Analysis of microtunnelling construction operations using process simulation

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Contents

List of Tables

List of Figures

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification at this or any other university. This dissertation is entirely the result of my own work and includes nothing which is the outcome of work done in collaboration. This dissertation contains less than 40,000 words and less than 90 figures.

Trung Thanh Dang
Bochum, August 2013

Abstract

Microtunnelling operations involve a complex interaction of processes that require a variety of supporting equipment and personal experience. Furthermore, different construction processes such as supply chain management for the machine or for material handling must be integrated. Breakdowns of critical processes will directly affect the performance of the construction, with impacts on extended construction time, increased cost as well as reduced productivity of the microtunnelling project. If the construction process is reasonably planned, the construction operations may be controlled and adjusted more efficiently. The use of operational process simulation can be a benefit for planning and operating a microtunnelling project. Thereby, problems at different construction phases can be anticipated and analyzed. Moreover, it has potential to optimize usage of resources, to develop better project plans, to minimize costs or project duration, to improve overall construction project management and to avoid costly mistakes.

This thesis presents an approach for analyzing construction operations with micro tunnel boring machines (MTBM) utilizing process simulation. The goal is to develop an appropriate and adaptable simulation module for microtunnelling construction operations. It helps to analyze the processes and to identify the factors, which influence the operation productivity of the construction process essentially. In addition, the influence of different soil conditions and of disturbances on the productivity of microtunnelling operations have to be determined. In view of these objectives, a System Modeling Language (SysML) model describing the microtunnelling process is developed in the first step. The simulation model consists of three types of diagram: block definition diagram (bdd), state machine diagram (stm) and sequence diagram (sd), which are supported in the SysML. The simulation model is used to analyze and understand the entire process involved in microtunnelling construction and identify the model variables for which information needs to be collected. Subsequently, the simulation software AnyLogic is applied to create the MiSAS (Microtunnelling: Statistics, Analysis and Simulation) simulation module based on the SysML formalization. The implementation of the proposed methodologies, utilizes discrete event simulation (DES) and system dynamic (SD) modelling. Three actual microtunnelling projects at the city of Recklinghausen, Germany, are used for the validation of the developed simulation module. After validation, the simulation module is expanded with considerations of different soil compositions and disturbances of operations. The simulation module allows to evaluate the impact of the different ground conditions, disturbances and predict the resulting tunnel advance rate. Further, the impact of varying resources on the MTBM advance rate is studied in a sensitivity analysis.

Kurzfassung

Die Vorgänge beim Microtunnelbau beinhalten ein komplexes Zusammenspiel von Prozessen, die eine Vielzahl von unterstützenden Geräten und persönlicher Erfahrung erfordern. Darüber hinaus müssen unterschiedliche Prozesse auf der Baustelle, wie „Supply Chain Management“ für Maschinen oder für das „Material Handling“, integriert werden. Ausfälle von kritischen Prozessen haben dabei direkte Auswirkungen auf die Leistungen der Konstruktion, wie z.B. verlängerte Bauzeiten, höhere Kosten sowie geringere Produktivität der Projekte. Wenn der Bauprozess geplant wird, können die Bau-Operationen effizienter kontrolliert und angepasst werden. Die Verwendung von operativen Prozesssimulationen kann einen Vorteil für die Planung und den Betrieb von Projekten bringen, da dadurch die Probleme bei den verschiedenen Bauphasen berechnet und analysiert werden. Darüber hinaus hat die Prozesssimulation das Potential, die Nutzung von Ressourcen, die Abwicklung der Projektpläne, die Minimierung von Kosten-oder Projektdauern, die Verbesserung der Gesamtkonstruktion und die Vermeidung von kostspieligen Fehlkalkulationen, zu optimieren.

