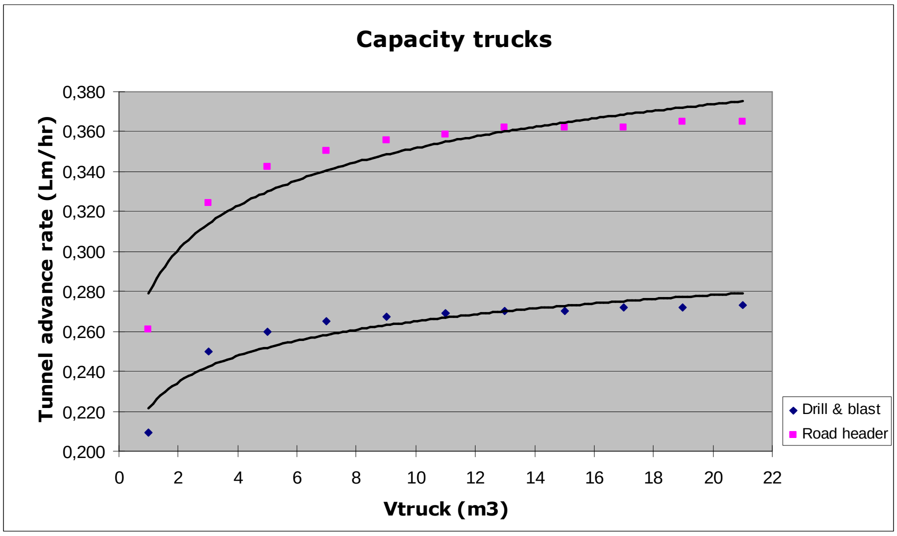


Figure 2. Sensitivity analysis on capacity of trucks

There is also a relationship between speed of the trucks and the tunnel advance rate. Although this relationship is less significant, the tunnel advance rate increases by increasing the speed of trucks until it reaches approximately 30-35 km/hr, for the tunnels constructed by both types of excavation methods.

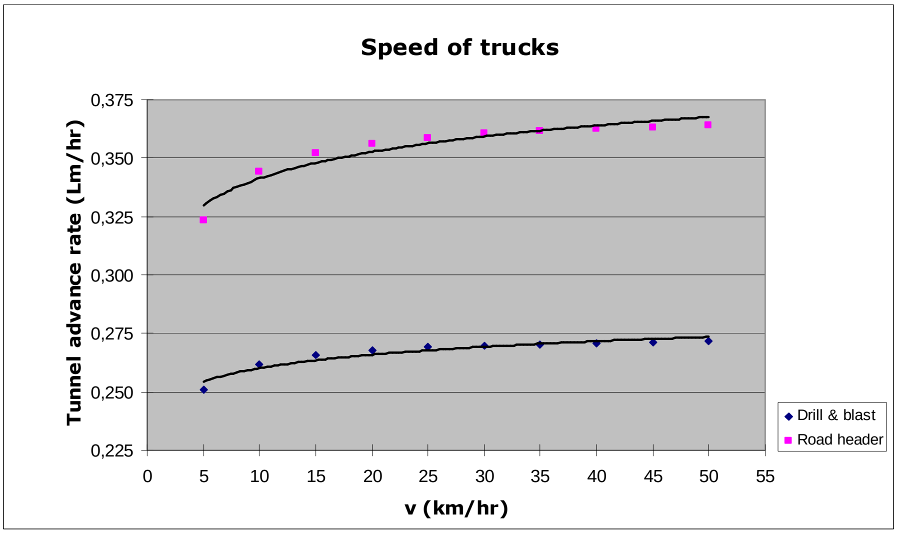


Figure 3. Sensitivity analysis on speed of trucks

Primary support advance rate

Figure 4 shows the relationship between the primary support advance rate and the tunnel advance rate. The tunnel advance rate increases significantly by increasing the primary support advance rate until the advance rate reaches approximately 6.0 m/hr.

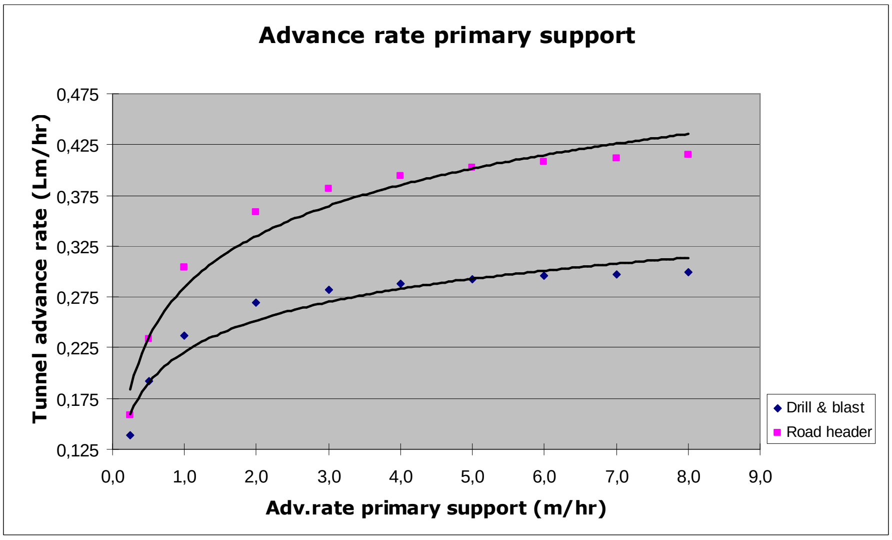


Figure 4. Sensitivity analysis on advance rate of primary support activities

Tunnel dimensions and swell factor soil

In figure 7 and 8 of appendix IV, the graphs are presented showing the relationship between the distance (L) and the tunnel advance rate, in relation to swell factor of the soil. The average tunnel advance rate per option is used to obtain the graph of figure 5. The figure shows that the tunnel advance rate decreases significantly by increasing the swell factor of the soil. Bigger swell factor means more volume of muck excavated, increasing the cycle time of the materials handling processes. This relationship is much more significant for the tunnel excavated by drill and blast than for the tunnel excavated by road header.

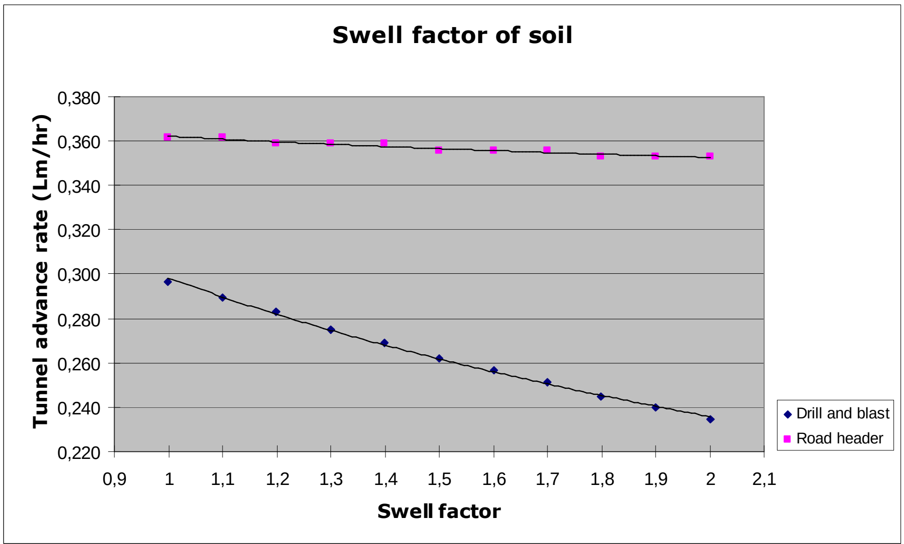


Figure 5. Sensitivity analysis on swell factor of soil

There is a difference in rate of change in the slope of the lines. For the tunnel excavated by road header, it is assumed that the calculated productivity (m^3/hr) increases as swell factor of the soil increases. Higher productivity of the road header leads to decreasing time duration for loading the trucks with excavated soil. Hence, the reason that the relationship between the swell factor and the tunnel advance rate is less significant compared with drill and blast excavation, is that on one hand the trucks need to make more runs to dispose the excavated soil, but on the other hand the time duration of filling one truck decreases. So, the cycle time of the construction process remains more constant as swell factor increases, compared to the tunnel excavated by drill and blast.

In figure 9 and figure 10 of appendix IV the graphs are presented showing the relationship between the distance (L) and the tunnel advance rate, in relation to the cross section area of the tunnel. The average tunnel advance rate per option is used to develop the graph showing the relationship of the cross section area of the tunnel and tunnel advance rate (figure 6). Assuming the time durations of the excavation activities (for drill and blast excavation) remain constant, the tunnel advance rate decreases significantly by increasing the cross section of the tunnel. For the section of tunnel excavated by road header it is assumed that the productivity of the road header (volume of muck excavated per hr in m^3/hr) stays constant, because the penetration rate is inversely proportional to the cross section area of the tunnel. If the surface area of the face of the tunnel increases with a certain rate, the penetration rate decreases with the same rate.

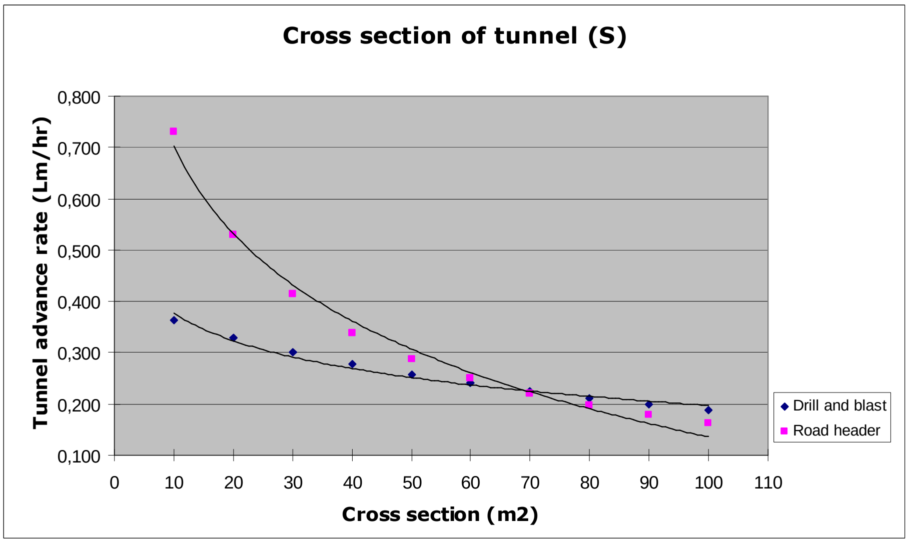


Figure 6. Sensitivity analysis on surface area of face of the tunnel

Larger cross section of the tunnel results in more volume of muck excavated, increasing the time durations of the soil disposal activities, resulting in decreasing tunnel advance rates. The relationship between cross section and tunnel advance rate is much more significant for the tunnel excavated by road header than for the tunnel excavated by drill and blast.

Laval metro tunnel project: drill and blast

Excavation length per cycle

Figure 7 shows the relationship between excavation length per cycle (L_j), and the tunnel advance rate. In figure 11 of appendix IV the graph is presented showing the relationship between the distance (L) and the tunnel advance rate, in relation to the excavation length per cycle. The average tunnel advance rate per option is used to obtain the graph of figure 7. The excavation length per cycle is the amount of meters of tunnel that is excavated (blasted) per excavation cycle. As the length of excavated tunnel increases also the time duration of the scaling and primary support (lining) activities increase. Assuming that the relationship between the time durations of these activities and the length of excavated tunnel is linear, the graph shows that the tunnel advance rate increases significantly by increasing the amount of meters excavated (by drill and blast) per cycle.

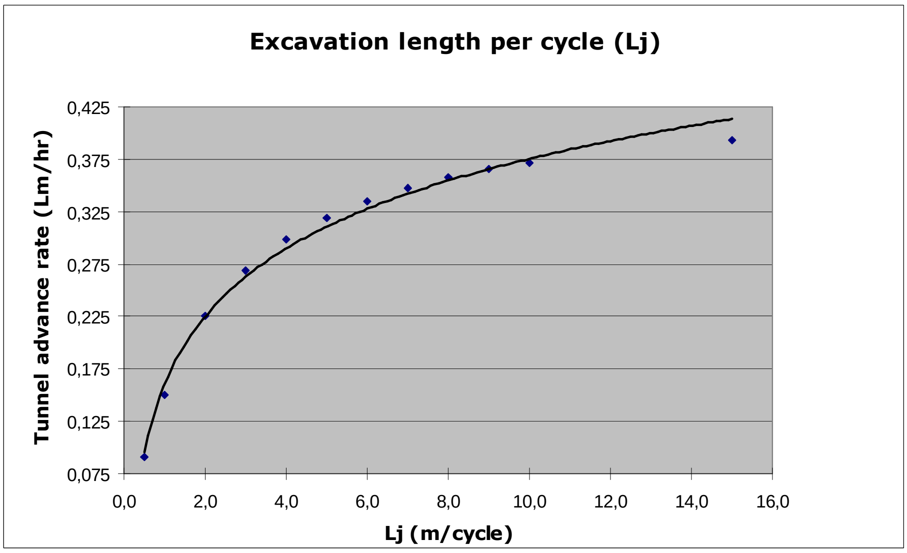


Figure 7. Sensitivity analysis on excavation length per cycle of drill and blast excavation

Loaders

In figure 12 and figure 13 of appendix IV the graphs are presented showing the relationship between the distance (L) and the tunnel advance rate, in relation to the number and productivity of loaders. The average tunnel advance rate is used to obtain the graph showing the relationship of respectively the number and productivity of loaders, and tunnel advance rate (figure 8 and figure 9). The tunnel advance rate increases significantly by increasing the number of loaders. Regarding the deterministic model it is assumed that there is only space for one truck at a time to manoeuvre and get loaded by a loader, at the face of the tunnel. Therefore, if multiple loaders are put into use, it is assumed that these loaders together load one truck at a time. It should also be mentioned that it is assumed in the sensitivity analysis that it may be possible to put into use 8 loaders inside the tunnel. In practice, because of the limited space inside the tunnel, no more than 2 loaders can load simultaneously one truck at the face of the tunnel.

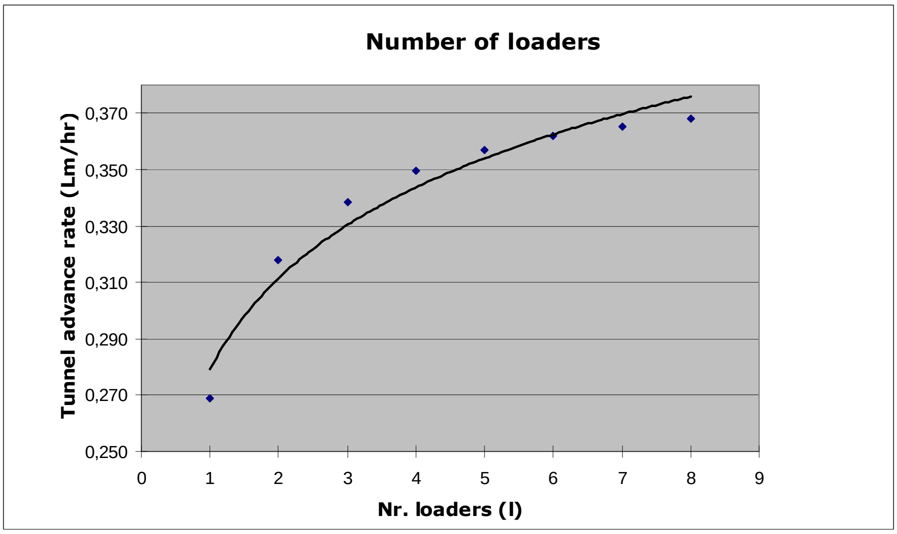


Figure 8. Sensitivity analysis on number of loaders

There is also a relationship between the productivity of the loaders and the tunnel advance rate. Figure 9 shows that the tunnel advance rate increases by increasing the productivity of the loaders.

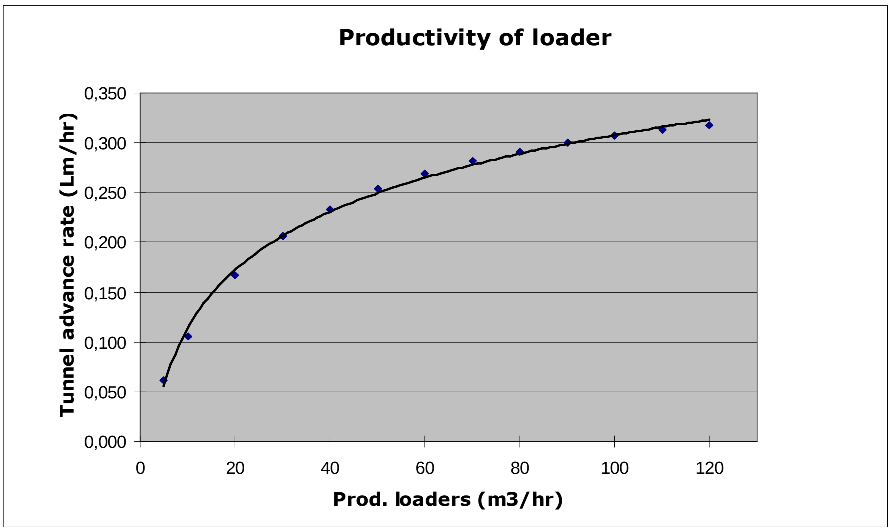


Figure 9. Sensitivity analysis on productivity of loaders

Efficiency factors

Figure 10 shows the relationship between the efficiency factors (U_1, U_2, U_3 and U_4) and the tunnel advance rate. The tunnel advance rate increases significantly by increasing the efficiency of all four efficiency factors (U_1, U_2, U_3 and U_4). The graph shows that it is important to model the efficiency of the excavation processes (U_1) and the efficiency of the materials handling processes (U_3) with greater care as they have a bigger impact on the tunnel advance rate than the other two factors. The efficiency of primary support processes (U_2) has a minor affect on the tunnel advance rate compared with the others.

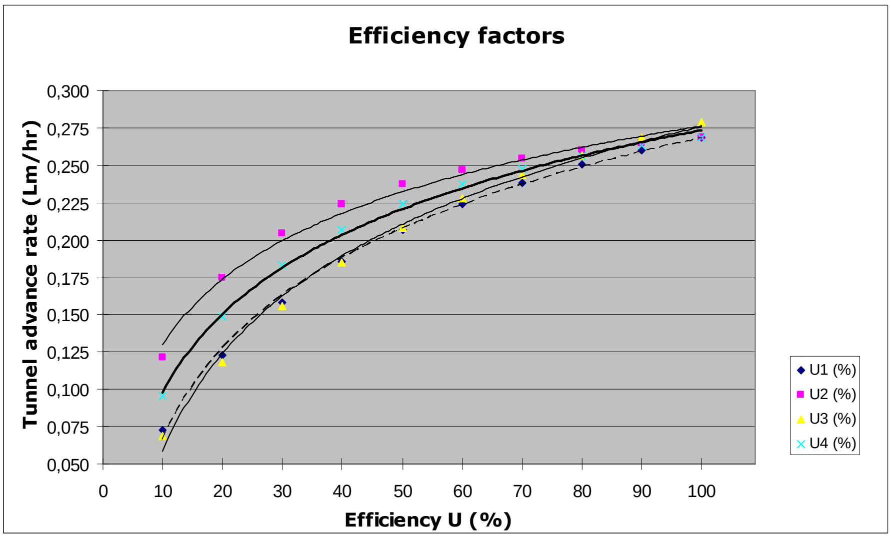


Figure 10. Sensitivity analysis on efficiency factors of drill and blast excavation

Laval metro tunnel project: road header

Excavation length per cycle

Figure 11 shows the relationship between excavation length per cycle (Lm/cycle), and the tunnel advance rate. In figure 14 of appendix IV the graph is presented showing the relationship between the distance (L) and the tunnel advance rate, in relation to the excavation length per cycle. The average tunnel advance rate per option is used to obtain the graph of figure 11. The excavation length per cycle is the amount of meters excavated by the road header per cycle. As the length of excavated tunnel increases it is assumed that the time duration of the primary support activities increase. Assuming that the relationship between the time durations of this activity and length of excavated tunnel is linear, the graph shows that the tunnel advance rate increases significantly by increasing the amount of meters excavated per cycle, until the excavation length reaches approximately 10 meters per cycle.

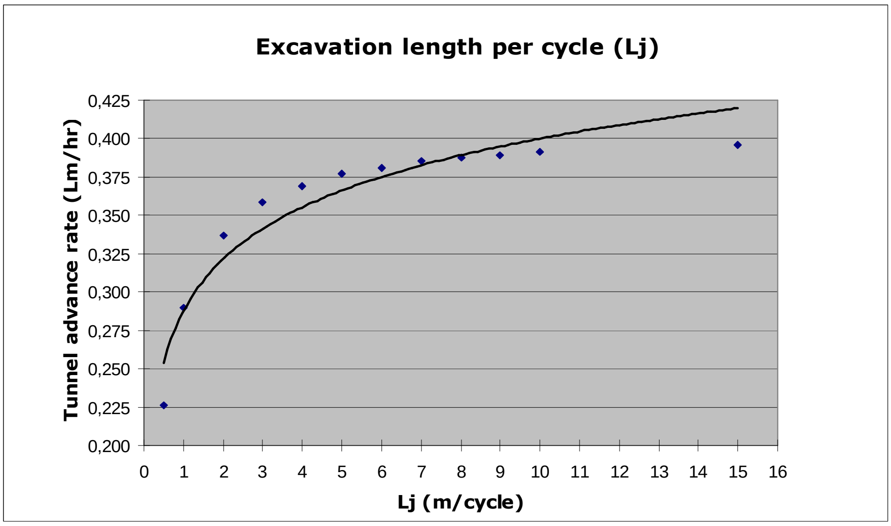


Figure 11. Sensitivity analysis on excavation length per cycle

In figure 12 the relationship between the excavation length per cycle and the tunnel advance rate is shown, in relation to the number of trucks. The figure shows that besides the chosen excavation length per cycle, the tunnel advance rate is also limited by the materials handling considerations (number of trucks that are in use: n). This trend is more significant as the excavation length per cycle increases. So if it is chosen to increase the excavation length per cycle in the Laval metro tunnel project, it is also necessary to put into service extra trucks (until the number of trucks reaches 6), in order to significantly increase the tunnel advance rate.