Diese Dissertation präsentiert einen Ansatz zur Analyse von Tunnelbauwerken mit Mikrotunnelbohrmaschinen (MTBM) unter Verwendung einer operativen Prozesssimulation. Das Ziel dabei ist die Entwicklung eines anpassungsfähigen Simulationsmodells für den Microtunnelbau, welches der Prozessanalyse und der Identifikation der Faktoren, die die Betriebsproduktivität der Konstruktionsprozesse im wesentlichen beeinflussen, dient. Darüber hinaus haben unterschiedliche Bodenverhältnisse einen Einfluss auf die Produktivität beim Tunnelbaubetrieb, sodass ihre Bestimmung von großer Bedeutung ist. In Hinblick darauf, wird in einem zweiten Schritt ein Systemsprachenmodell (SysML) zur Beschreibung der Microtunnelbauprozesse entwickelt. Das Simulationsmodell besteht aus drei Arten von Diagrammen, die in SysML unterstützt werden: block definitions diagramm (bdd), maschinenzustands diagramm (stm) und sequenzdiagramm (sd). Das Simulationsmodell wird zur Analyse und zum Verständnis der gesamten Prozesse im Mikrotunnelbau verwendet, indem die Informationen der Modellvariablen gesammelt werden. Anschließend wird die Simulationssoftware AnyLogic angewendet, um die MiSAS (Microtunnelling: Statik, Analyse und Simulation) –Simulation, die auf der Formalisierung des SysML-Moduls basiert, zu erstellen. Die Umsetzung der vorgeschlagenen Methoden nutzt die diskrete Ereignis-Simulation (DES) und System-dynamische (SD)-Modellierung. Dabei werden drei gegenwärtige Mikrotunnelbau Projekte der Stadt Recklinghausen (Deutschland) zur Validierung des entwickelten Simulationsdoduls verwendet. Nach der Validierung wird das Simulationsmodul durch verschiedene Bodenzusammensetzungen und Betriebsstörungen erweitert. Das Simulationsmodul ermöglicht es, die Auswirkungen der Störungen der unterschiedlichen Bodenverhältnisse beurteilen und die resultierende Tunnelvortriebsgeschwindigkeit vorhersagen zu können. Ferner wird in einer Sensitivitätsanalyse, der Einfluss der unterschiedlichen Ressourcen auf die Vortriebsgeschwindigkeit der MTBM untersucht.

Acknowledgements

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And finally, I would like to thank my wife Ngoc Linh Hoang, and my daughter Linh Chi Dang for cheering me up and standing by me through the good times and the bad. I would like to dedicate this work to my beloved wife and daughter.

Trung Thanh Dang
Bochum, August 2013

Chapter 1

Introduction

1.1 Motivation

The first Microtunnel Boring Machines (MTBM) were used in Japan in the early 1970s and spread to Europe before eventually being applied in the United States. According to the information from Herrenknecht AG (the largest manufacturer of tunnel boring machines in the world) more than one thousand microtunnelling machines have been sold in the last 20 years (Herrenknecht AG, 2013a). And currently, the use of microtunnelling methods for small tunnels is growing continuously. In Japan, several hundred kilometers of tunnel construction using MTBM are built per year; in Germany and the UK it spans several dozen kilometers whereas in France it is less than 10 kilometers per year (French Society for Trenchless Technology, 2004). In addition, since the tunnel construction with microtunnelling has been established, it has been proven that it can significantly minimize the social and environmental impacts related to the traditional open-trench method of small tunnel construction. At the same time, the implementation of microtunnelling has also been proven to be cost effective with regard to direct costs of the construction as well as social costs, while increasing intangible benefits (Nido et al., 1999).

Microtunnelling operations involve complex operation processes that require a variety of supporting equipment, personal experience and the integration of different construction processes such as supply chain management for the machine or for material handling. Breakdowns of critical processes might directly affect the performance of the construction, which can include extended construction time as well as reduction of productivity of the microtunnelling project. Furthermore, the productivity of microtunnelling underlies several dynamic, uncertain variables and disturbances, such as weather, limited space, staff absenteeism, regulatory requirements, design changes and reworks. Hence, there is a need for a better understanding of the construction process and of those factors influencing productivity. The efficiency of MTBM will be increased by that knowledge.