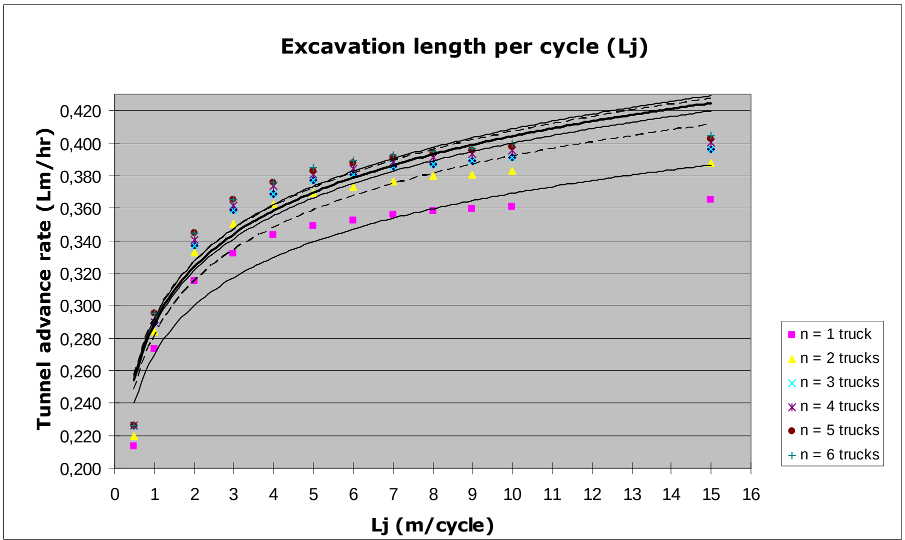


Figure 12. Sensitivity analysis on excavation length per cycle, in relation to the number of trucks

Road header excavator

Several simulation runs are performed by changing the number of road headers used to excavate the tunnel and load the soil trucks. In figure 15 of appendix IV the graph is presented showing the relationship between the distance (L) and the tunnel advance rate, in relation to the number of road headers. The average tunnel advance rate per option is used to obtain the graph showing the relationship of number of trucks and tunnel advance rate (figure 13). The figure shows that the tunnel advance rate increases significantly by increasing the number of road headers used during excavation. However, it should be noticed that having many road headers at he face of the tunnel could be impractical, unsafe and economically unfeasible.

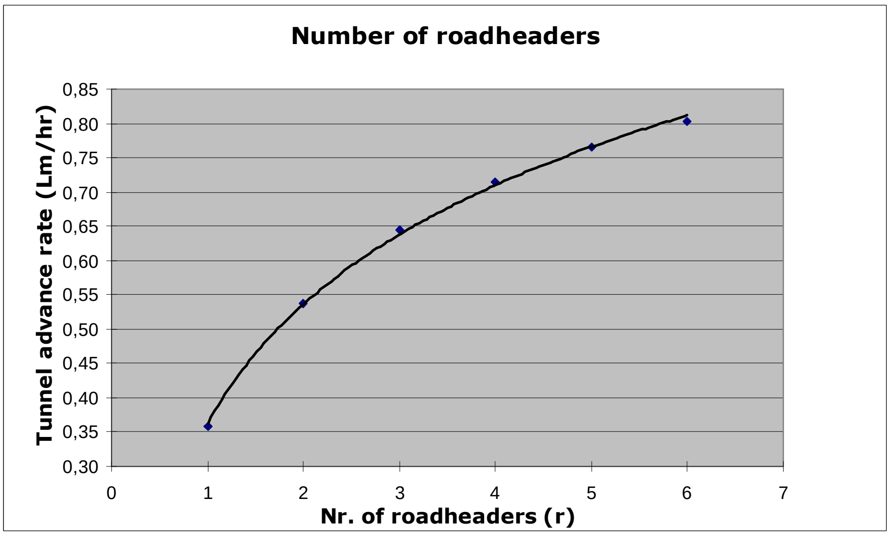


Figure 13. Sensitivity analysis on number of road headers

Regarding the deterministic model, it is assumed that there is space for only one truck at a time to manoeuvre at the face of the tunnel, and get loaded by a road header. Therefore, if multiple road headers are put into use, it is assumed that these road headers together load one truck at a time.

Figure 14 shows the relationship between the penetration rate of the road header (Lm/hr), and the tunnel advance rate. In figure 16 of appendix IV the graph is presented showing the relationship between the distance (L) and the tunnel advance rate, in relation to the penetration rate. The average tunnel advance rate per option is used to develop the graph showing the relationship between penetration rate and tunnel advance rate (figure 14). The tunnel advance rate increases significantly by increasing the penetration rate of the road header machine. This factor has a significant affect on the tunnel advance rate of tunnelling construction, and hence needs to be modelled with great care.

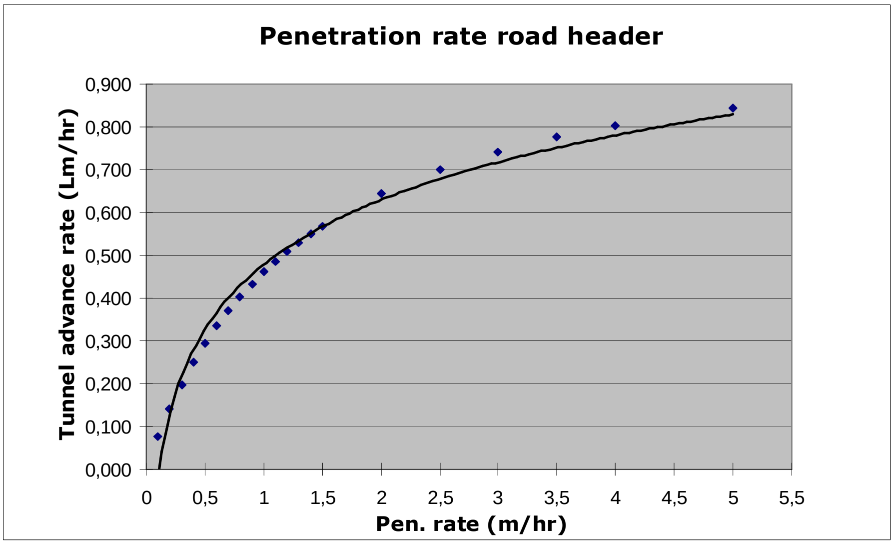


Figure 14. Sensitivity analysis on penetration rate of the road header machine

In figure 15 another set of values for the penetration rate is used to asses the relationship between the penetration rate and tunnel advance rate, in relation to the number of trucks. The figure shows that besides the road header capacity, the tunnel advance rate is also limited by the materials handling considerations (number of trucks that are in use: n). This trend is more significant as penetration rate increases. So, as the penetration rate increases, it is also necessary to put into service extra trucks (until the number of trucks reaches 5), in order to significantly increase the tunnel advance rate.

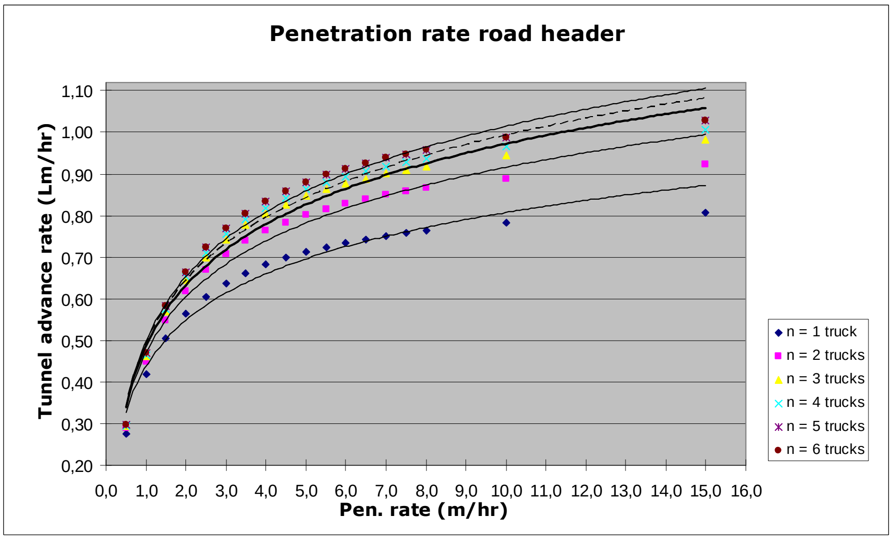


Figure 15. Sensitivity analysis on penetration rate of the road header machine

Efficiency factors

Figure 16 shows the relationship between the efficiency factors (U_1, U_2, U_3 and U_4) and the tunnel advance rate. The tunnel advance rate increases significantly by increasing the efficiency of all four efficiency factors (U_1, U_2, U_3 and U_4). The graph shows that it is important to model the efficiency of the excavation processes (U_1) with greater care as it affects the tunnel advance rate more significantly than the other factors. The efficiency of minor processes (U_4) and the efficiency of the materials handling processes (U_3) have a minor affect on the tunnel advance rate compared with the others.

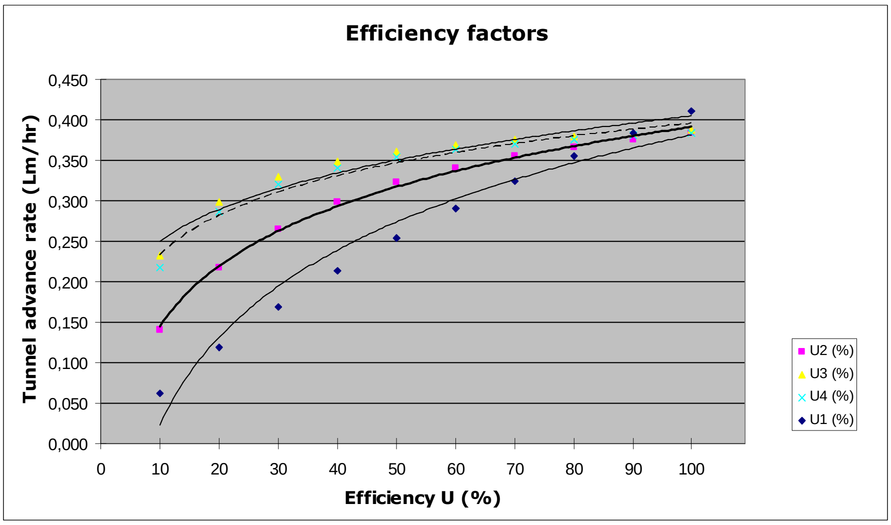


Figure 16. Sensitivity analysis on efficiency factors of road header excavation

Appendix IV: Sensitivity analysis Laval metro tunnel

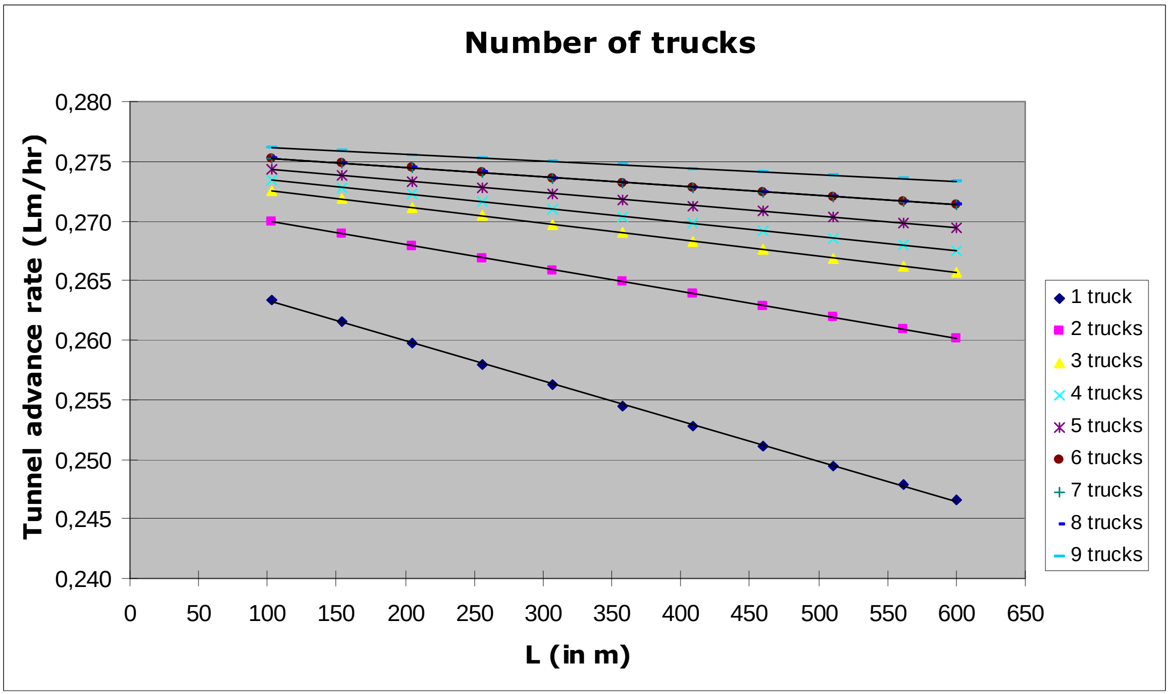


Figure 1. Sensitivity analysis on number of trucks (tunnel excavated by drill and blast)

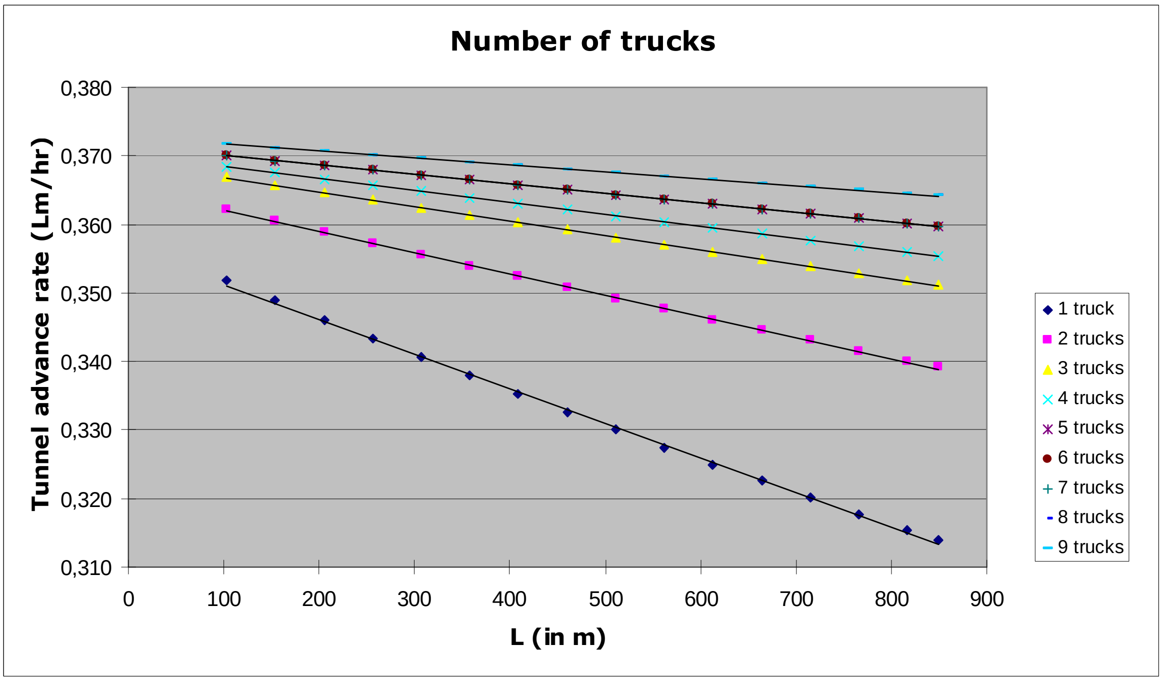


Figure 2. Sensitivity analysis on the number of trucks (tunnel excavated by road header)

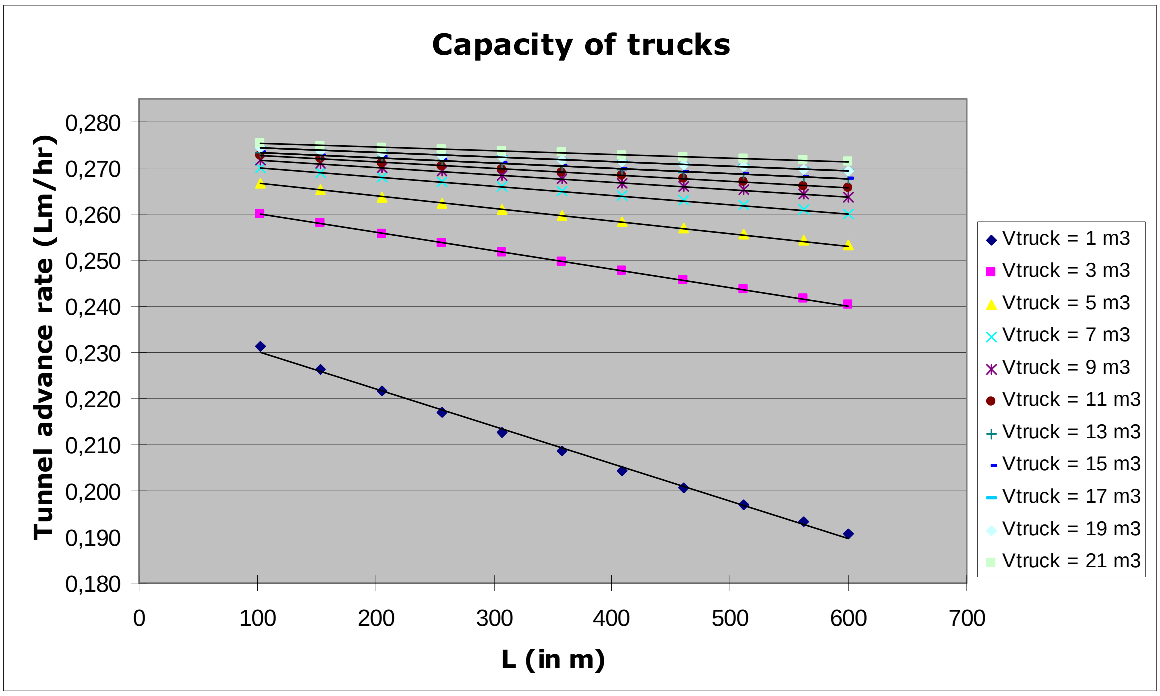


Figure 3. Sensitivity analysis on capacity of trucks (tunnel excavated by drill and blast)

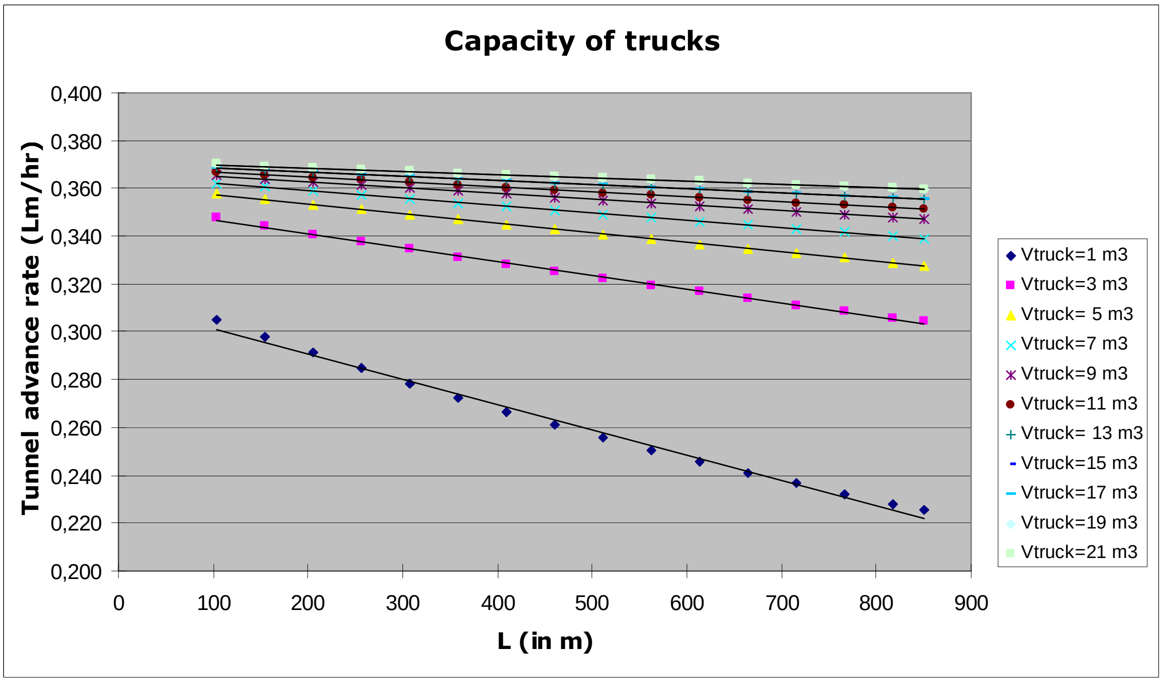


Figure 4. Sensitivity analysis on the capacity of trucks (tunnel excavated by road header)

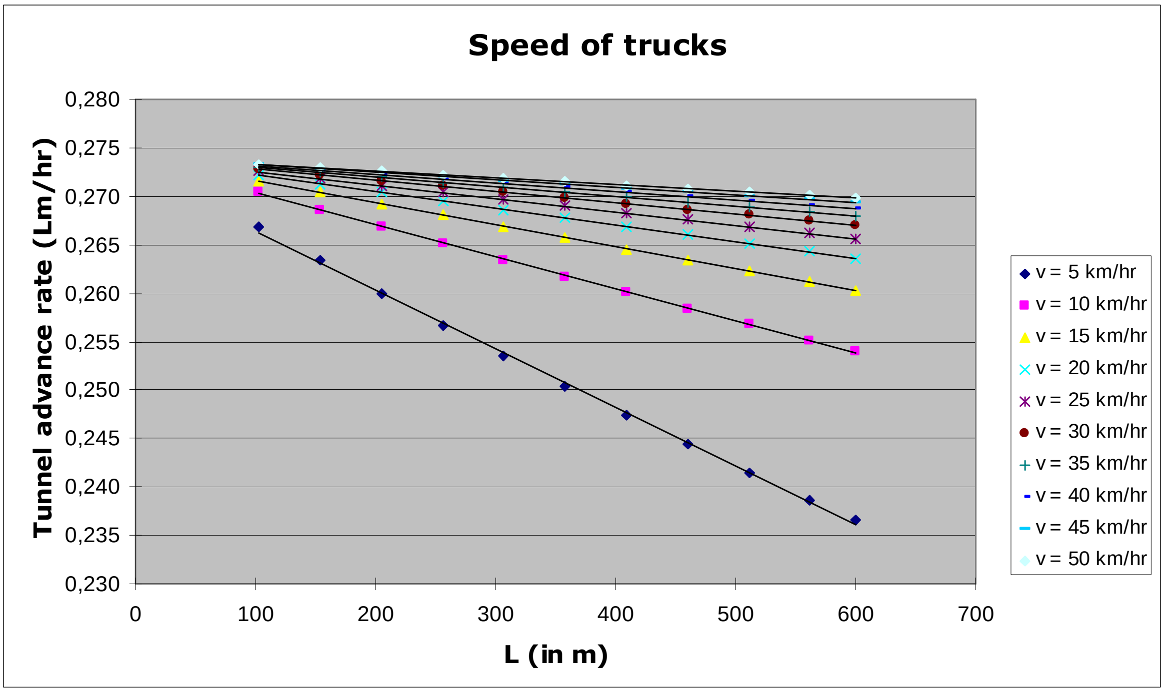


Figure 5. Sensitivity analysis on speed of trucks (drill and blast excavation)

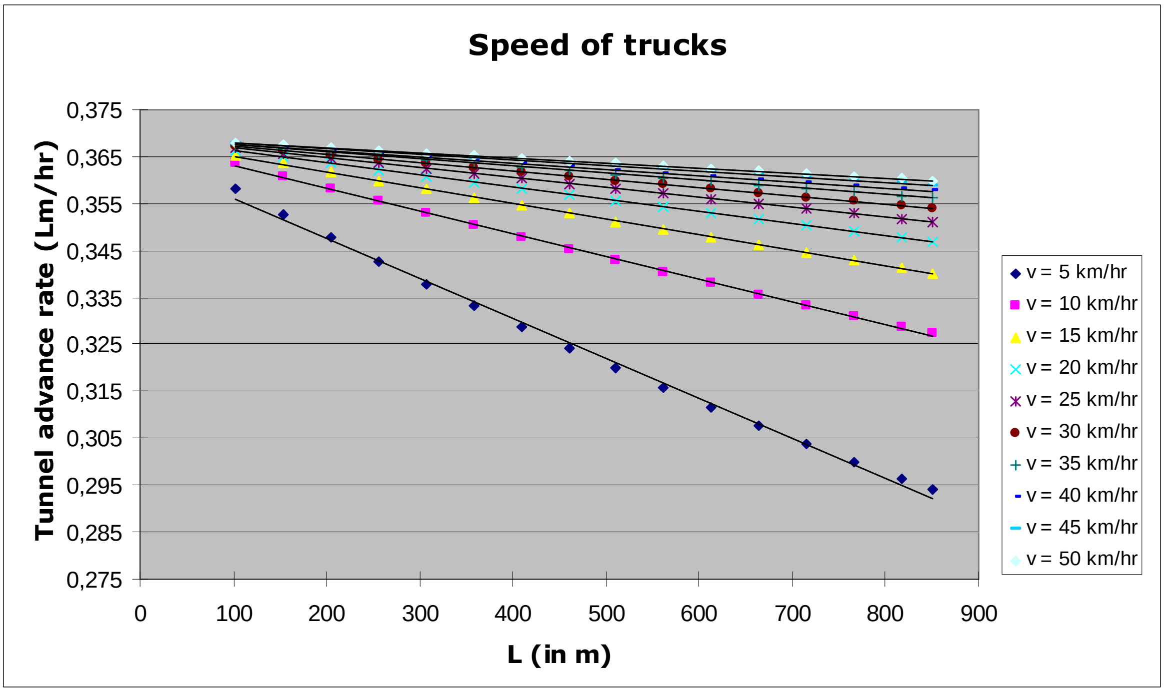


Figure 6. Sensitivity analysis on speed of trucks (road header excavation)

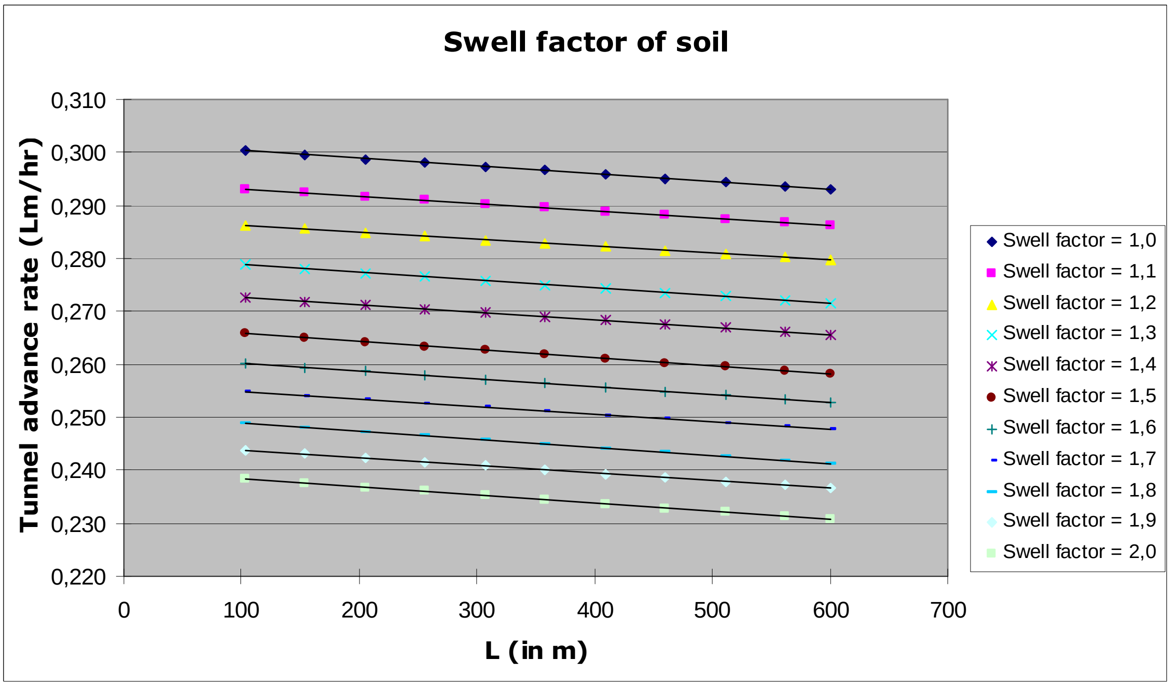


Figure 7. Sensitivity analysis on swell factor of the soil (drill and blast excavation)

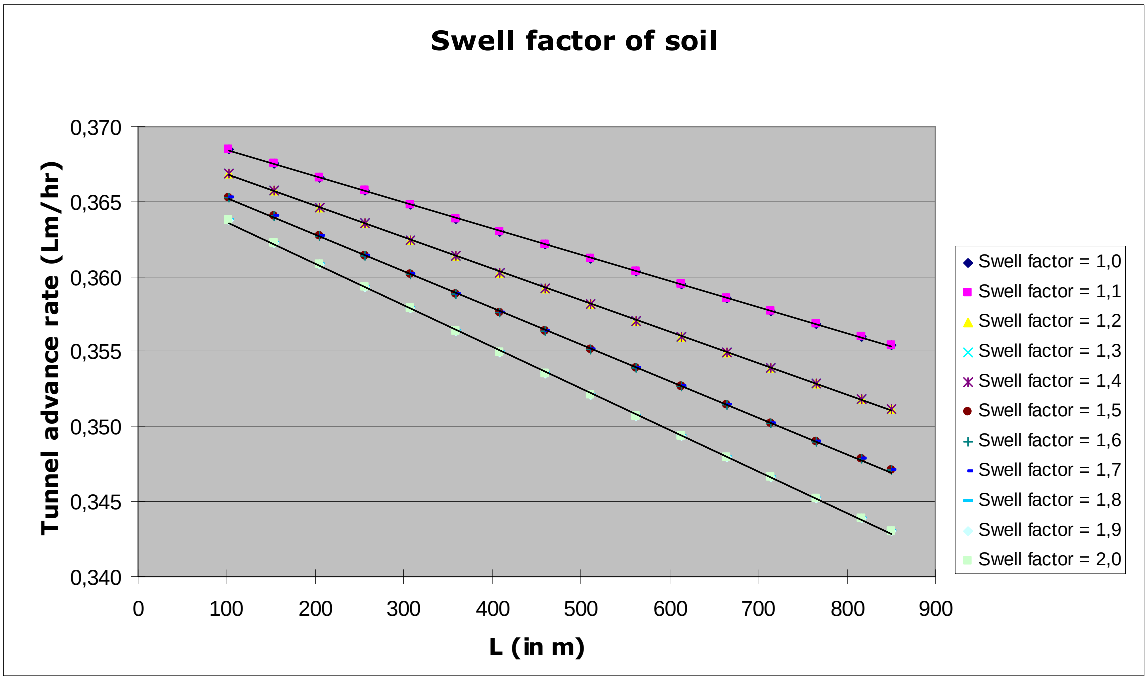


Figure 8. Sensitivity analysis on swell factor of the soil (road header excavation)

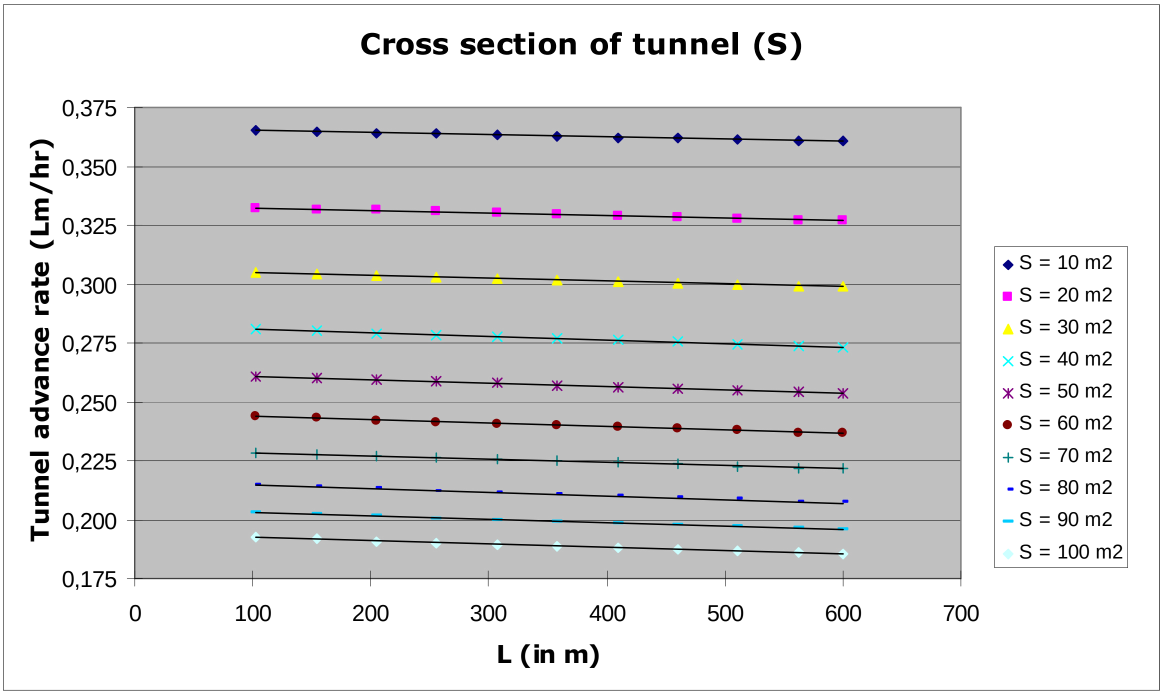


Figure 9. Sensitivity analysis on the surface area of the face of the tunnel (drill and blast excavation)

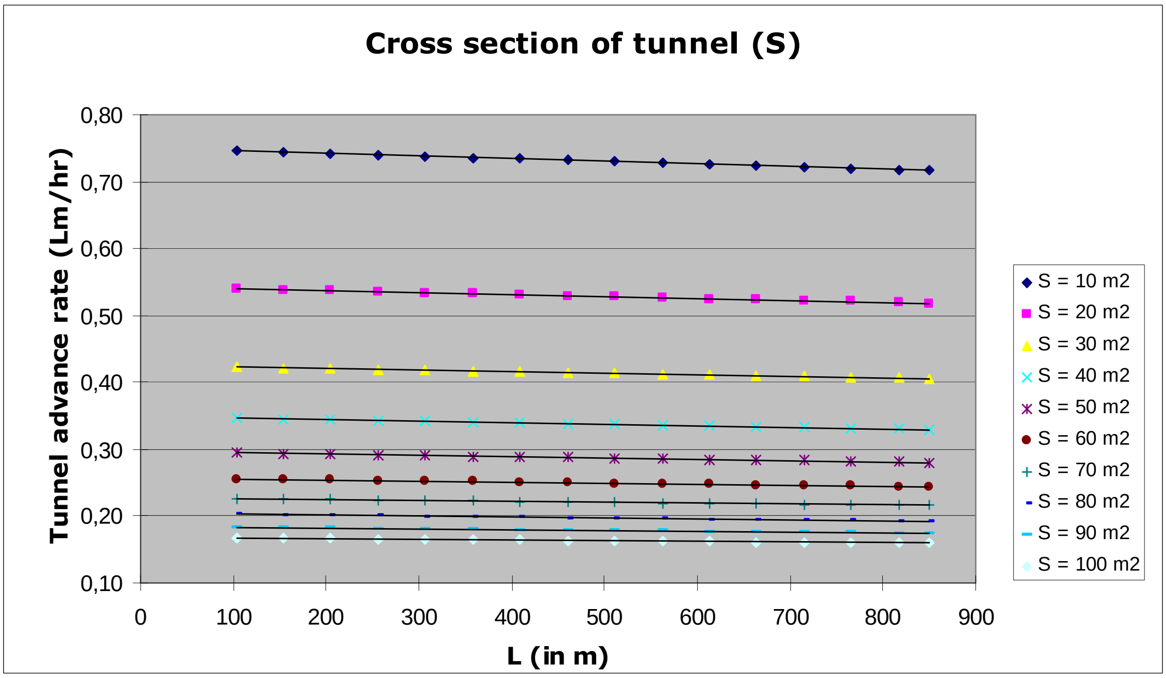


Figure 10. Sensitivity analysis on the surface area of the face of the tunnel (road header excavation)

Drill and blast excavation

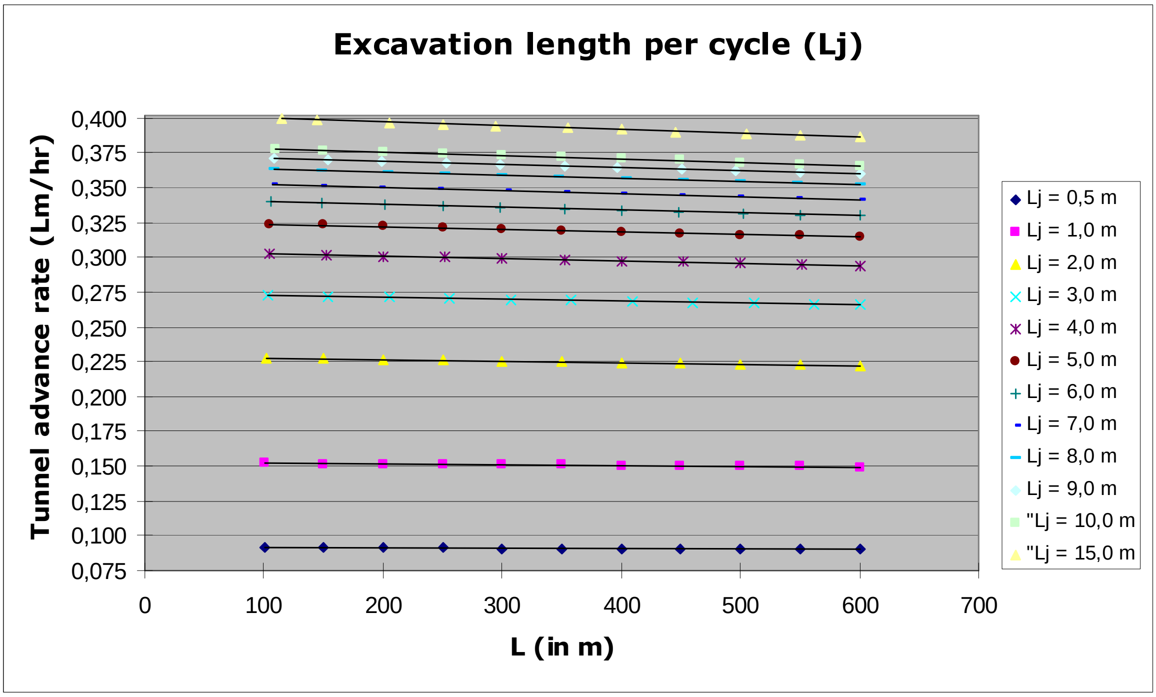


Figure 11. Sensitivity analysis on excavation length per cycle (Lj)