Various types of methods and tools are found to be useful in order to analyze the construction operations. For instance, in construction management mathematical models are often used for estimating problems of planning and control, such as project scheduling, cash flow management and resource management. And nowadays, the use of process simulation methodology in construction is found as being one of the most effective methods for the modeling, analysis and understanding of processes related to analyzing, planning and scheduling of construction projects. Using process simulation, real operations can reasonably accurately be modeled and the whole construction process can be analyzed in depth, so that potential problems can be identified. Furthermore, 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 a certain level of productivity (resource allocation), and site planning. This information can be useful and valuable for construction managers in the construction site, so that processes can be redesigned and resources reallocated, if necessary, to improve the productivity of construction operations.

Due to the issues discussed above, the process simulation methodology is used in order to simulate and analyze microtunnelling projects in this research.

1.2 The role of simulation in the analysis and improvement of construction operations

Simulation methods in construction operations have been used for various objectives and had different contributions. Such as a few roles of process simulation already discussed in the previous paragraph, other roles of operation simulation are described in the literature. Banks (1999) and Ruwanpura et al. (2000) described the role of process simulation for tunnelling construction operations as follows:

- 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.
- Analysis of bottlenecks to identify the factor that causes system delay.
- Prediction of a system performance under different conditions.

- Examining productivity improvements and optimizing resource utilization: Simulation enables 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.

- The use of sensitivity analysis to identify the factors affecting the performance of a system.

In addition, for the special purpose simulation template, a process simulation method is useful for evaluating various tunnelling options, and allows to test the validity of the various construction planning strategies. It is also useful for predicting the productivity of tunnelling and evaluating the cost and duration of various construction scenarios. By using process simulation, it is possible to help the managers to view and understand all of the activities, behaviors or disturbances that can occur in the system. Thereby, the expensive mistakes can be avoided in fact. The relevance of process simulation to the research work presented here is gaining understanding regarding the disturbances, different types of soil conditions affecting project total time of microtunnelling projects.

1.3 Content of the thesis

1.3.1 Objectives of research

The goal of this thesis is the development of an appropriate and adaptable simulation model for microtunnelling operations. The focus is on the evaluation of the effects of alternating soil conditions and disturbances on the productivity of the microtunnelling process. In addition, the impact of the resources on the MTBM advance rate is carried out by sensitivity analysis in this research as well. For tackling this goal, the specific objectives of this thesis are summarized as follows:

- Analysis of the tunnel construction processes and the resources required during tunnel construction with MTBM;

- Analysis and assumption of the effect of the disturbances on the construction site;

- Development of a simulation model describing the tunnel construction process with microtunnelling based on Systems Modeling Language (SysML);

- Development of the simulation module MiSAS (Microtunnelling: Statistics, Analysis and Simulation) based on the developed SysML simulation model and AnyLogic simulation software;

- Validation and enhancement of the MiSAS simulation module with consideration of the soil composition and disturbances;
- Analysis of the correlation between soil composition, disturbances and productivity by using the MiSAS simulation module.

1.3.2 Structure

In Chapter 2, a broader view on simulation will be illustrated. The chapter begins with the review of the evolution of process simulation methodology and the use of simulation for different types of analysis in construction followed by tunnelling construction processes. Subsequently, the advantage and limitation of the methodology will be described. The overview of AnyLogic simulation software, which has been used for the study, will be represented as well. This software has been applied for the development of the simulation module, which helps to understand the construction processes and the factors that have an impact on productivity.

In Chapter 3, the analysis of the processes of microtunnelling will be presented. Next, important resources, equipment and construction process sequences required during tunnel construction with MTBM will be analyzed. The description and assumptions of the disturbances affecting the construction sequences will be focused on at the end of Chapter 3.

Chapter 4 outlines the fundamental principle of the Systems Modeling Language (SysML) methodology. The characteristics of simulation language used in order to develop the simulation model will be described. Subsequently, the application of SysML simulation language for establishing the simulation model for tunnel construction with MTBM will be illustrated towards the end of that chapter.

At the beginning of Chapter 5, the development of the simulation module MiSAS will be presented. After that, a short introduction on the core functions of MiSAS will be given.