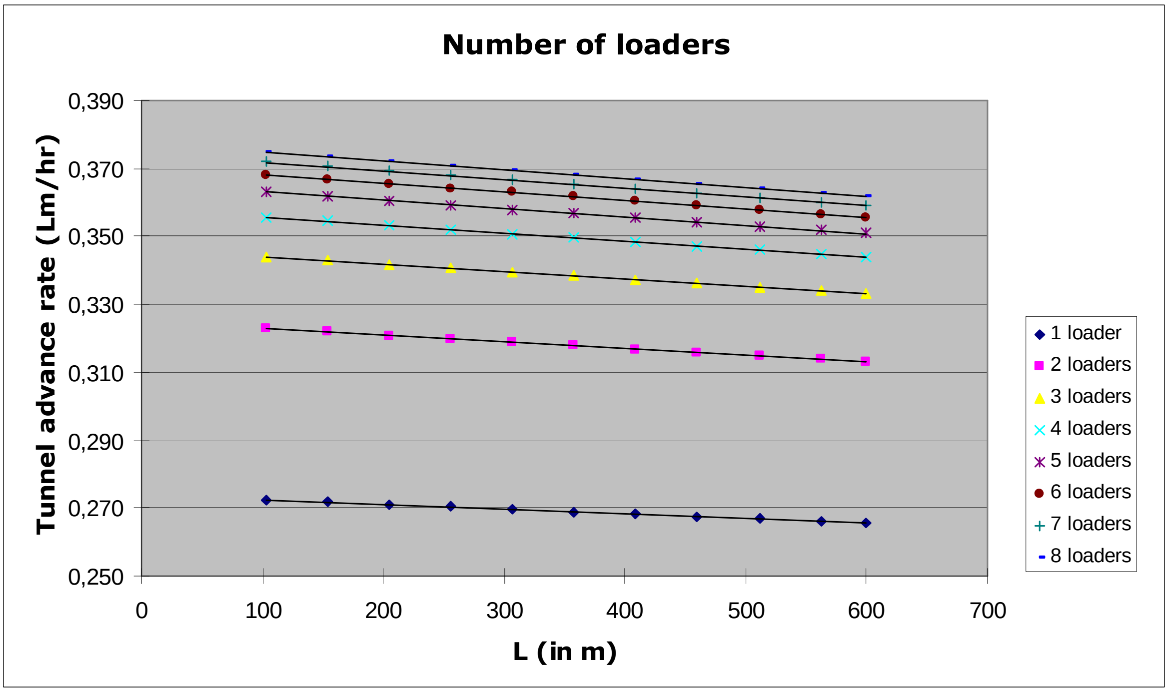


Figure 12. Sensitivity analysis on number of loaders

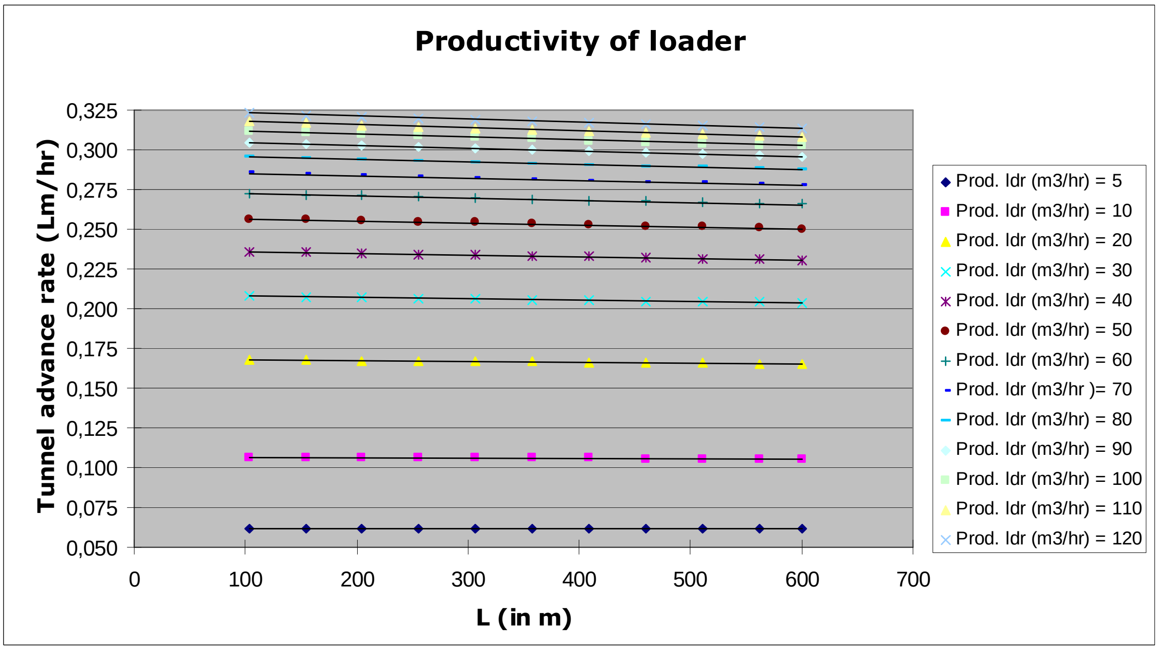


Figure 13. Sensitivity analysis on productivity of loaders

Road header excavation

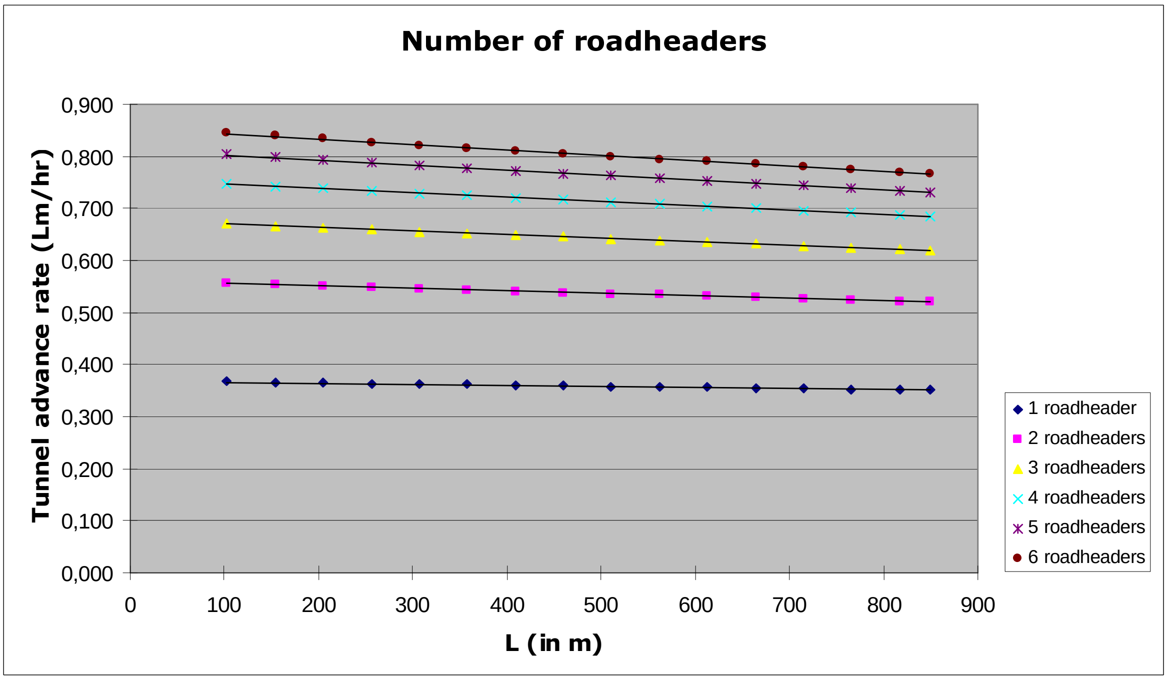


Figure 14. Sensitivity analysis on the number of road headers

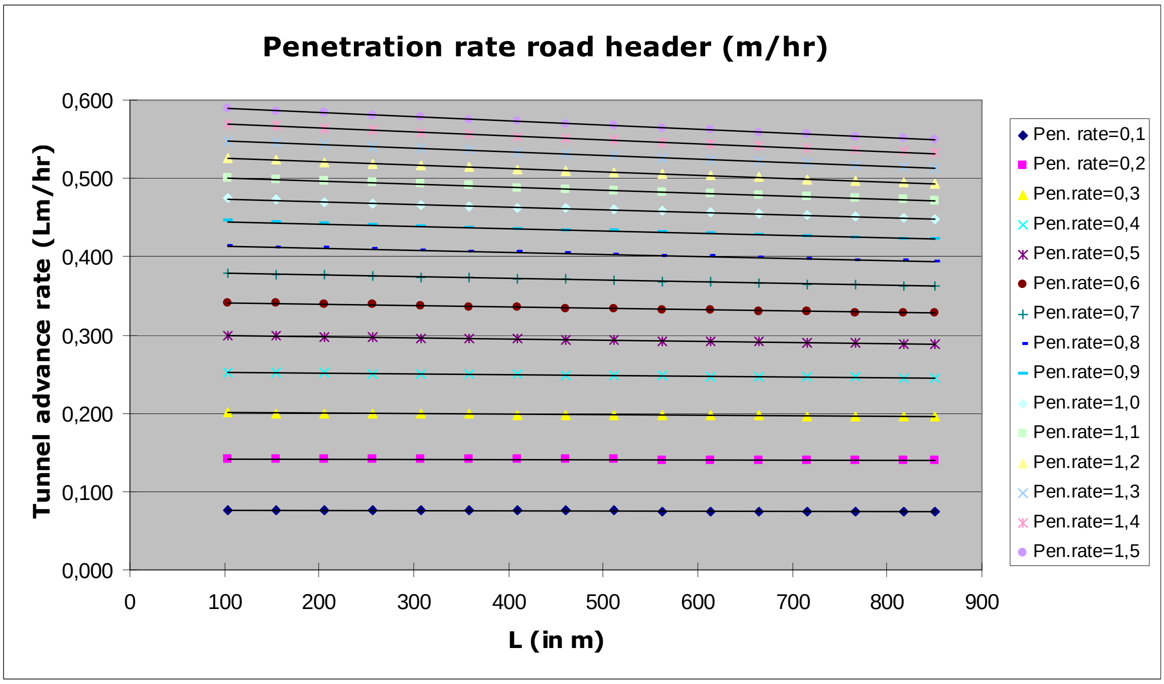


Figure 15. Sensitivity analysis on the penetration rate of the road header

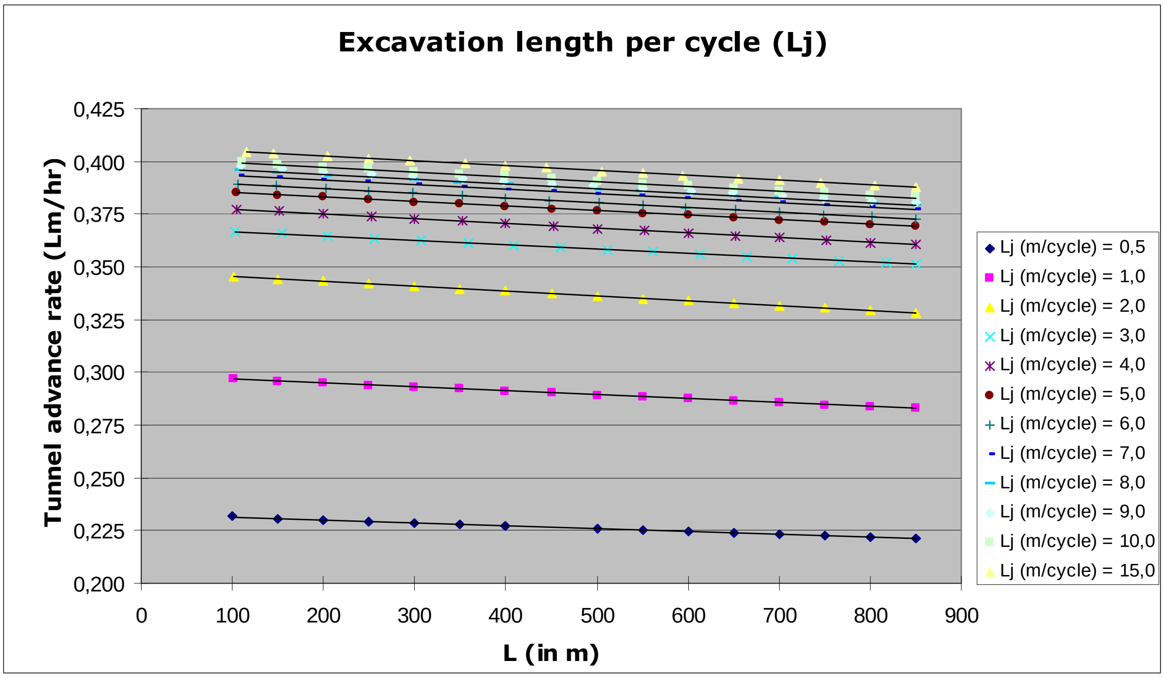


Figure 16. Sensitivity analysis on the excavation length per cycle (Lj)

Appendix V: Sensitivity analysis Bathurst & Langstaff tunnel

TBM properties

Figure 1 shows the relationship between the TBM penetration rate and the tunnel advance rate. The graph shows that the tunnel advance rate increases significantly by increasing the penetration rate of the TBM. This factor has a significant affect on the tunnel advance rate, and hence should be modelled accurately.

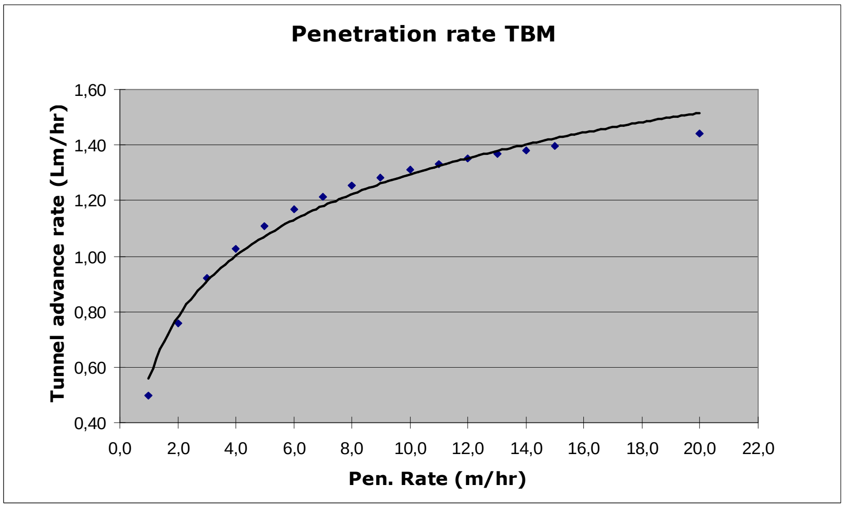


Figure 1. Sensitivity analysis on penetration rate of the TBM

Figure 2 shows the relationship between the stroke length of the TBM and the tunnel advance rate. The stroke length is the amount of meters the TBM can excavate before it needs to get reset and repositioned (grippers of TBM) at the face of the tunnel for the next excavation cycle. It is assumed that per excavation cycle exactly one train, consisting of four muck cars, is filled with excavated soil. In that case, the tunnel advance rate increases significantly by increasing the stroke length of the TBM.

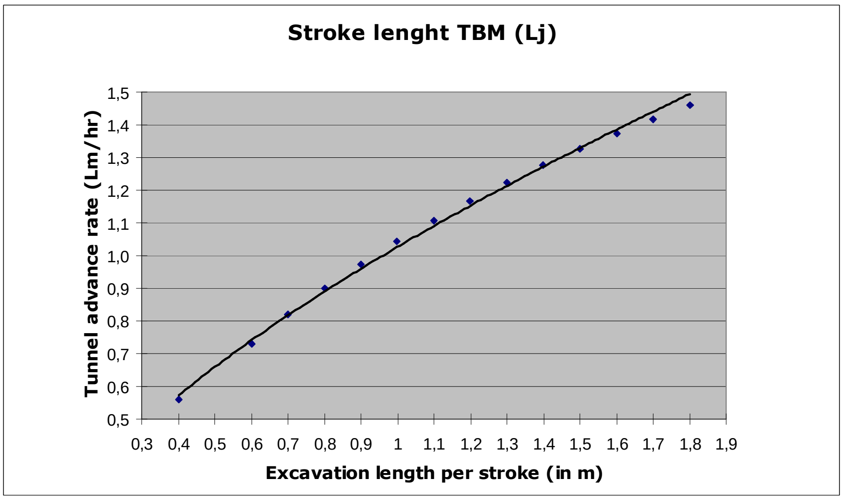


Figure 2. Sensitivity analysis on stroke length per excavation cycle of the TBM

In figure 3 also the relationship between the stroke length of the TBM and the tunnel advance rate is shown. It is assumed that per excavation cycle one train is filled with excavated soil. But In this case more muck cars are added to the train as the volume of excavated soil increases. Also more material cars are added for the transportation of the pre-cast lining segments as the length of the excavation per cycle increases (pre-cast lining segments have a length of 1.2 meters and per excavation cycle (of 1.2 meters) two half segments are brought into the tunnel). The graph shows that the tunnel advance rate increases by increasing the stroke length of the TBM until the stroke length reaches approximately 3.6 meters per cycle. In order to excavate 3.6 meters per cycle, one train consisting of 8 muck cars and 6 material cars, has to be used.

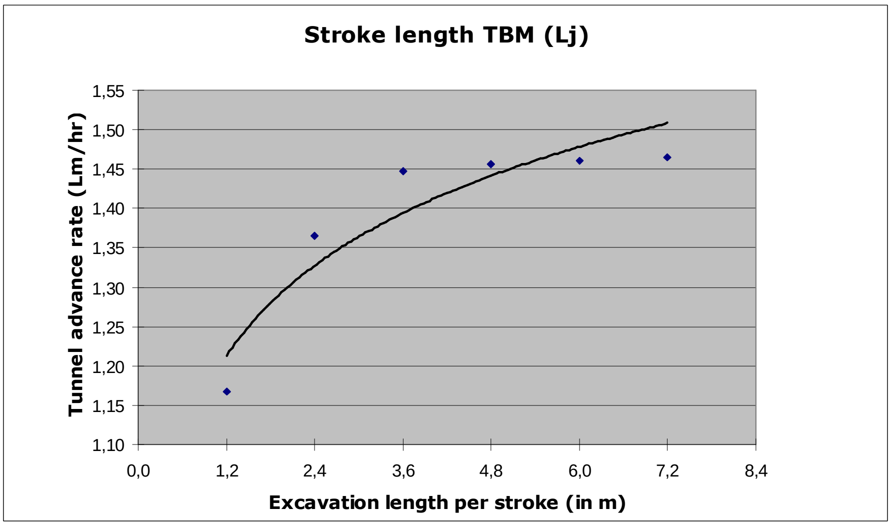


Figure 3. Sensitivity analysis on stroke length per excavation cycle of the TBM

Train properties

Several simulation runs are performed by changing the number of trains used to transport the muck from the face to the shaft of the tunnel, and lining material from shaft to the face of the tunnel. The travel time of the trains depend on the distance (L) between the face of the tunnel and shaft (figure 4). The average tunnel advance rate is used to obtain the graph showing the relationship between the number of trucks and tunnel advance rate (figure 5). The tunnel advance rate increases significantly by increasing the number of trains until the number of trains reaches 2 or more.

In the actual tunnel project 1 to 3 trains were used based on the excavated length of the tunnel. There was a switch installed somewhere between the face and shaft of the excavated tunnel, and at the shaft of the tunnel there was space for two trains to be serviced. As tunnel excavation proceeded multiple trains were put into use primarily to decrease the travelling time duration inside of the tunnel each construction cycle.

Assuming multiple trains are in use, the time duration to transfer lining material from the shaft to the face of the tunnel is assumed to be 0. As soon as multiple trains are used, this time factor is assumed to be non critical, because this particular activity is performed parallel with other construction activities

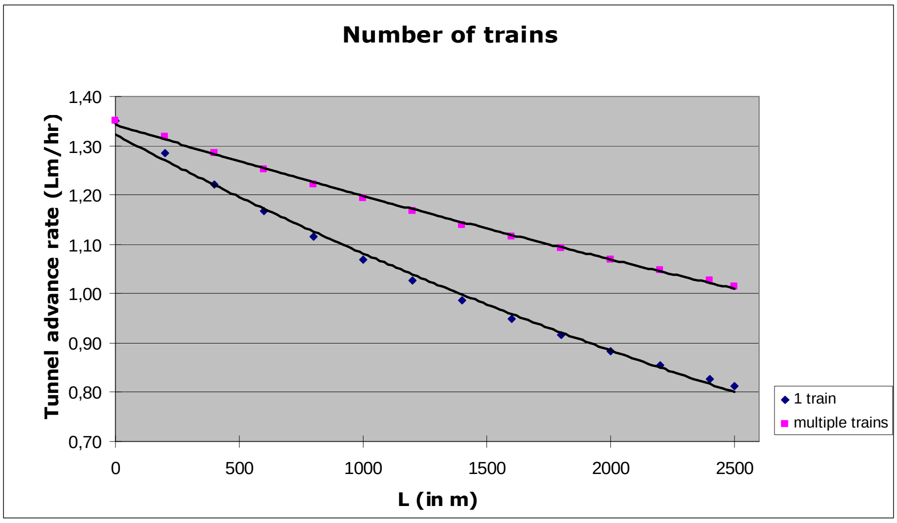


Figure 4. Sensitivity analysis on number of trains

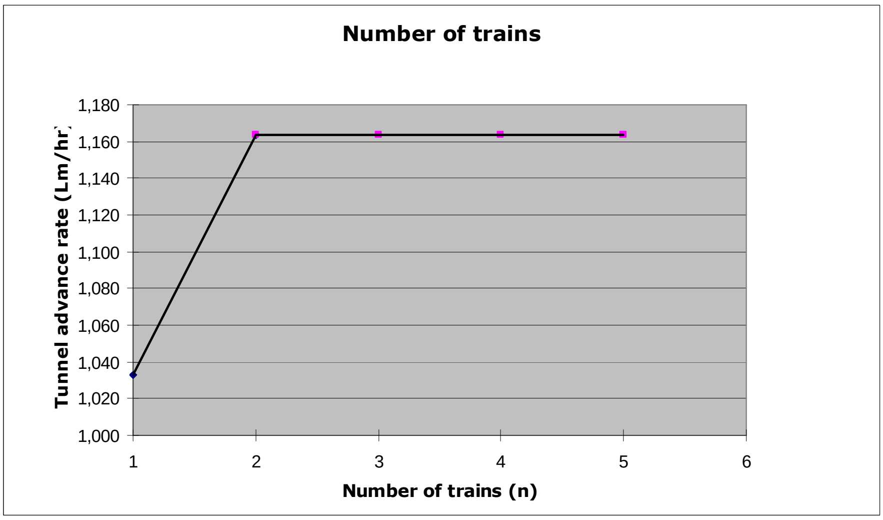


Figure 5. Sensitivity analysis on number of trains

Same type of analysis is also performed regarding the speed of the trains. Figure 6 shows that there is a relationship between speed of the trains and the tunnel advance rate. The tunnel advance rate increases significantly by increasing the speed of the trains until it reaches approximately 35 km/hr.

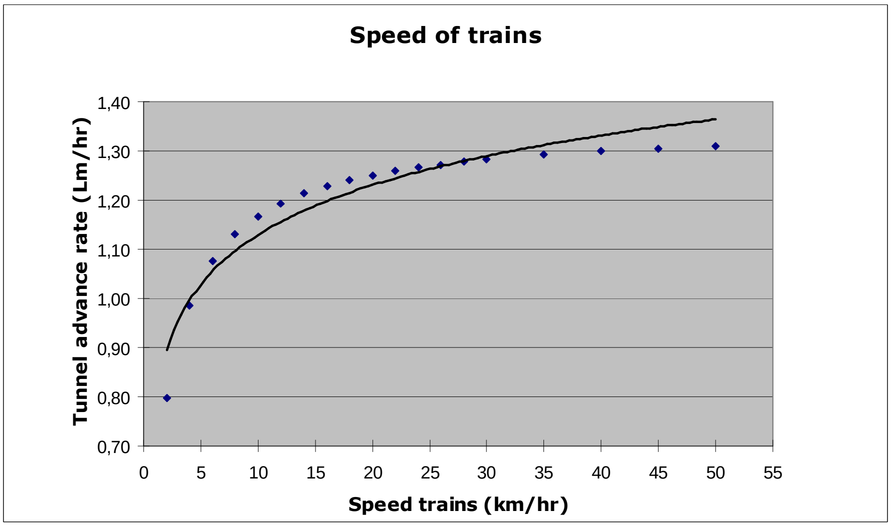


Figure 6. Sensitivity analysis on speed of the trains

Vertical materials handling system

Each construction cycle one train, consisting of several muck cars and material cars, arrives at the shaft of the tunnel. One by one the muck cars get loaded on the crane system, transported to ground level, emptied and transported back to the shaft of the tunnel. Subsequently, two (half) pre-cast lining segments are transported and loaded one by one on the material cars at the shaft of the tunnel. Once the pre-cast lining segments are loaded, the train is ready to travel back to the face of the tunnel.

Several simulation runs are performed by changing the number of cranes used to transport the muck cars from the shaft of the tunnel to ground level, and lining material from ground level to the shaft of the tunnel. The average tunnel advance rate is used to obtain the graph showing the relationship between number of cranes and tunnel advance rate (figure 7). The tunnel advance rate increases significantly by increasing the number of cranes at the shaft of the tunnel. However, it should be noticed that using many cranes at the shaft of the tunnel, in a tunnel with certain dimensions could be unpractical, unsafe and economically unfeasible.

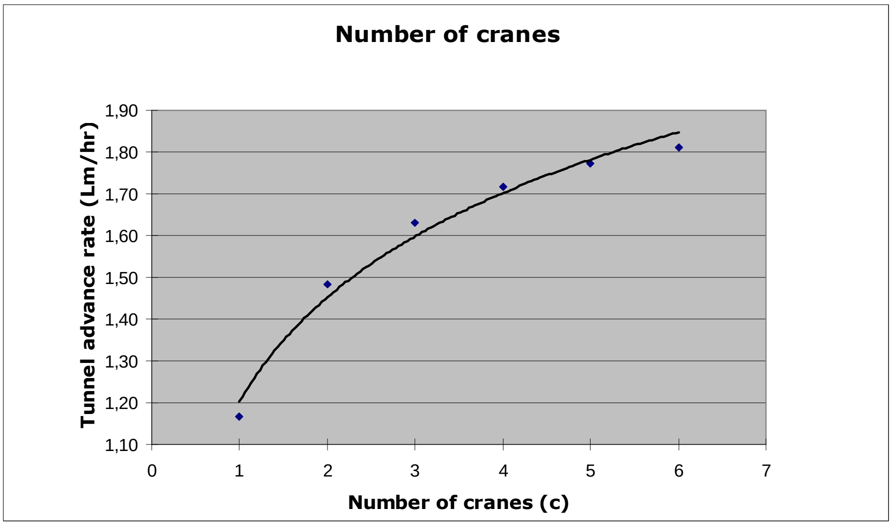


Figure 7. Sensitivity analysis on number of cranes at the shaft of the tunnel

Figure 8 shows the relationship between the number of muck cars per train and the tunnel advance rate. Assuming that the total capacity of the train stays the same (enough to transport the total volume of muck excavated per cycle) and the crane is able to carry bigger and heavier cars, the tunnel advance rate decreases significantly by increasing the number of muck cars per train. So from a manager's point of view it is advisable to use less but bigger muck cars, than more and smaller cars.

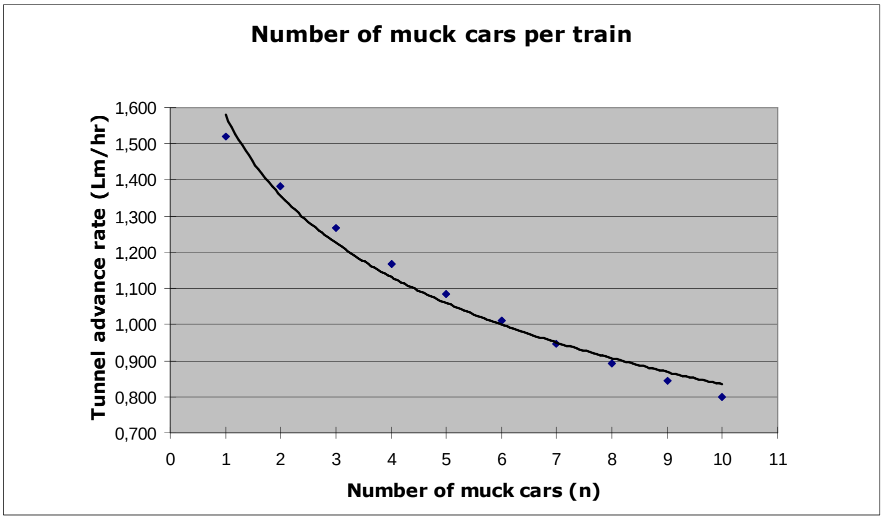


Figure 8. Sensitivity analysis on number of muck cars per train

The time duration of the vertical material handling processes depends not only on the number of cranes used and number of muck cars to be unloaded, but also on the height (length) of the vertical shaft and speed of the system in use. The speed of the system is assumed to be different as it is empty or loaded. The average tunnel advance rate is used to develop the graph showing the relationship of respectively the height of the shaft and speed of the system, and the tunnel advance rate (figure 9 and figure 10). The figure shows that the tunnel advance rate decreases by increasing the height of the shaft.

There is also a relationship between speed of the trucks and the tunnel advance rate. The tunnel advance rate increases by increasing the speed of the system until it reaches approximately 60 km/hr.

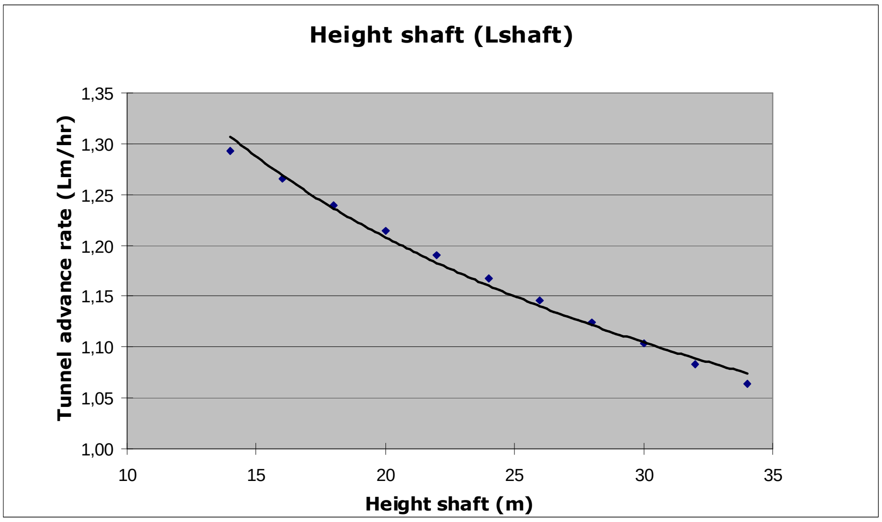


Figure 9. Sensitivity analysis on height of the shaft

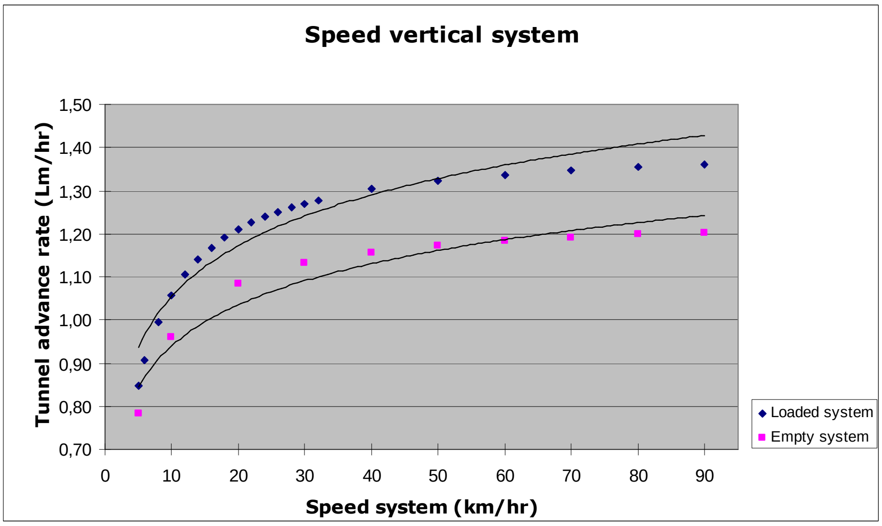


Figure 10. Sensitivity analysis on speed of vertical materials handling system

Efficiency factors

Figure 11 shows the relationship between the efficiency factors (U_1, U_3 and U_4) and the tunnel advance rate. The tunnel advance rate increases significantly by increasing the efficiency of all the efficiency factors. The graph shows that it is important to model the efficiency of the materials handling processes (U_3) with greater care as it affects the tunnel advance rate more significantly than the other two factors. The efficiency of minor processes (U_4) has a minor affect on the tunnel advance rate compared with the others. The efficiency factor of the primary support processes (U_2) is not included in this analysis, because for this type of tunnelling the primary support processes are not critical.

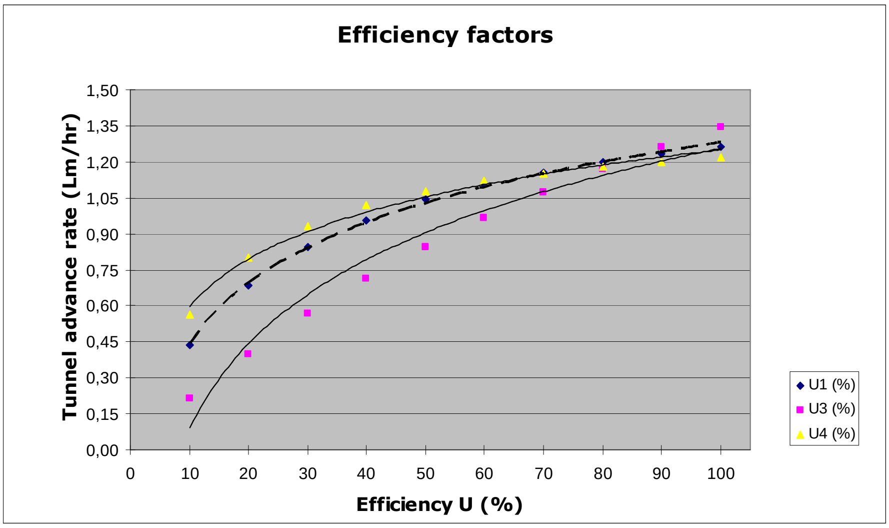


Figure 11. Sensitivity analysis on the efficiency factors of the deterministic model

Appendix VI: Sensitivity analysis Parramatta tunnel

TBM properties

Figure 1 shows the relationship between the TBM penetration rate and the tunnel advance rate. The tunnel advance rate increases significantly by increasing the penetration rate of the TBM, and hence can be considered a very important factor affecting the tunnel advance rate of tunnelling construction.

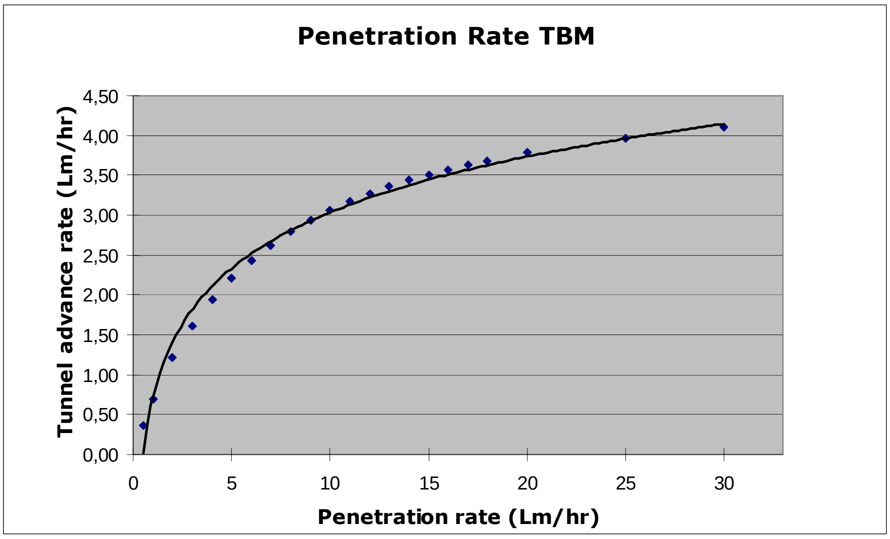


Figure 1. Sensitivity analysis on penetration rate of the TBM

Figure 2 shows the relationship between the stroke length of the TBM and the tunnel advance rate. The stroke length is the amount of meters the TBM can excavate before it needs to get reset and repositioned (grippers of TBM) at the face of the tunnel for the next excavation cycle. The tunnel advance rate increases significantly by increasing the stroke length of the TBM until the stroke length reaches approximately 3 meters. An increasing stroke length of the TBM means increasing cycle times of the excavation and primary support processes. This causes the tunnel advance rate to eventually reach a limit.

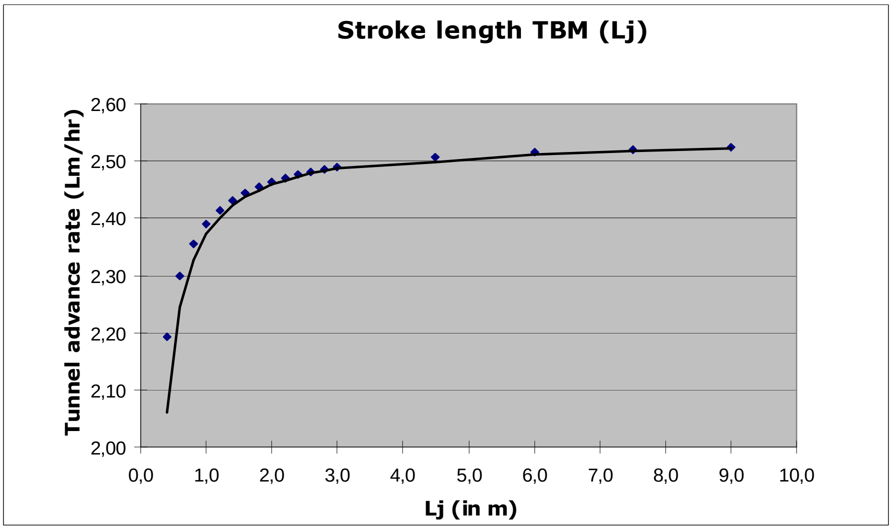


Figure 2. Sensitivity analysis on stroke length of the TBM

Primary support advance rate

Figure 3 shows the relationship between the primary support advance rate and the tunnel advance rate. It is assumed that the advance rate of the primary support processes is equal to the penetration rate of the TBM. Hence, the tunnel advance rate increases significantly by increasing the primary support advance rate, at the same rate as showed in figure 1.

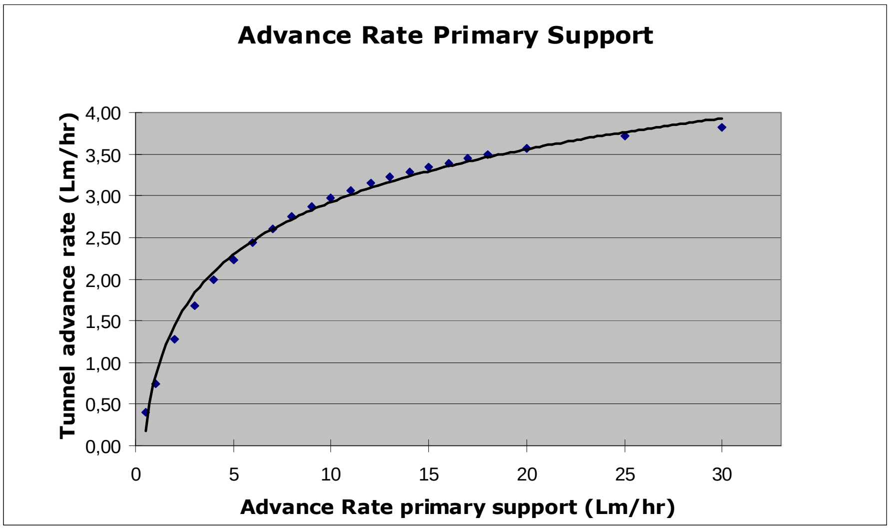


Figure 3. Sensitivity analysis on the primary support advance rate

Efficiency factors

Figure 4 shows the relationship between the efficiency factors (U_1, U_2 and U_4) and the tunnel advance rate. The tunnel advance rate increases by increasing the efficiency of the efficiency factors. The graph shows that it is important to model the efficiency of the excavation processes (U_1) and primary support processes (U_2) with greater care as they affect the tunnel advance rate more significantly than the other factor. The efficiency factor of the materials handling processes (U_3) is not included in this analysis, because for this type of tunnelling the materials handling processes are considered to be not critical.

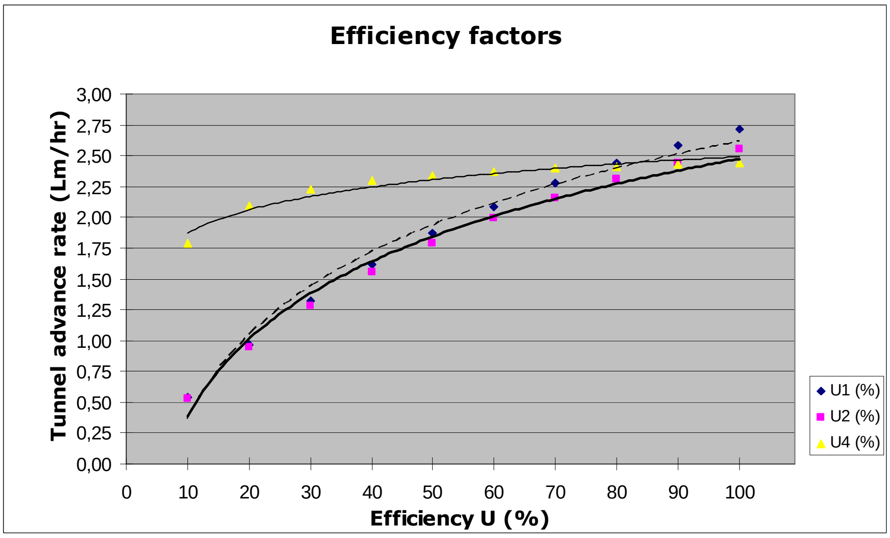


Figure 4. Sensitivity analysis on efficiency factors

Appendix VII: Model description of Laval metro tunnel project

Tunnel section excavated by drill and blast

Excavation cycle

1. The excavation cycle starts with placing the drill jumbo at the face of tunnel (modelled by activity 'PlacingJumbo'), only if two conditions are met: space should be available at the face of the tunnel (expressed by queue 'SpcAvlbl'), as well as two drill jumbos (queue 'DrillJumbo').

2. Subsequently, holes are drilled at the face of the tunnel (activity 'Drilling'), following a specific pattern based on shape of the tunnel (and dimensions), and the types of explosives to be used. In order to drill the holes two drill jumbos are used as expressed by the queue 'DrillJumbo'.

3. Once the holes are drilled, the heading of the tunnel is cleared for the blasting activity. Therefore, the drill jumbos are displaced (activity 'DisplaceJumbo').

4. The drill jumbo sometimes suffers breakdowns or other (mechanical) problems. If this happens the jumbo gets repaired. In the simulation model this activity is modelled by the variable 'Repair'. It is assumed (based on data collected) that the probability of occurrence of this event is 5%. A fork (probabilistic routing element) is used to choose the likelihood of a successive activity, depending on the probability 'P'.

5. The next phase of the excavation cycle consists of loading the explosives in the holes (activity 'LoadExplosives') and blasting the face of the tunnel. The loading activity is performed only if two platform trucks are available, as expressed by the queue 'PlatfTruck'.

6. Blasting the tunnel produces dust and gases that have to be cleared from the face of the tunnel by ventilation (activity 'BlastVent'), before next construction operations can be performed. The total volume of soil that is blasted each construction cycle is modelled by the variable 'SoilAmt' and is expressed in the queue element 'ExcvSoil'. The total volume of soil excavated is calculates by multiplying the cross section area of the tunnel by the excavation length and the swell factor of the soil.

Soil disposal cycle

7. The activity manoeuvring truck starts as three conditions are met. The blasting and ventilation activity is finished (expressed by queue 'RdyMnvr'), there should be excavated soil available at the face of the tunnel (fusion queue 'ExcvSoil') and trucks (queue 'Trucks') should be available in order to transport the soil.

8. Once the truck has manoeuvred at the face of the tunnel, it is ready to be loaded. In order for this activity to start the resources loaders (queue 'Loader') and excavated soil

(fusion queue 'ExcvSoil') should be ready. Each time the activity loading soil (activity 'LoadSoil') is performed an amount of excavated soil is loaded on the truck, equal to the capacity of the truck. The capacity of the truck is expressed by the variable 'TruckCap' in the model. As the truck is loaded and ready to transport the soil towards the soil disposal area, the next truck can come to the face of the tunnel to manoeuvre and be loaded. This is modelled by invoking the queue 'RdyMnvr', after the loading of the truck is finished.

9. After loading the truck, the truck travels from the face of the tunnel to the soil disposal area outside the tunnel. This is modelled by the activity 'TransferSoil'. The time duration of this activity depends on the distance between face of tunnel and soil disposal area, and the speed of the trucks.

10. As soon as the truck arrives at the soil disposal area, it unloads (activity 'UnloadSoil'). One truckload of soil is unloaded at a time and left behind at the soil disposal area. The amount of soil dumped at the soil disposal area is expressed by the queue 'DmpdSoil'. The variable modelling the amount of soil that gets unloaded per truck is 'TruckCap'.

11. After being unloaded the (empty) truck travels back towards the face of the tunnel (activity 'ReturnEmpty'), so that it will be ready for the next cycle, as one instance of truck is added to the queue 'Trucks'.

12. As soon as all the excavated soil is transported and dumped at the soil disposal area, the soil disposal cycle has to end. The activity 'StopSoilDisp' is added to model this process. If the amount of dumped soil at the soil disposal area (represented by queue 'DmpdSoil') is equal to the total amount of excavated soil (expressed by the function '==SoilAmt' of the fusion queue 'DmpdSoil'), and the last truck is loaded, the activity 'StopSoilDisp' starts. This activity does not have time duration, as it is not a real activity of the tunnel construction process.

Looking especially at the activity of manoeuvring the truck at the face of the tunnel, it is modelled to start only if three conditions are met. The previous activity of blasting and ventilating of the tunnel has to be terminated, trucks should be available and the amount of excavated soil should be more than 0 (modelled by the function '!=0' of the fusion queue 'ExcvSoil'). As the activity of stopping the soil disposal processes starts, no excavated soil will be available at the face of the tunnel, so the activity of manoeuvring the truck will not start anymore, as the amount of soil represented by the queue 'ExcvSoil' is equal to 0 and this particular condition is not met anymore. As soon as the last truck load of excavated soil is transported to the soil disposal area and returns to its starting position the soil disposal cycle ends.

Scaling cycle

13. The scaling cycle consists of mechanical and manual scaling of the roof and walls of the excavated tunnel. The surface area of the roof and walls of the tunnel has to be smoothened out by removing loose pieces of rock. To perform the mechanical scaling activity, as expressed by 'MechScaling' in the simulation model, an excavator in the form of a backhoe is used (queue 'Excavator').

It has to be mentioned that the mechanical scaling activity only starts as three conditions are met. The soil disposal processes have to be finished (expressed by the queue 'RdySclng'), all trucks used for the soil disposal processes are at their starting position (expressed by the variable '==nSoilTr' of the fusion queue 'Trucks'), and an excavator is available (modelled by queue 'Excavator'). The variable 'nSoilTr' represents the number of trucks in use.

14. Subsequently as the area is safe enough for labourers, the activity of manual scaling is performed (modelled by activity 'ManualScaling'). Two platform trucks (or truck-mounted scissors) have to be available to perform this activity (queue 'PlatfTruck').

Primary support cycle

15. As soon as the manual scaling activity is terminated (expressed by queue 'RdyGrSp') and a material truck is available (queue 'MatTruck'), the lining material is transported towards the face of the tunnel. This activity is modelled by 'TransferLining'. Transportation time duration depends on the speed of the trucks and the distance travelled. The lining material that is transported consists mainly of rock bolts, and wire mesh.
16. Once the truck arrives at the face of the tunnel the lining material (rock bolts and wire mesh) is unloaded from the truck (activity 'UnloadLining').
17. Subsequently, the (empty) truck travels back to its starting position. This is modelled by the activity 'ReturnMatTruck'.
18. Lining of the tunnel (primary support) consists of installing rock bolts and wire mesh along the excavated surface of the tunnel, depending on the ground conditions on site. These resources are modelled by the queue 'LiningMat' in the simulation model. The activity is modelled by the variable 'LiningTunnel'. In order to perform these activities a drill jumbo (modelled by fusion queue 'DrillJumbo') is used, in combination with two platform trucks (queue 'PlatfTruck').

The holes drilled by the drill jumbo may vary from 2.4 – 6.0 metres long. Next a steel rod with a wedge attached on the end is inserted in the hole, and placed correctly. The spacing and depth of the rock bolts required is determined by the ground conditions on site. Under poor ground condition wire mesh is installed on the walls and roof, mainly to prevent loose material from falling on labourers during construction.

Surveying cycle

19. Surveying is done to monitor the position of the tunnel and to determine where the holes should be drilled at the face of the tunnel for the next excavation cycle. This activity is modelled by the variable 'Surveying'. A man-lift with two operators is used to perform this activity (queue 'Manlift').

Extending services cycle

20. Extending services consist of extending the water and air lines inside the tunnel (modelled by activity 'ExtendServ'). This activity is performed simultaneously to the lining and surveying activities. The next construction cycle will start as soon as the queue 'SpcAvlbl' has the value of 1. In order to be sure that the next construction cycle starts after these parallel activities are finished, a value of ½ is attributed to the queue 'SpcAvlbl' after the surveying activity is finished, as well as the extending services activity.

Tunnel section excavated by road header

Excavation and soil disposal cycle

1. The construction cycle starts with placing the road header at the face of tunnel (modelled by activity 'RelocateRdhdr'), only if two conditions are met: space should be available at the face of the tunnel (expressed by queue 'SpcAvlbl'), as well as one road header machine (queue 'RoadHeader').
2. Once the road header is positioned at the face of the tunnel (expressed by queue 'RdyMnvr'), the activity manoeuvring truck can start (modelled by activity 'ManouevreTruck'), as soon as trucks are available (queue 'Trucks') in order to transport the soil towards the soil disposal area outside the tunnel.

It should be mentioned, that the excavation process using road header is not continuous. The road header performs, only when there is a truck available to be loaded with soil excavated by the road header. The soil is transported from the road header to the truck by a belt-conveyor system that is incorporated in the road header machine. It is assumed, due to limited space inside the tunnel, that only one truck at a time can manoeuvre and be loaded by the road header at the face of the tunnel.

3. Once the truck has manoeuvred at the face of the tunnel, and is ready to be loaded, the road header excavates until the truck is filled (activity 'ExcavLoad'). Each time the activity of excavation and loading soil is performed, an amount of excavated soil is loaded on the truck equal to the capacity of the truck. The capacity of the truck is modelled by the variable 'TruckCap'. The queue 'ExcvSoil' represents the amount of excavated soil. As the truck is loaded and ready to transport muck towards the soil disposal area, the next truck can come to the face of the tunnel to manoeuvre and subsequently loaded. This is modelled by invoking the queue 'RdyMnvr', as soon as the excavation and loading of the previous truck is finished.
4. The road header sometimes suffers breakdowns or other (mechanical) problems during excavation. If this happens the road header needs to be repaired. In the simulation model this activity is represented by the variable 'Repair'. It is assumed (based on data collection) that the chance of occurrence of this event is 10%. A fork (probabilistic routing element) is used to choose the likelihood of a successive activity, depending on the chance 'P'.
5. After loading the truck, it travels from the face of the tunnel to the soil disposal area outside the tunnel. This is modelled by the activity 'TransferSoil'. The time duration of this activity depends on the distance between face of tunnel and soil disposal area, and the speed of the trucks.
6. As soon as the truck arrives at the soil disposal area, it unloads (modelled by activity 'UnloadSoil'). One truckload of soil is unloaded at a time and left behind at the soil disposal area. The amount of soil dumped at the soil disposal area is expressed by the queue 'DmpdSoil'. The variable modelling the amount of soil that gets unloaded per truck is 'TruckCap'.
7. After being unloaded the (empty) truck travels back towards the face of the tunnel (activity 'ReturnEmpty'), so that it will be ready for the next cycle, as one instance of truck is added to the queue 'Trucks'.
8. As soon the pre-established amount of meters of tunnel is excavated by the road header (modelled by variable L_j) and all the excavated soil is dumped at the soil disposal area, the excavation and soil disposal cycle has to end. The activity 'StopSoilDisp' is added to model this process. If the amount of excavated soil (represented by queue 'ExcvSoil') is equal to total amount of soil to be excavated each cycle (expressed by the function '==SoilAmt' of fusion queue 'ExcvSoil'), and the last truck is loaded, the activity 'StopSoilDisp' starts. This activity does not have time duration, as it is not a real activity of the tunnel construction process.

Looking especially at the activity of manoeuvring the truck at the face of the tunnel, it is modelled to start if two conditions are met. The previous activity of placing the road header at the face of the tunnel has to be terminated, as well as trucks should be available. As the activity of stopping the excavation processes starts, no instance of the queue 'RdyMnvr' is available, so the activity of manoeuvring the truck will not start, as the conditions to start this activity is not met anymore. As soon as the last truck load of excavated soil is transported to the soil disposal area and returns to its starting position the soil disposal cycle ends.