In Chapter 6, the data collection from job sites will be discussed. The procedures for data collection and chosen construction sites will be described. Details of each job site, including soil conditions and disturbances will be represented. The duration for preparation as well as excavation for microtunnelling will also be characterized.

In Chapter 7, the implementation of the developed simulation module will be described. The verification of the simulation module will be discussed at the beginning of that chapter. Subsequently, the analysis of the factors that effect the productivity of microtunnelling will be implemented by using the enhanced simulation module.

In Chapter 8, the contributions of the research proposed in this thesis will be summarized along with an outline of future work.

Chapter 2

State of the art

2.1 Perspective on the evolution of simulation systems

Process simulation methodology has been applied in different fields including computer science, manufacturing, business, environmental, and construction (Roberts and Dessouky, 1998; Banks et al., 2000). Shannon (1975) defined the simulation 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”*.

Simulation has been a widely used tool for design and analysis for more than 50 years (Jeffrey, 2003). In the 1960’s, the simulation language GPSS (General Purpose Simulation System) was introduced (Greenberg, 1972). It pioneered an emphasis on a modeling methodology that conceals from the user the mechanics of the simulation. GPSS was built upon a predefined class of entities called *”transactions”* which flowed through a flowchart of selected operations; similar to the flowcharts of procedural programming languages (Thomas, 1984). In the 1970’s and 80’s, several languages were introduced and/or modified e.g. SIMSCRIPT (Russell, 1988), SLAM (Pritsker, 1986), SIMAN (Pegden, 1985) and GPSS/H (Schriber, 1974). These languages tried to satisfy the dual goals of generality found in programming languages, and convenience of simulation languages by providing a set of predefined concepts for modeling.

The prevalent approach for simulating construction operations has traditionally been discrete-event simulation (DES) and system dynamics (SD). The DES is an old method created in the 1960s. The DES is used for modeling the operation of a system as a chronological sequence of events. The SD is older than DES and was found in the mid-1950s by an electrical engineer (Forrester, 1961). The SD is employed to analyze and understand the behavior of complex systems over time. Using the DES and SD, since the 1970s, researchers have spent considerable effort to develop simple simulation tools so that they can be applied in the industry. According to the author's point of view, the use of DES, SD in construction is not widespread due to computer technology being undeveloped at that time. In the next paragraph the progress of the application of process simulation in construction after the 1970s will be reviewed.

After the 1970s the progress of the application of process simulation methodology has been growing very fast, and in the opinion of AbouRizk (2010), has occurred over three stages of construction simulation development:

The first stage was led by Halpin (1977) with his introduction of the CYCLONE method (based on Discrete-Event Simulation methodology). The CYCLONE method is the oldest one and helped to make process simulation methodology popular. It is a modeling technique that allows the graphical elements (e.g. queue, normal, and combined nodes in CYCLONE) representation and simulation of discrete systems that deals with deterministic or stochastic variables. Since the development of CYCLONE, the simulation methodology has proven to be an extremely useful analysis tool and improved the performance of construction processes with many successful applications. In the next chapter some of the successful applications of the CYCLONE model in construction and tunnel construction will be described. The advantages of the CYCLONE model are that it is well established, widely used, as well as its simplicity and the ability to effectively model many simple construction operations. But due to the simplicity of the method and the CYCLONE's inability to explicitly model resources, it creates limitations for developers to built the complex simulation model. As a simple example, using the CYCLONE in order to simulate the earth-moving, if two trucks with different properties are used in the model, it would be difficult to distinguish them and the user would need to manipulate the trucks in the CYCLONE model (AbouRizk, 2010). Therefore, many of the enhancements of CYCLONE overcame the limitations and thus offered the modeler more flexibility. The different simulation implementations have been enhancements developed utilizing CYCLONE which involve INSIGHT of Paulson et al. (1987), RESQUE of Chang and Carr (1987), UM-CYCLONE of Ioannou (1989), MicroCYCLONE of Halpin (1990), ABC of Shi (1999), DISCO of Huang et al. (1994), HSM of Sawhney and AbouRizk (1995b), and HKCONSIM of Lu et al. (2003). Besides the method described above, there are three types of methodologies in the field of simulation: DES, SD and ABM (agent based modelling) which have become common simulation methodologies nowadays. The integration of DES, SD and ABM are used in this research. Thus, the fundamental principles of DES, SD and ABM will be presented