9. Subsequently, the road header is displaced from the face of the tunnel to its starting position, as expressed by the activity 'DisplaceRdhdr'. However, in order for this activity to start, two conditions have to be met. The excavation and soil disposal cycle has to be terminated (modelled by queue 'RdyDsplc'), as well as all trucks have to be at their starting position (expressed by the variable ==nSoilTr of the fusion queue 'Trucks'). The variable 'nSoilTr' represents the number of trucks in use. After displacing of the road header, one instance of this resource is attributed to the queue 'RoadHeader', and two activities are ready to start parallel to each other (expressed by queues 'RdyMntnc' and 'RdyGrSp').

Maintenance cycle

10. As the excavation and soil disposal cycle has finished and the road header is displaced to its starting position, maintenance is performed on the road header machine. Among other things, the cutter head of the machine is inspected and parts of the cutter head (the bits) that suffered from wear are changed. The maintenance process is modelled in the simulation model by the activity 'Maintenance'. As maintenance is performed on the road header machine, one instance of this resource is necessary to start this activity. Maintenance is performed parallel to the primary support (lining) processes.

Primary support cycle

11. As soon as the displacing of the road header activity is terminated (expressed by queue 'RdyGrSp') and a material truck is available (queue 'MatTruck'), the lining material is transported towards the face of the tunnel. This activity is modelled by 'TransfLining'. Transportation time duration depends on the speed of the trucks and the distance travelled. The lining material that is transported consists of rock bolts and wire mesh.
12. Once the truck arrives at the face of the tunnel the lining material (rock bolts and wire mesh) is unloaded from the truck (activity 'UnloadLining').
13. Subsequently, the (empty) truck travels back to its starting position. This is modelled by the activity 'ReturnMatTruck'.
14. Lining of the tunnel (primary support) consists of installing rock bolts and wire mesh along the excavated surface of the tunnel, depending on the ground conditions on site.

These resources are modelled by queue 'LiningMat' in the simulation model. The lining processes are modelled by the activity 'LiningTunnel'. In order to perform these activities a drill jumbo (modelled by queue 'DrillJumbo') is used, in combination with two platform trucks (queue 'PlatfTrck').

The holes drilled by the drill jumbo may vary from 2.4 – 6.0 metres long. Next a steel rod with a wedge attached on the end is inserted in the hole, and placed correctly. The spacing and depth of the rock bolts required is determined by the ground conditions on site. Under poor ground condition wire mesh is installed on the walls and roof, mainly to prevent loose material from falling on labourers during construction.

Surveying cycle

15. Surveying is done to monitor the position of the tunnel and to determine where the holes should be drilled at the face of the tunnel for the next excavation cycle. This activity is modelled by the variable 'Surveying'. A man-lift with two operators is used to perform this activity (queue 'Manlift').

Extending services cycle

16. Extending services consist of extending the water and air lines inside the tunnel (modelled by activity 'ExtendServ'). This activity is performed parallel to the lining and surveying activities. The next construction cycle will start as soon as the queue 'SpcAvlbl' has the value of 1. In order to be sure that the next construction cycle starts after these parallel activities are finished, a value of ½ is attributed to the queue 'SpcAvlbl' after the surveying activity is finished, as well as the extending services activity.

Appendix VIII: Variables and equations of simulation model

The simulations models consist of many distinctive variables which interact with each other. A distinction is made between variables used in the simulation to model the resources' properties, variables modelling the probability distributions of the model's activities, and variables modelling the behaviour of the resources (e.g. productivity of loader and penetration rate of road header) as well as tunnel properties (e.g. cross section area of face tunnel, swell factor). Subsequently, the equations used to determine the triangular distributions of some model's activities are described.

Simulation model variables

The variables representing the resources of the simulation models of the Laval metro tunnel project are listed in table 1. Also their modelling symbols and actual values are described, as expressed in the simulation models.

Model variables	**Symbol**	**Value**
Number of soil trucks	nSoilTr	3
Capacity of soil trucks (m^3)	TruckCap	11
Number of material trucks	nMatTr	1
Number of loaders	nLdrs	1
Number of road headers	nRdhdr	1
Number of drill jumbos: drill and blast excavation	nJumbo	2
Number of drill jumbos: road header excavation	nJumbo	1
Number of platform trucks	nPlatfTrck	2
Number of excavators	nExcv	1
Number of man-lifts	nMnlift	1
Number of construction workers per cycle	nCrew	9
Total volume of soil excavated per cycle: drill and blast (m^3)	SoilAmt	187.0
Total volume of soil excavated per cycle: road header (m^3)	SoilAmt	154.0
Amount of excavated soil (m^3)	ExcvSoil	n.a.
Amount of dumped soil at soil disposal area (m^3)	DmpdSoil	n.a.

Table 1. Tunnelling construction variables and their values of the Laval metro tunnel project

The time durations probability distributions of each activity used both in the simulation model of the tunnel excavated by drill and blasts, as well as the tunnel excavated by road header, are described in table 2. The numbers in the table correspond with the activity numbers of the simulation model, for the tunnel section excavated by drill and blast. Table 3 shows the remaining probability distributions of activities that are used only in the simulation model of the tunnel excavated by road header. In order to describe the behaviour of the various activities of the simulation model, triangular distributions are used to model the time durations. As to the value of the distributions, it is mainly based on minimum, maximum and most probable knowledge of the construction managers.

Nr.	Model activity	Variable	Value (in minutes)
1	Placing drill jumbo	PlcngJmbTm	Triangular [5,10,15]
2	Drilling holes	DrllTm	Triangular [90,120,150]
3	Displacing drill jumbo	DsplngJmbTm	Triangular [2,5,10]
4	Repair drill jumbo	RepJumboTm	Triangular [10,30,120]
5	Loading explosives	LdgExplTm	Triangular [45,60,90]
6	Blasting and ventilation	BlstnVntltnTm	Triangular [15,20,30]
7	Manoeuvre truck	MnvrTrckTm	Triangular [0.2,0.4,1]
8	Load soil in truck	LdSlTm	Triangular [8.3,11.0,16.5]
9	Transport soil by truck	TrnspTrckTm	Triangular [0.21,0.72,2.4]
10	Unload soil	UnldSlTm	Triangular [0.8,1.0,1.2]
11	Return empty truck	TrnspTrckTm	Triangular [0.21,0.72,2.4]
13	Mechanical scaling	MchSclngTm	Triangular [15,30,45]
14	Manual scaling	MnlSclngTm	Triangular [45,60,75]
15	Transport lining material	TrnspTrckTm	Triangular [0.21,0.72,2.4]
16	Unload lining material	UnlLnngTm	Triangular [10,15,20]
17	Return empty material truck	TrnspTrckTm	Triangular [0.21,0.72,2.4]
18	lining tunnel	LnngTnnlTm	Triangular [60,90,120]
19	Surveying tunnel	SrvyTnnlTm	Triangular [20,30,45]
20	Extending services	ExtndngSrvcsTm	Triangular [20,37.5,45]

Table 2. Tunnelling construction variables of Laval metro tunnel, excavated by drill & blast and road header

Model activity	Variable	Value (in minutes)
Relocate road header	RelRdHdrTm	Triangular [3,5,15]
Excavation and loading trucks	ExcLdSlTm	Triangular [13.41,19.08,38.6]
Displacing road header	DisplRdHdrTm	Triangular [3,5,15]
Maintenance road header	MntncRdHdrTm	Triangular [30,60,90]
Repair road header	RepRdHdrTm	Triangular [10,30,120]
Transportation by truck	TrnspTrckTm	Triangular [0.21,1.0,3.4]

Table 3. Remaining tunnelling construction variables of the Laval metro tunnel, excavated by road header

In order to determine the triangular distributions of certain activities, such as the transportation time durations and loading of trucks time durations, the variables described in table 4 are used. Also variables used to calculate the total amount of excavated soil per construction cycle, are described in table 4. For example, to calculate the excavated amount of soil per cycle the variables: excavation length per cycle, swell factor of the soil and cross section area of the tunnel, are relevant. The various equations that are used to determine the triangular distribution of certain model's activities are described in the next paragraph of this chapter.

Model variables	Symbol	Value
Penetration rate road header (Lm/hr)	A	Triangular [0.33,0.67,0.95]
Productivity of loader (m^3/hr)	P_{loader}	Triangular [40,60,80]
Speed of trucks (km/hr)	v_{truck}	Triangular [15,25,30]
Capacity of trucks (m^3)	V_{truck}	11
Distance tunnel and soil disposal area (m)	L_{sd}	100
Excavation length per cycle (Lm/cycle)	L_j	3,0
Swell factor of soil	S	1,4
Cross section area tunnel exc. by drill and blast (m^2)	W	44,1
Cross section area tunnel exc. by road header (m^2)	W	37,0

Table 4. Tunnelling construction variables and their values of the Laval metro tunnel project

Simulation model equations

Most of the time durations of the activities are determined based on data collected doing interviews with the construction experts. However, in order to determine the minimum, most probable and maximum values for the triangular distribution regarding some activities, additional calculations are performed. Most of these calculations are already described in the deterministic model of the Laval metro tunnel (see section 4.3). For this reason only the equations are provided in this paragraph.

Total volume of soil excavated per cycle (variable 'SoilAmt')

V_{muck}: total volume of soil excavated per cycle (in m^3)

$$V_{muck} = L_j \times S \times W$$

Where,

S is the surface area face of the tunnel (m^2)

W is the swell factor of the soil

L_j is the excavated length of tunnel of section j (in m)

To facilitate simulation, it is assumed that the total volume of soil excavated per cycle is a multiplication of the capacity of the trucks. The multiplication factor is determined by dividing the total volume of excavated soil (V_{muck}) by the capacity of the truck (V_{truck}).

$$N = \left(\frac{V_{muck}}{V_{truck}} \right)$$

It is assumed that variable N is an integer, and is rounded up to the nearest number, if the decimal fraction is at least 0.25. If the decimal fraction is less than 0.25 the number of the multiplication factor is rounded down. To determine the total volume of soil (modelled by variable 'SoilAmt') the multiplication factor N is multiplied by the capacity of the truck (V_{truck}).

$$SoilAmt = N \times V_{truck}$$

Where,

V_{truck} is the capacity of the truck (in m^3)

V_{muck} is the total volume of excavated soil per cycle (in m^3)

N is the multiplication factor

Loading soil in truck by loader

T_{lm}: time duration of loading muck by loader (in min)

$$T_{lm} = \left(\frac{V_{truck} x60}{P_{loader}} \right)$$

Where,

P_{loader} is the productivity of the loader (in m^3/hr)

V_{truck} is the capacity of the truck (in m^3)

Excavation and loading truck by road header

P_{exc}: productivity of the road header (in m^3/hr)

$$P_{exc}\,(m^3/hr) = A \times S \times W$$

The penetration rate (A) is inversely proportional to the cross section area of the tunnel (S). The relationship between both variables is assumed to be constant. If the surface area of the face of the tunnel increases with a certain rate, it is assumed that the penetration rate decreases with the same rate.

T_{lm}: time duration of excavation and loading muck (in min)

$$T_{lm} = \left(\frac{V_{truck} x60}{P_{exc}} \right)$$

Where,

A is the penetration rate of road header (in m/hr)

S is the surface area face of the tunnel (m^2)

W is the swell factor of the soil

P_{exc} is the productivity of the road header (in m^3/hr)

V_{truck} is the capacity of the truck (in m^3)

Transportation times of trucks

T_s =T_{sb}: time duration of transportation of muck and lining material (in min)

$$T_s = T_{sb} = \left(\frac{\sum_{j=1}^{k} L_j + L_{sd}}{v_{truck}} \right)$$

Where,

L_j is the excavated length of tunnel of section j (in m)

L_{sd} is distance between the tunnel and the disposal area outside of the tunnel (in m)

v_{truck} is speed trucks (km/hr)

In order to determine the minimum, most probable and maximum value of the triangular distributions for the activities 'loading soil in truck using loader', 'excavation and loading truck using road header' and 'transportation times of trucks', the penetration rate of the road header machine (P_{exc}), the productivity of the loader (P_{exc}), and the speed of the trucks (v_{truck}) are modelled as triangular distributions. For example, in order to calculate the maximum value of the triangular distribution of the transportation time duration of trucks, the minimum value of the triangular distribution of the variable 'speed of truck' is used. So, the minimum, most probable and maximum values of this particular triangular distribution are based on speed of the trucks.

Appendix IX: Output EZstrobe simulation

CT	Cycle time of excavation processes	((SimTime/60))/nCycles
ProdRate	Tunnel advance rate (m/hr)	3.0/CT
TtlCst	Total cost per construction cycle	(TrckCst*(nSoilTr+nMatTr)+RdhdrCst*nRdHdr+JumboCst*nJumbo+PlatfTruckCst*nPlatfTrck+ManliftCst*nMnlift+LaborCst*nCrew)*CT
HourlyCst	Hourly cost per construction cycle	TtlCst/CT
UnitCst	Cost per meter excavation ($/m)	HourlyCst/ProdRate
UnitCstVol	Cost per volume soil excavation ($/m3)	TtlCst/(DmpdSoil.CurCount/nCycles)

```
** Calculated results after simulation **

Cycle time of excavation processes    : 9.67296
Total cost per construction cycle     : 10553.2
Cost per volume soil excavation ($/m3): 68.5273
Hourly cost per construction cycle    : 1091
Tunnel advance rate (m/hr)            : 0.310143
Cost per meter excavation ($/m)       : 3517.73

Statistics report at simulation time 580.378


Queue           Res             Cur       Tot  AvWait    AvCont    SDCont MinCont   MaxCont
============================================================================================
Cycles          ezs            0.00      1.00    0.00      0.00      0.00    0.00      1.00
DmpdSoil        ezs          154.00    154.00  343.94     91.26     53.71    0.00    154.00
DrillJumbo      ezs            1.00      2.00  242.55      0.84      0.37    0.00      1.00
ExcvSoil        ezs            0.00    154.00  190.92     50.66     49.49    0.00    154.00
LiningMat       ezs            0.00      1.00    0.00      0.00      0.00    0.00      1.00
Manlift         ezs            1.00      2.00  269.60      0.93      0.26    0.00      1.00
MatTruck        ezs            1.00      2.00  282.21      0.97      0.16    0.00      1.00
PlatfTrck       ezs            2.00      4.00  242.55      1.67      0.74    0.00      2.00
RdyDsplc        ezs            0.00      1.00    2.41      0.00      0.06    0.00      1.00
RdyExtServ      ezs            0.00      1.00    0.00      0.00      0.00    0.00      1.00
RdyGrSp         ezs            0.00      1.00    0.00      0.00      0.00    0.00      1.00
RdyMntnc        ezs            0.00      1.00    0.00      0.00      0.00    0.00      1.00
RdyMnvr         ezs            0.00     15.00    0.00      0.00      0.00    0.00      1.00
RdySrvy         ezs            0.00      1.00    0.00      0.00      0.00    0.00      1.00
RoadHeader      ezs            1.00      3.00   29.94      0.15      0.36    0.00      1.00
SpcAvlbl        ezs            1.00      2.00   25.78      0.09      0.19    0.00      1.00
Trucks          ezs            3.00     17.00   72.55      2.13      0.67    0.00      3.00
```

```
Activity        Cur     Tot     1stSt     LstSt   AvDur  SDDur    MinD     MaxD   AvInt  SDInt    MinI     MaxI
=================================================================================================================
DisplaceRdHdr    0       1     423.59    423.59    5.09             5.09     5.09
ExcavLoad        0      14      10.67    392.51   28.67   0.00   28.67    28.67   29.37   0.00   29.37    29.37
ExtendServ       0       1     443.91    443.91   33.34            33.34    33.34
LiningTunnel     0       1     443.91    443.91   95.29            95.29    95.29
Maintenance      0       1     428.67    428.67   61.89            61.89    61.89
ManoeuvreTruck   0      14       9.96    391.80    0.70   0.00    0.70     0.70   29.37   0.00   29.37    29.37
RelocateRdHdr    0       1       0.00      0.00    9.96             9.96     9.96
Repair           0       1     274.31    274.31   62.79            62.79    62.79
ReturnEmpty      0      14      41.03    422.87    0.71   0.00    0.71     0.71   29.37  11.26    4.05    58.74
ReturnMatTruck   0       1     443.91    443.91    0.71             0.71     0.71
StopSoilDisp     0       1     421.18    421.18    0.00             0.00     0.00
Surveying        0       1     539.20    539.20   41.18            41.18    41.18
TransfLining     0       1     428.67    428.67    0.71             0.71     0.71
TransferSoil     0      14      39.34    421.18    0.71   0.00    0.71     0.71   29.37  11.26    4.05    58.74
UnloadLining     0       1     429.39    429.39   14.52            14.52    14.52
UnloadSoil       0      14      40.05    421.89    0.99   0.00    0.99     0.99   29.37  11.26    4.05    58.74


Detailed statistics on content of queue RoadHeader

   Content     TotTime  %Time
============================
    < 1.00      490.56  84.52
    < 2.00      580.38 100.00
   >= 2.00        0.00   0.00


Detailed statistics on content of queue Trucks

   Content     TotTime  %Time
============================
    < 1.00        4.82   0.83
    < 2.00       89.31  15.39
    < 3.00      413.62  71.27
   >= 3.00      166.76  28.73
```

```
** Model input parameters **

truck capacity in m3                      : 11
number of soil trucks                     : 3
number of material trucks                 : 1
number of labor per construction cycle    : 9
Roadheader cost ($/hr)                    : 450
number of Roadheaders                     : 1
amount of soil excavated per cycle in m3: 154
number of platform trucks                 : 2
number of Drill Jumbo's                   : 1
number of man-lifts                       : 1
Truck cost ($/hr)                         : 80
Jumbo cost ($/hr)                         : 150
platform-truck cost ($/hr)                : 80
Labor cost ($/hr)                         : 50
Man-lift cost ($/hr)                      : 70
number of cycles                          : 1
Relocate Roadheader time                  : Triangular[3,5,15]
Displacement Roadheader time              : Triangular[3,5,15]
Manouevre truck time                      : Triangular[0.2,0.4,1]
Excavate and Load soil in truck time      : Triangular[13.41,19.08,38.6]
Transportation time truck                 : Triangular[0.21,1.0,3.4]
Unload soil time                          : Triangular[0.8,1,1.2]
Unload lining material time               : Triangular[10,15,20]
Repair Roadheader time                    : Triangular[10,30,120]
Maintanance Roadheader time               : Triangular[30,60,90]
Lining tunnel time                        : Triangular[60,90,120]
Surveying tunnel time                     : Triangular[20,30,45]
Extending services time                   : Triangular[30,37.5,45]


** Calculated results after simulation **

    Run              CT          TtlCst      UnitCstVol       HourlyCst        ProdRate         UnitCst
======= =============== =============== =============== =============== =============== ===============
      1      8.22804696      13164.8751      85.4862022            1600     0.364606573      4388.29171
      2      8.78405095      14054.4815      91.2628671            1600     0.341528073      4684.82718
      3      8.56968124        13711.49      89.0356493            1600     0.350071364      4570.49666
```

```
   9969      8.52316005      13637.0561      88.5523122            1600     0.351982127      4545.68536
   9970      7.90674959      12650.7993      82.1480477            1600     0.379422665      4216.93312
   9971      8.41112363      13457.7978      87.3882974            1600     0.356670539       4485.9326
   9972       8.8693219       14190.915      92.1487989            1600     0.338244573      4730.30501
   9973      9.03389301      14454.2288      93.8586286            1600     0.332082746      4818.07627
   9974      8.71779703      13948.4752      90.5745146            1600     0.344123635      4649.49175
   9975      7.95664961      12730.6394      82.6664894            1600     0.377043121      4243.54646
   9976      8.15266647      13044.2664      84.7030283            1600     0.367977766      4348.08879
   9977      8.59279423      13748.4708      89.2757842            1600     0.349129738      4582.82359
   9978      9.34280463      14948.4874         97.0681            1600     0.321102722      4982.82913
   9979      8.73722634      13979.5621      90.7763775            1600     0.343358394      4659.85405
   9980      8.35825672      13373.2108      86.8390309            1600      0.35892652      4457.73692
   9981      8.19238205      13107.8113      85.1156577            1600     0.366193859      4369.27043
   9982      8.38902419      13422.4387      87.1586929            1600     0.357610126      4474.14624
   9983      8.39406586      13430.5054      87.2110738            1600     0.357395338      4476.83512
   9984      7.99663487      12794.6158      83.0819208            1600     0.375157807      4264.87193
   9985      7.92981931      12687.7109      82.3877331            1600     0.378318834      4229.23697
   9986      8.49271929      13588.3509      88.2360446            1600     0.353243749      4529.45029
   9987      7.94022991      12704.3679      82.4958952            1600     0.377822813      4234.78928
   9988      7.69892253       12318.276      79.9888055            1600     0.389664916      4106.09202
   9989      8.23973585      13183.5774      85.6076452            1600     0.364089342      4394.52578
   9990      8.34783636      13356.5382      86.7307674            1600     0.359374558      4452.17939
   9991      7.55481187       12087.699      78.4915519            1600     0.397097909        4029.233
   9992      9.22756701      14764.1072      95.8708261            1600     0.325112784      4921.36907
   9993      8.42557011      13480.9122      87.5383907            1600     0.356058992      4493.63739
   9994       8.0411686      12865.8698      83.5446088            1600     0.373080102      4288.62325
   9995      10.1762818      16282.0509      105.727603            1600     0.294803156      5427.35031
   9996      9.42247195      15075.9551      97.8958124            1600     0.318387788      5025.31837
   9997      9.38283083      15012.5293      97.4839567            1600     0.319732931      5004.17644
   9998      8.25080285      13201.2846       85.722627            1600      0.36360098      4400.42819
   9999      9.20346728      14725.5477      95.6204393            1600     0.325964108      4908.51588
  10000      8.34090612      13345.4498      86.6587649            1600     0.359673152      4448.48327
======= =============== =============== =============== =============== =============== ===============
Average      8.44982435       13519.719      87.7903828            1600     0.356427769      4506.57299
Std Dev     0.536536799      858.458878       5.5744083               0    0.0220050718      286.152959
Minimum       6.5366006       10458.561      67.9127335            1600     0.279551115      3486.18699
Maximum        10.73149       17170.384         111.496            1600     0.458954154      5723.46134
--------------------------------------
Execution    Time = 124.531 seconds
```

Appendix X: Sensitivity analysis Laval metro tunnel

Drill and blast excavation

Excavation length per cycle

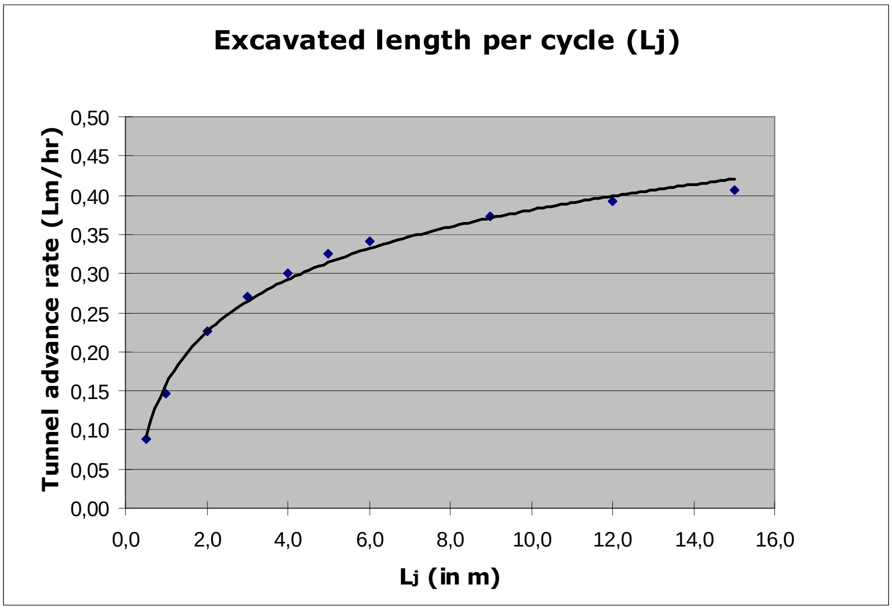


Figure 1. Sensitivity analysis on excavated length per cycle

Figure 1 shows the relationship between excavation length per cycle (L_j), and the tunnel advance rate. The excavation length per cycle is the amount of meters of tunnel that is excavated (blasted) per excavation cycle. As the length of excavated tunnel increases also the time duration of the scaling and primary support (lining) activities increase. Assuming that the relationship between the time durations of these activities and the length of excavated tunnel is linear, the graph shows that the tunnel advance rate increases significantly by increasing the amount of meters excavated (by drill and blast) per cycle.

Trucks properties

Several simulation runs are performed by changing the number of trucks used to transport the muck from the face of the tunnel to the disposal area outside of the tunnel. These trucks have a capacity of 11 m^3. The relationship between the number of trucks and tunnel advance rate is showed in figure 2. The tunnel advance rate increases by increasing the number of trucks until the number of trucks reaches 2, for the tunnel section excavated by drill and blast. For the tunnel section excavated by road header the tunnel advance rate increases by increasing the number of trucks until the number of trucks reaches 3.

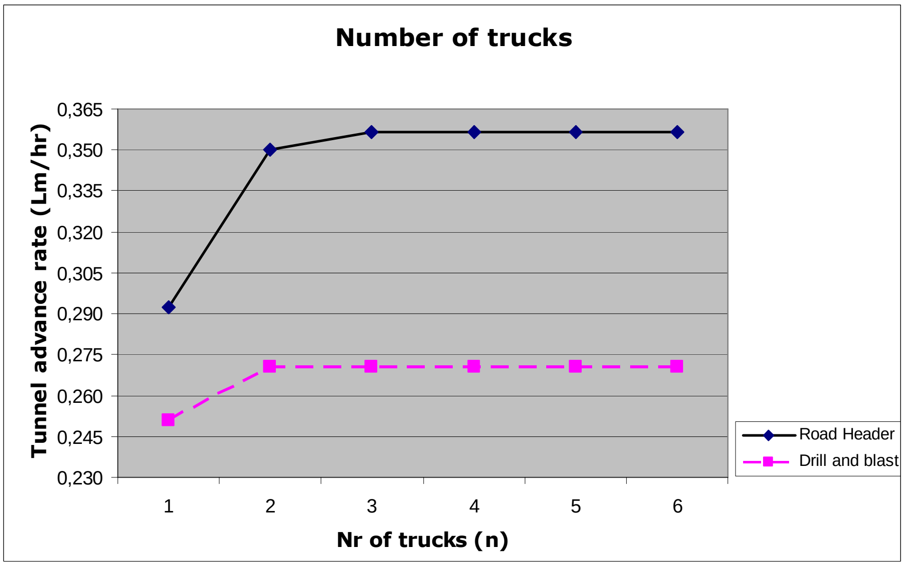


Figure 2. Sensitivity analysis on number of trucks. Trucks have capacity of 11 m^3.

Same type of analysis is also performed on the capacity of the trucks. In figure 3 the graph is presented for the relationship between capacity of the trucks and tunnel advance rate, for both drill and blast and road header excavation. The tunnel advance rate increases significantly by increasing the capacity of the trucks until the capacity reaches approximately 11 m^3, for both the tunnel section excavated by drill and blast as well as the tunnel section excavated by road header.

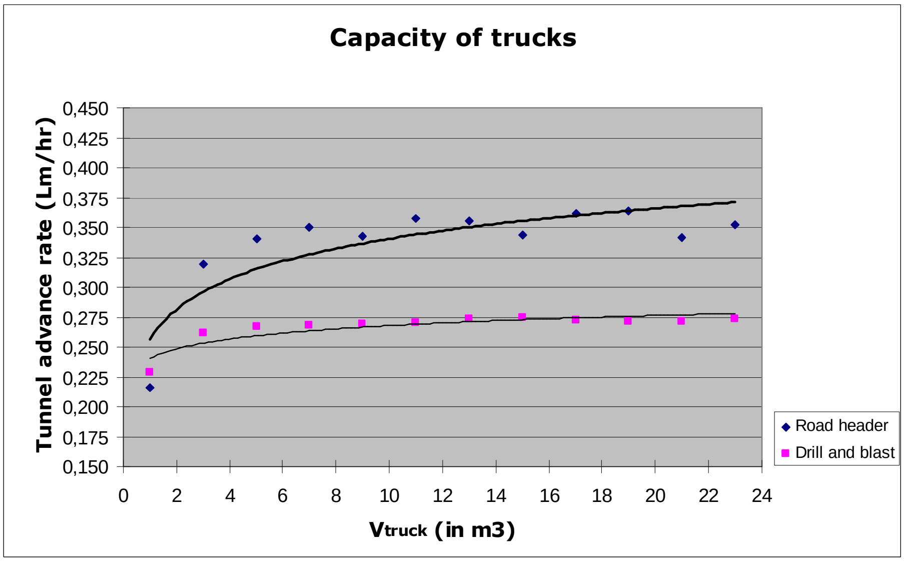


Figure 3. Sensitivity analysis on capacity of trucks

The relationship between the variable speed of trucks (km/hr) and tunnel advance rate is not explicitly investigated by sensitivity analysis. However, in the simulation model the speed of the trucks is modelled by a triangular distribution (15km/hr–25km/hr–30km/hr).

Loaders

In figure 4 the relationship of the number of loaders and tunnel advance rate is showed. The tunnel advance rate increases significantly by increasing the number of loaders. Regarding the simulation model it is assumed that there is space for only one truck at a time to manoeuvre at the face of the tunnel, and get filled by a loader. Therefore, if multiple loaders are put into use, it is assumed that these loaders load one truck at a time. It should also be mentioned that it is assumed in the sensitivity analysis that it may be possible to put into use up to 9 loaders inside the tunnel. In practice, because of the limited space inside the tunnel, no more than 2 loaders can load simultaneously one truck at the face of the tunnel. The figure also shows that besides the number of loaders, the tunnel advance rate is also limited by the materials handling considerations (number of trucks that are in use: n). If it is chosen to increase the number of loaders in the Laval metro tunnel project, it is also necessary to put into service extra trucks (until the number of trucks reaches 3), in order to significantly increase the tunnel advance rate.

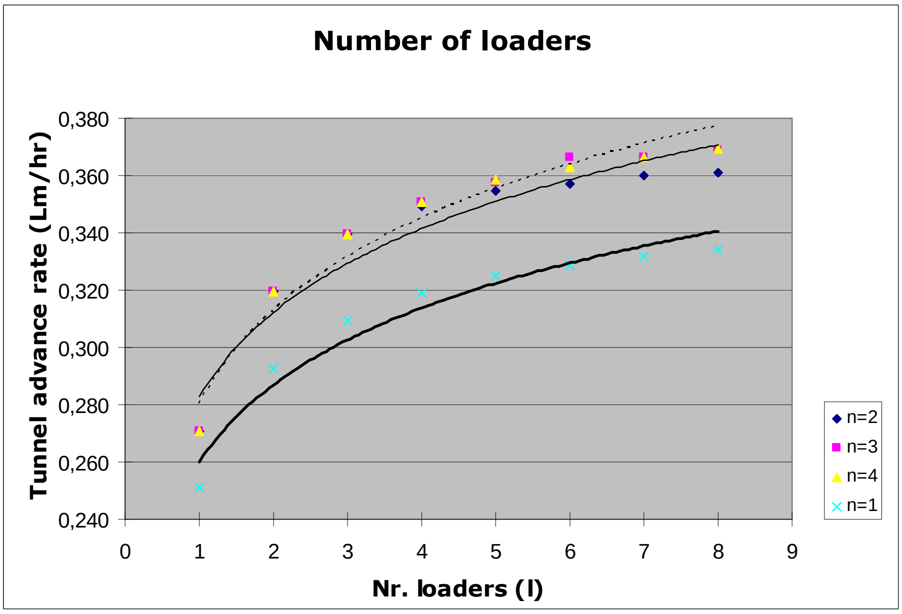


Figure 4. Sensitivity analysis on number of loaders

The relationship between the productivity of the loader (m^3/hr) and tunnel advance rate is shown in figure 5. It is based on loading trucks with capacity of 11 m^3. The tunnel advance rate increases by increasing the productivity of the loader.

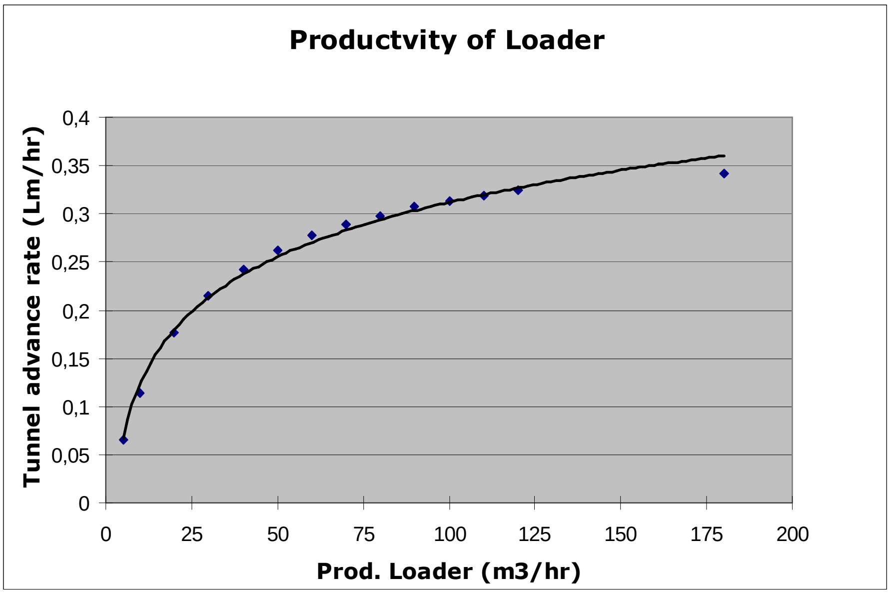


Figure 5. Sensitivity analysis on productivity of the loader

Number of resources

Figure 6 shows the relationship between various resources used in the construction process, such as drill jumbos, excavators (backhoe) and platform trucks, and the tunnel advance rate. Because of limited space inside the tunnel it is assumed that at most 2 resources of each type can be put into use simultaneously. Therefore, the tunnel advance rate increases by increasing the number of platform trucks, drill jumbos and excavators until the number of these resources reaches 2. Figure 6 shows that the numbers of platform trucks have the biggest impact on the tunnel advance rate, followed by respectively the number of drill jumbos and excavators.

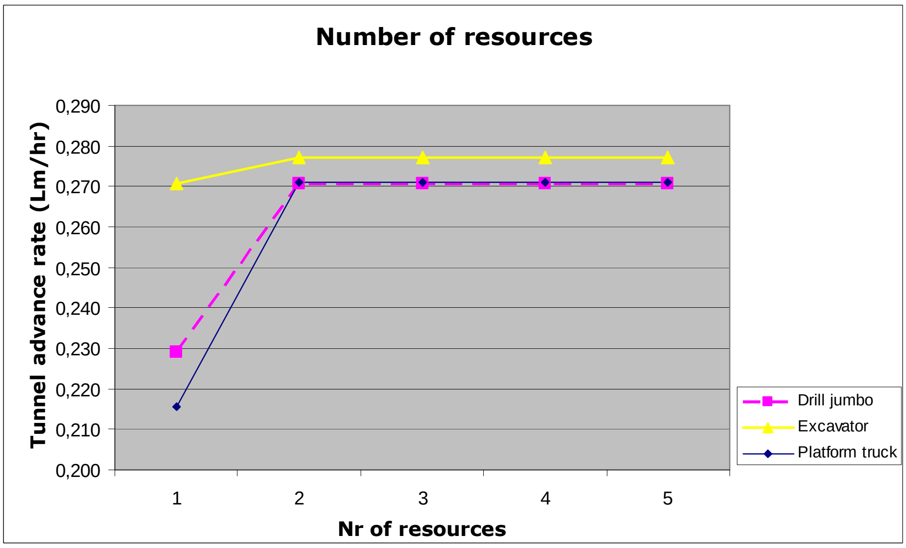


Figure 6. Sensitivity analysis on number of other resources

Tunnel dimensions and swell factor soil

In figure 7 the relationship between the swell factor of the soil and the tunnel advance rate is showed. The tunnel advance rate decreases significantly by increasing the swell factor of the soil. Bigger swell factor means more volume of muck excavated, increasing the time durations of the soil disposal activities. The impact is much more significant for the tunnel excavated by drill and blast than for the tunnel excavated by road header.

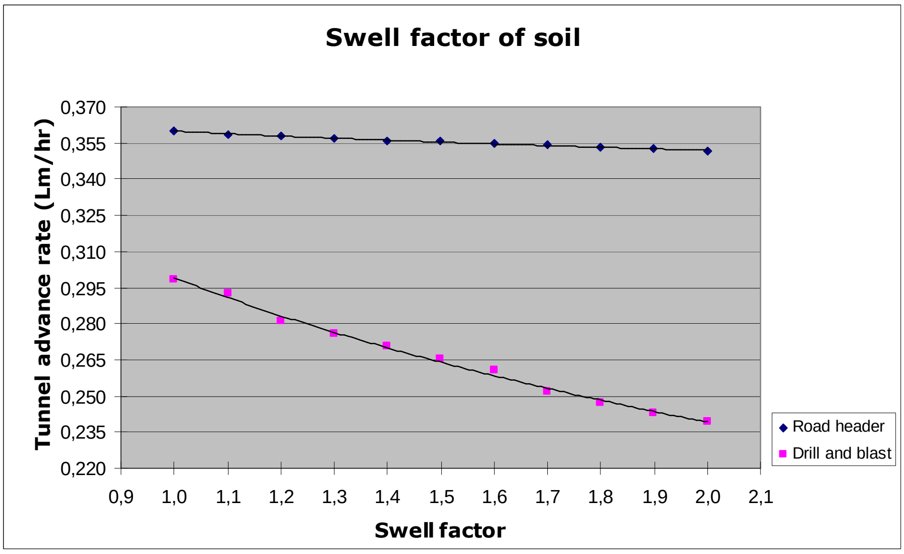


Figure 7. Sensitivity analysis on swell factor of soil

There is a difference in rate of change in the slope of the lines. For the tunnel excavated by road header, it is assumed that the calculated productivity (m^3/hr) increases as swell factor of the soil increases. Higher productivity of the road header leads to decreasing time duration for loading the trucks with excavated soil. Hence, the reason that the relationship between the swell factor and the tunnel advance rate is less significant compared with drill and blast excavation, is that on one hand the trucks need to make more runs to dispose the excavated soil, but on the other hand the time duration of filling one truck decreases. So, the cycle time of the construction process remains more constant as the swell factor increases, compared to the tunnel excavated by drill and blast.

Figure 8 shows the relationship between the cross section area of the tunnel and the tunnel advance rate. Assuming the time durations of the excavation activities (for drill and blast excavation) remain constant, the tunnel advance rate decreases significantly by increasing the cross section of the tunnel. For the section of tunnel excavated by road header it is assumed that the productivity of the road header (volume of muck excavated per hr in m^3/hr) stays constant, because the penetration rate is inversely proportional to the cross section area of the tunnel. If the surface area of the face of the tunnel increases with a certain rate, the penetration rate decreases with the same rate. Larger cross section of the tunnel results in more volume of muck excavated, increasing the time durations of the soil disposal activities, resulting in decreasing tunnel advance rates. The relationship between cross section and tunnel advance rate is much more significant for the tunnel excavated by road header than for the tunnel excavated by drill and blast.

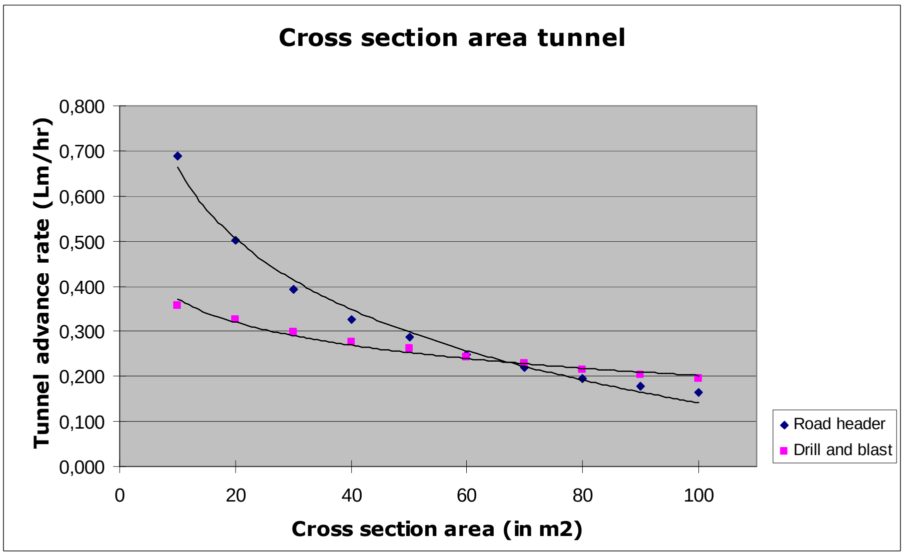


Figure 8. Sensitivity analysis on cross section area of the tunnel

As it is stated, these analyses are performed under the assumption that the time durations of the excavation activities remain constant (for the tunnel excavated by drill and blast), as the cross section area of the tunnel increases. This can be obtained by putting into service extra resources used in the excavation processes, such as drill jumbos, platform trucks and qualified personnel.

Road header excavation

Excavation length per cycle

Figure 9 shows the relationship between excavation length per cycle (Lm/cycle), and the tunnel advance rate. The excavation length per cycle is the amount of meters excavated by the road header per cycle. As the length of excavated tunnel increases it is assumed that also the time duration of the primary support (lining) activities increase. Assuming that there is a linear relationship between the time durations of this activity and the length of excavated tunnel, the tunnel advance rate increases significantly by increasing the amount of meters excavated per cycle. The figure shows that besides the pre determined excavation length per cycle, the tunnel advance rate is also limited by the materials handling considerations (number of trucks that are in use: n). This trend is more significant as the excavation length per cycle increases. So if it is chosen to increase the excavation length per cycle, it is also necessary to put into service extra trucks (until the number of trucks reaches 3), in order to significantly increase the tunnel advance rate.

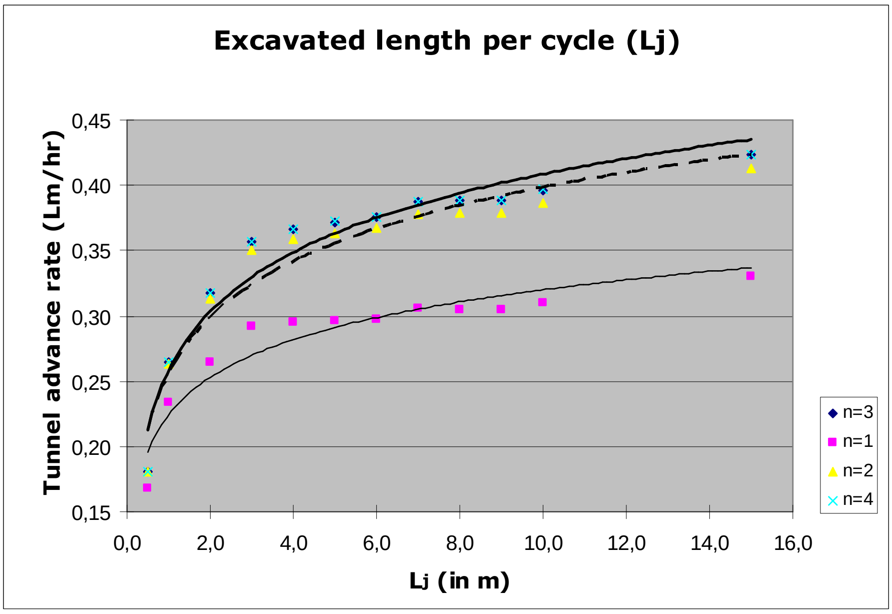


Figure 9. Sensitivity analysis on excavated length per cycle

Road header excavator

Several simulation runs are performed by changing the number of road headers used to excavate the face of the tunnel. Figure 10 shows the relationship between the number of road headers and the tunnel advance rate. The tunnel advance rate increases significantly by increasing the number of road headers used during excavation. However, it should be noticed that having many road headers in the Laval metro tunnel could be impractical, unsafe and economically unfeasible. In practice, because of the limited space at the face of the tunnel, no more than 2 road headers simultaneously can excavate and load a truck at the face of the tunnel.

Regarding the simulation model it is assumed that there is space for only one truck at a time to manoeuvre at the face of the tunnel, and get filled by a road header. Therefore, if multiple road headers are put into use, it is assumed that these road headers load one truck at a time. The figure also shows that besides the number of road header excavating at the face of the tunnel, the tunnel advance rate is also limited by the materials handling considerations (number of trucks that are in use: n). If it is chosen to increase the number of road headers in the Laval metro tunnel project, it is also necessary to put into service extra trucks (until the number of trucks reaches 4), in order to increase the productivity.