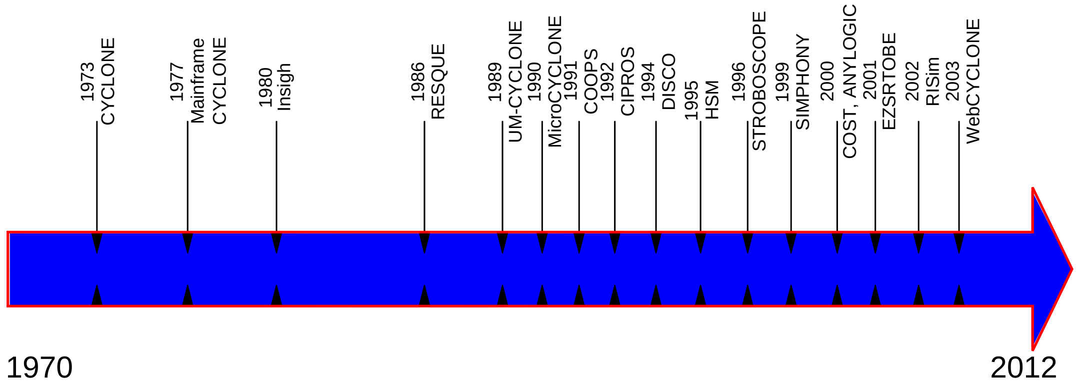


Figure 2.1: The evolution of process simulation programs (modified from Abduh et al. (2010))

in more detail in the next section 2.2.

The second stage is the evolution in programming language. The characterization of the second stage of development is the emphasis on more modeling and simulation capability compared to previous tools. To achieve this, since the early 1990s until 2000, a number of simulation systems and simulation applications were introduced. Liu and Ioannou (1992) developed a new object-oriented system that enhances CYCLONE's methodology, called COOPS. The COOPS models are defined via a graphical user interface where the simulator can capture resources, define different resources and can link with the calendars that can be used to pre-empt activities during work breaks. Odeh et al. (1992) and Tommelein et al. (1994) developed an object-oriented system CIPROS that models construction processes by matching resource properties to those of design components. CIPROS enables the user to relate construction plans and specifications to a construction plan. It also integrates process level and project level planning by representing activities through process networks, all of which can use a common resource pool. McCahill and Bernold (1993) developed a general purpose system called STEPS with a library consisting of standard models for common construction processes. STEPS has been expanded for the U.S. Navy and supported the notion of different resource sizes in the same queue. Martinez and Ioannou (1994); Martinez (1996) introduced STROBOSCOPE as a general purpose simulation programming language. In order to apply STROBOSCOPE for the construction operation, the modeler needs to write a series of programming statements that define the network modeling elements. STROBOSCOPE is used in the analysis of construction operations. It is designed for modeling complex construction operations in detail and for the development of special purpose simulation tools. AbouRizk and Hajjar (1998) developed a simulation language called Simphony capable of general purpose modeling, as well as useful for creating special purpose simulation tools for industry.

The third stage is a concentrated move towards the integration of simulation with other tools, especially visualization. Since 1990 many applications have been developed e.g. Xu and AbouRizk (1999) introduced how 3D AutoCAD models can be integrated with computer simulation to facilitate better decision-making during construction. Kamat and Martinez (2003) introduced the Vitascope language, a discrete-event simulation system designed for the integration with 3D visualization capabilities developed for simulation of construction applications as an integrated platform.

The perspective on the evolution of process simulation methodology has been summarized above. It has been shown that process simulation methodology has evolved since its inception in the 1970s and the documented successes have mostly been in academic and research fields rather than in industry. The historical evolution of process simulation methodology is summarized in Figure 2.1.