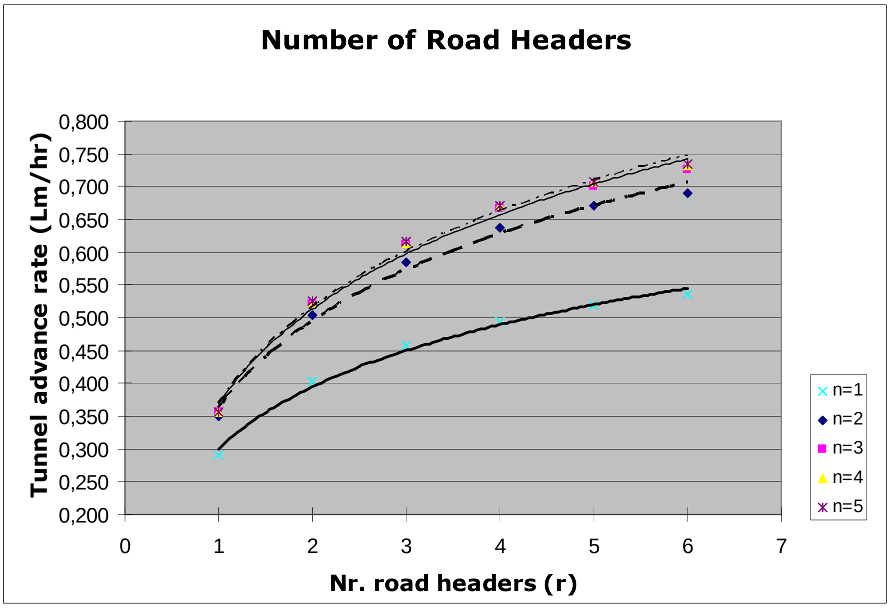


Figure 10. Sensitivity analysis on number of road headers

Figure 11 shows the relationship between the penetration rate of the road header (Lm/hr), and the tunnel advance rate. The tunnel advance rate increases significantly by increasing the penetration rate of the road header machine. The figure shows that besides the road header capacity, the tunnel advance rate is also limited by the materials handling considerations (number of trucks that are in use). This trend is more significant as penetration rate increases. Hence, as the penetration rate increases, it is also necessary to put into service extra trucks (until the number of trucks reaches 4), in order to increase the tunnel advance rate of the Laval metro tunnel project.

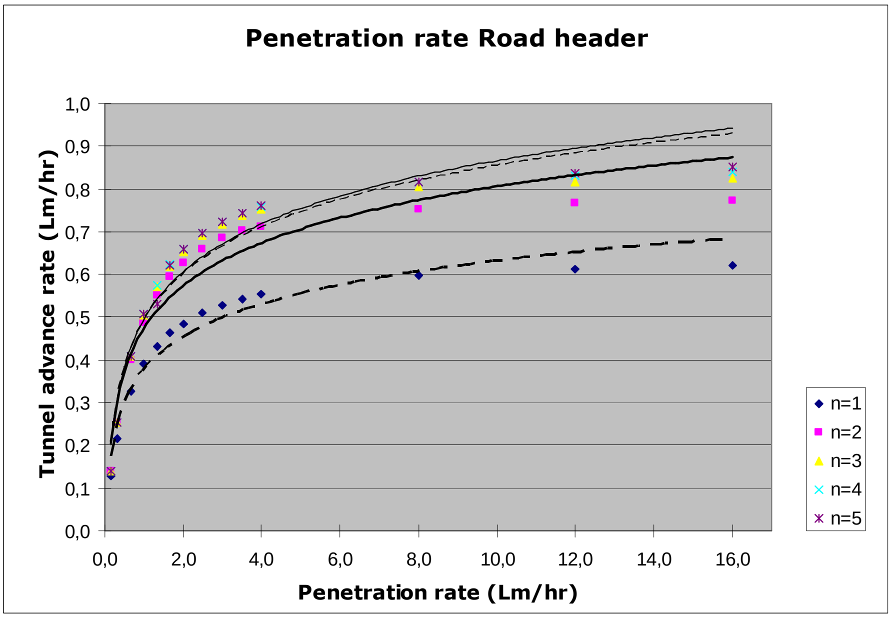


Figure 11. Sensitivity analysis on penetration rate of road header

Number of platform trucks

Figure 12 shows the relationship between number of platform trucks and the tunnel advance rate. Because of limited space inside the tunnel it is assumed that at most 2 resources can be put into use simultaneously. Therefore, the tunnel advance rate increases by increasing the number of platform trucks, until the number of platform trucks reaches 2.

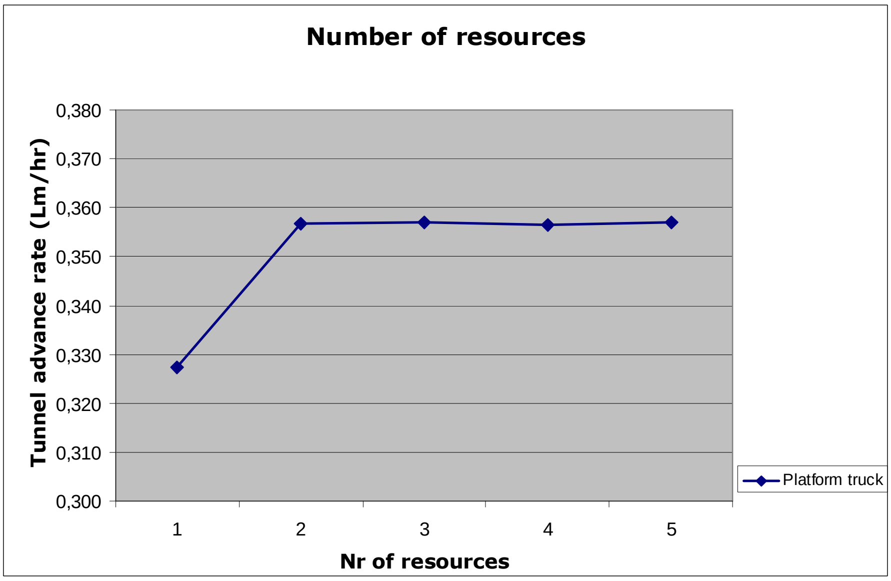


Figure 12. Sensitivity analysis on number of platform trucks

Appendix XI: Productivity and cost analysis

Resource combinations			Productivity (Lm/hr)	Unit rate ($/Lm)	Efficiency
Road headers	Soil trucks	Platform trucks			
1	1	1	0,272	4870,41	5,585E-05
1	2	1	0,322	4333,00	7,431E-05
1	3	1	0,328	4503,78	7,283E-05
1	4	1	0,328	4747,89	6,908E-05
1	5	1	0,328	4989,97	6,573E-05
1	1	2	0,292	4821,05	6,057E-05
1	2	2	0,350	4212,63	8,308E-05
1	3	2	0,357	4363,49	8,182E-05
1	4	2	0,357	4583,71	7,788E-05
1	5	2	0,357	4809,73	7,422E-05
2	1	1	0,363	4931,80	7,36E-05
2	2	1	0,447	4151,58	0,0001077
2	3	1	0,462	4184,44	0,0001104
2	4	1	0,464	4341,11	0,0001069
2	5	1	0,464	4511,61	0,0001028
2	1	2	0,400	4694,76	8,52E-05
2	2	2	0,504	3842,93	0,0001311
2	3	2	0,522	3862,69	0,0001351
2	4	2	0,524	4000,45	0,000131
2	5	2	0,524	4151,28	0,0001262

Table 1. Productivity and cost analysis resource allocation, road header excavation

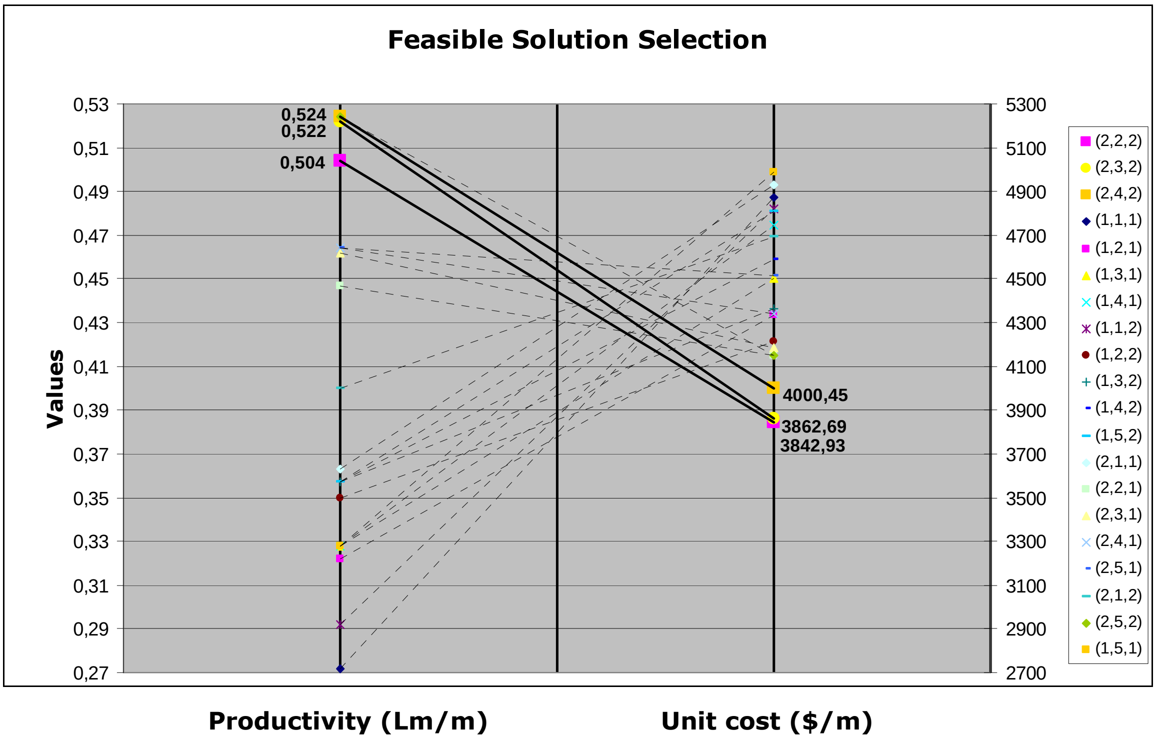


Figure 1. Feasible solution selection graph for Laval metro tunnel excavated by road header

Resource combinations					Productivity (Lm/hr)	Unit rate ($/Lm)	Efficiency
Drill Jumbos	Soil trucks	Loaders	Excavators	Platform trucks			
1	1	1	1	1	0,179	5905,62	3,031E-05
1	2	1	1	1	0,189	6030,01	3,134E-05
1	3	1	1	1	0,189	6453,48	2,929E-05
1	1	2	1	1	0,199	5789,39	3,437E-05
1	2	2	1	1	0,211	5844,59	3,61E-05
1	3	2	1	1	0,211	6225,34	3,389E-05
1	1	1	2	1	0,182	6371,20	2,857E-05
1	2	1	2	1	0,192	6461,23	2,972E-05
1	3	1	2	1	0,192	6876,71	2,792E-05
1	1	1	1	2	0,215	5283,62	4,069E-05
1	2	1	1	2	0,229	5309,41	4,313E-05
1	3	1	1	2	0,229	5657,11	4,048E-05
2	1	1	1	1	0,203	5940,09	3,417E-05
2	2	1	1	1	0,216	5969,34	3,618E-05
2	3	1	1	1	0,216	6338,44	3,408E-05
2	1	2	1	1	0,230	5675,70	4,052E-05
2	2	2	1	1	0,246	5632,52	4,367E-05
2	3	2	1	1	0,245	5962,62	4,109E-05
2	1	1	2	1	0,207	6329,58	3,27E-05
2	2	1	2	1	0,220	6317,77	3,482E-05
2	3	1	2	1	0,220	6683,42	3,292E-05
2	1	1	1	2	0,251	5123,07	4,899E-05
2	2	1	1	2	0,270	5054,45	5,342E-05
2	3	1	1	2	0,271	5350,20	5,065E-05
1	1	1	2	2	0,219	5641,63	3,882E-05
1	2	1	2	2	0,234	5633,37	4,154E-05
1	3	1	2	2	0,234	5979,70	3,913E-05
1	1	2	2	2	0,250	5333,08	4,688E-05
1	2	2	2	2	0,269	5250,88	5,123E-05
1	3	2	2	2	0,269	5544,87	4,851E-05
2	1	2	2	2	0,300	4941,98	6,07E-05
2	**2**	**2**	**2**	**2**	**0,328**	**4762,85**	6,887E-05
2	3	2	2	2	0,328	5012,66	6,543E-05
2	1	1	2	2	0,257	5406,14	4,754E-05
2	2	1	2	2	0,277	5301,17	5,225E-05
2	3	1	2	2	0,277	5587,79	4,957E-05
1	1	2	1	2	0,245	5030,65	4,87E-05
1	2	2	1	2	0,263	4986,83	5,274E-05
1	3	2	1	2	0,263	5287,95	4,974E-05
1	1	2	2	1	0,202	6187,82	3,264E-05
1	2	2	2	1	0,215	6204,64	3,465E-05
1	3	2	2	1	0,215	6582,02	3,266E-05
2	1	2	1	2	0,292	4727,38	6,177E-05
2	**2**	**2**	**1**	**2**	**0,319**	**4580,73**	6,964E-05
2	3	2	1	2	0,319	4832,50	6,601E-05
2	1	2	2	1	0,234	6001,78	3,899E-05
2	2	2	2	1	0,251	5918,88	4,241E-05
2	3	2	2	1	0,251	6238,82	4,023E-05

Table 2. Productivity and cost analysis resource allocation, drill and blast excavation

Resource combinations			**Productivity (Lm/hr)**	**Unit Cost ($/Lm)**	**Efficiency**
Road headers	Soil trucks	Platform trucks			
1	1	1	0,241	5503,90	4,3787E-05
1	2	1	0,285	4893,53	5,824E-05
1	3	1	0,290	5089,47	5,698E-05
1	4	1	0,290	5363,62	5,4068E-05
1	5	1	0,290	5642,07	5,14E-05
1	1	2	0,256	5482,76	4,6692E-05
1	2	2	0,307	4806,39	6,3873E-05
1	3	2	0,312	4976,90	6,269E-05
1	4	2	0,313	5229,30	5,9855E-05
1	5	2	0,313	5485,24	5,7062E-05
2	1	1	0,330	5421,86	6,0865E-05
2	2	1	0,408	4538,93	8,9889E-05
2	3	1	0,422	4578,54	9,2169E-05
2	4	1	0,424	4744,77	8,9362E-05
2	5	1	0,424	4933,64	8,5941E-05
2	1	2	0,361	5201,12	6,9408E-05
2	2	2	0,454	4260,70	0,00010656
2	3	2	0,472	4261,92	0,00011075
2	4	2	0,474	4418,71	0,00010727
2	5	2	0,474	4578,98	0,00010352

Table 3. Productivity and cost analysis resource allocation, road header excavation

Appendix XII: Simulation model of Bathurst & Langstaff tunnel project

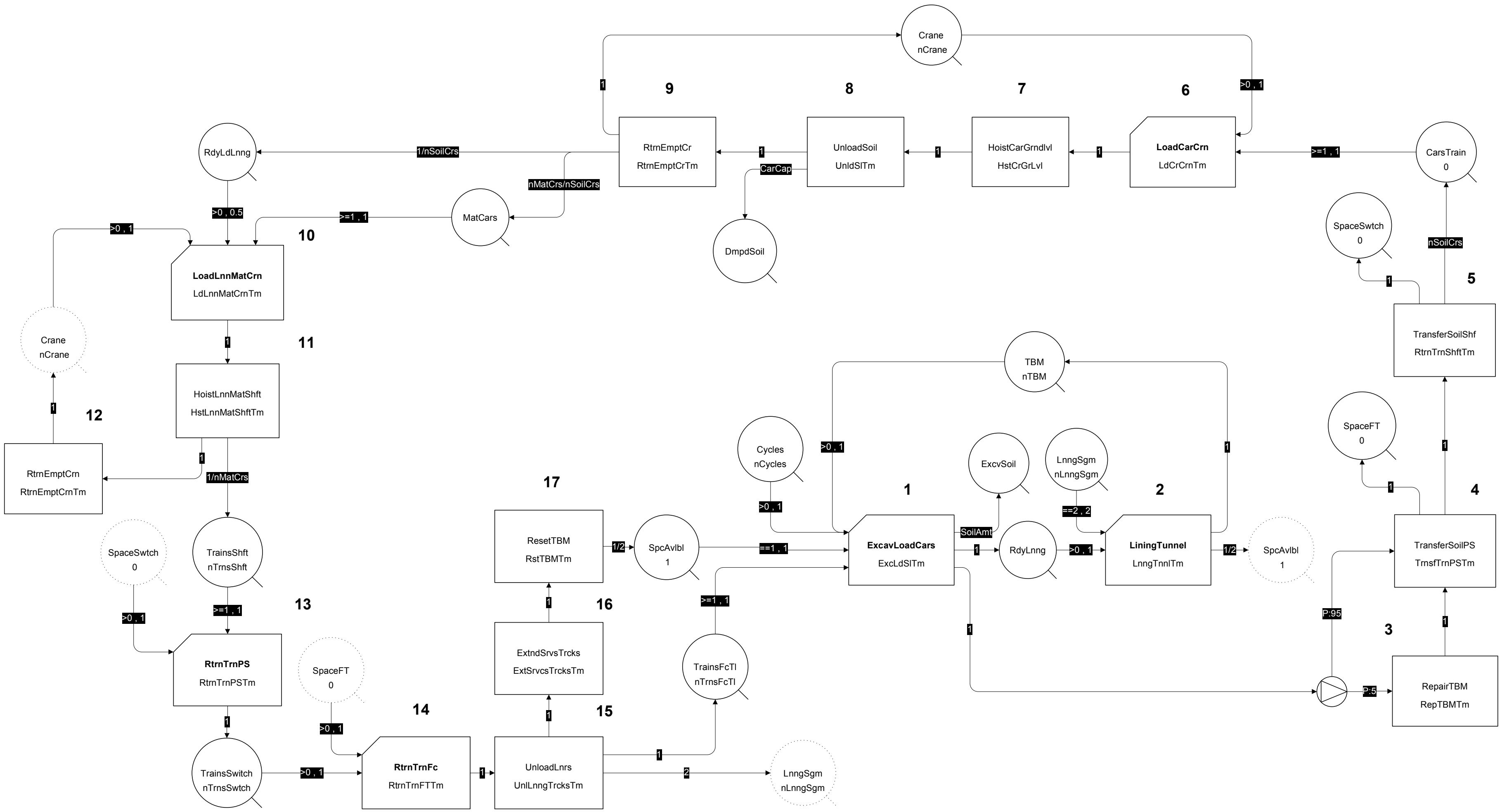


Figure 1. EZstrobe simulation model of Bathurst & Langstaff sewer tunnel project

The EZstrobe simulation model of the Bathurst & Langstaff sewer tunnel project is described in figure 1. In table 1 the tunnelling activities, as presented in the simulation model, are described.

Nr.	Model activity	Activity description
1	Excavate and load train	Excavating and simultaneously loading cars with soil produced by the TBM
2	Lining tunnel	Lining of the tunnel with TBM machine to install the pre-cast lining segments
3	Repair TBM	Repairing the TBM
4	Transfer train towards passing station (switch)	Travelling of train from face of the tunnel to the passing station inside the tunnel
5	Transfer train towards shaft	Travelling of train from the passing station inside the tunnel towards the shaft of the tunnel
6	Load car on crane	Loading muck car on crane system at shaft
7	Hoist muck car to ground level	Hoisting the muck car towards ground level by crane
8	Unload soil	Unload soil from muck car
9	Return empty crane	Returning of empty crane system towards undercut area of the shaft, to hoist next muck car
10	Load lining material on crane	Loading pre-cast lining segment on crane system at ground level
11	Hoist lining material	Hoisting the lining material towards undercut area of the shaft by crane
12	Return empty crane	Returning of empty crane system towards ground level, to hoist next pre-cast lining segment
13	Return train towards passing station (switch)	Travelling of train from shaft of the tunnel to the passing station inside the tunnel
14	Transfer train towards face tunnel	Travelling of train from the passing station inside the tunnel towards the face of the tunnel
15	Unload liners	Unloading the pre-cast lining segments
16	Extending services and rail tracks	Extending the air and water lines , and rail tracks inside the tunnel
17	Reset TBM	Resetting TBM for next excavation cycle

Table 1. Simulation model's activities of Bathurst & Langstaff sewer tunnel project

Table 2 and 3 describe the various parameters used in the simulation model, with their corresponding values and description. Also cost figures are included of resources. Table 2 discusses the variables that are not explicitly described in the simulation model, but are used to determine the probability distributions of various model's activities.

Model variables	Symbol	Value
Penetration rate TBM (Lm/hr)	A	Triangular[1.2,6.0,12.0]
Speed of train (km/hr)	v_{train}	Triangular[7.5,10,12.5]
Length tunnel (in m)	L	2550
Speed crane system empty and loaded (in km/hr)	$v_{vert,\,e}$-$v_{vert,\,l}$	46 – 16
Height shaft (in m)	L_{shaft}	24
Excavation length / stroke length TBM (in Lm/cycle)	L_j	1.2
Swell factor of soil	S	1.2
Cross section area tunnel (in m2)	W	8.3

Table 2. Tunnelling construction variables of Bathurst & Langstaff sewer tunnel project

Par. Name	Parameter Discription	Parameter Value
SoilAmt	amount of soil excavated per train in m3	12
CarCap	car capacity in m3	3
nTrnsFcTl	number of trains at face tunnel	1
nTrnsShft	number of trains at shaft tunnel	1
nTrnsSwtch	number of trains at switch inside tunnel	1
nSoilCrs	number of soil cars	4
nMatCrs	number of material cars	2
nTBM	number of TBM	1
nCrane	number of cranes	1
nLnngSgm	number of precast lining segments	2
nCrew	number of labor in crew	6
TBMCst	TBM cost ($/hr)	850
TrainCst	Train cost ($/hr)	15
TrainCarCst	Train car cost ($/hr)	1
CraneCst	Crane cost ($/hr)	90
LaborCst	Labor cost ($/hr)	50

Table 3. Tunnelling construction parameters of Bathurst & Langstaff sewer tunnel project

In table 4 the probability distributions of the time durations per activity are described. The transportation time durations of the trains are not specified. These time durations depend on the length of the tunnel, the position of the passing station (switch) inside the tunnel and the speed of the trains.

Activity nr.	Parameter Name	Parameter Description	Parameter Value (in min)
1	ExcLdSlTm	Excavate and Load soil in train time	Triangular[6.0,12.0,60.0]
2	LnngTnnlTm	Lining tunnel time	Triangular[10,15,20]
3	RepTBMTm	Repair TBM time	Triangular[30,120,240]
4	TrnsfTrnPSTm	Transfer train passing station time	Triangular[x,x,x]
5	TrnsfTrnShftTm	Transfer train shaft time	Triangular[x,x,x]
6	LdCrCrnTm	Load soil car on crane time	Triangular[1,1.5,2]
7	HstCrGrLvl	Hoist car towards ground level time	Triangular[1.2,1.5,2.4]
8	UnldSlTm	Unload soil time	Triangular[0.25,0.5,0.75]
9	RtrnEmptCrTm	Return empty car time	Triangular[0.44,0.52,0.69]
10	LdLnnMatCrnTm	Load lining material on crane time	Triangular[0.5,1,1.5]
11	HstLnnMatShftTm	Hoist material towards ground level time	Triangular[1.2,1.5,2.4]
12	RtrnEmptCrnTm	Return empty crane time	Triangular[0.44,0.52,0.69]
13	RtrnTrnPSTm	Return train passing station time	Triangular[x,x,x]
14	RtrnTrnFTTm	Return train face tunnel time	Triangular[x,x,x]
15	UnlLnngTrcksTm	Unload lining material, rail tracks time	Triangular[0.5,1,1.5]
16	ExtSrvcsTrcksTm	Extending services and rail tracks time	Triangular[1.33,1.67,2.5]
17	RstTBMTm	Reset TBM time	Triangular[3,5,7.5]

Table 4. Parameters of probability distributions of simulation model's activities