In the following section, the fundamental principles of DES, SD, ABM and the use of process simulation methodology for different types of analysis of construction and tunnelling construction processes will be presented, respectively.

2.2 Fundamental principles of DES, SD and ABM

This section is by no means a full description of DES (discrete-event simulation), SD (system dynamics) and ABM (agent based modelling), there are many books or papers on these methodologies. But a brief introduction of the core meaning of the methodologies will be given. More information concerning DES, SD and ABM methodologies are provided in Goti (2010); Doebelin (1998); d'Amours and Guinet (2003), respectively.

2.2.1 Discrete-Event Simulation (DES)

The DES paradigm is typically used in simulation studies to model and analyze construction sequences. It is an old method created in the 1960s by Geoffrey Gordon when he conceived and evolved the idea for GPSS (General Purpose Simulation System) and brought about its IBM implementations (Gordon, 1962). The method is the most commonly used one for modeling sequences of a system, e.g. construction sequences (Koenig, 2011). The entities (transactions in GPSS) are passive objects that represent people, parts, documents, tasks, messages, etc. They travel through the blocks of the flowchart where they stay in queues, are delayed, processed, seize and release resources, split, combined, etc (Borshchev and Filippov, 2004). Each event occurs at an instant in time and marks a change of state in the system (Robinson, 2004).

The common technique is called flowcharts and state-charts (state-machines) that

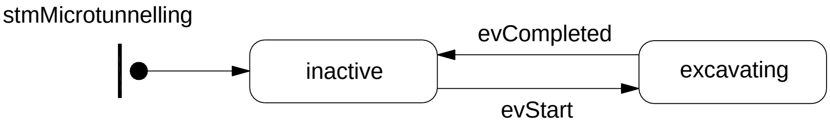


Figure 2.2: Discrete event description of MTBM operation

uses the DES concept to graphically illustrate the application of the paradigm. Normally, one state-charts is integrated by two major elements - namely states and transitions (Rahm et al., 2012). The states represent the behavior of a system. The transitions describe the movement between different states as time passes (Object Management Group, 2007).

A simple example of the use of state-machines (stm) in order to explain the application of the discrete event modeling in the simulation model. Figure 2.2 represents the stm of MTBM. The initial state of the system is *inactive*. When the event *evStart* is active, the system changes to the state *excavating*. The *excavating* state is finished when the transition *evCompleted* occurs, the system changes to the state *inactive* again.

2.2.2 System Dynamics (SD) modeling

Another widely used simulation technique is SD. The SD modeling is almost as old as DES. The system dynamics is created in the mid-1950s by an electrical engineer Forrester (1961) and the principles of system dynamics were formed in the 1950s and early 1960s, and remain unchanged today. System dynamics is *"the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise"* (Forrester, 1958, 1961). The range of SD applications includes also urban, social and ecological types of systems. In system dynamics, the real world processes are represented in terms of stocks (e.g. of material, knowledge, people, money), flows between these stocks, and information that determines the values of the flows (Borshchev and Filippov, 2004). It is also an approach to understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system.

The so-called stock, flow diagram is a common technique that is used for system dynamics modeling to graphically illustrate the application of the paradigm. Basically, stocks are basic stores, accumulations or characterize the state of the system. Flows define the movement of items between different stocks in the system and out/in the system itself. The flow describes the rates at which these system states change. Units of measure can help to identify stocks and flows. Stocks are usually quantities such as people, inventory, money and knowledge. Flows are measured in the same units per time period, e.g. kilometers per hour, volume per day, clients per month or dollars per year (XJ Technologies, 2012).

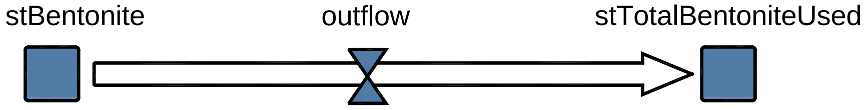


Figure 2.3: System dynamics representing the use of the bentonite

A brief example will clarify the application of this technique. Figure 2.3 displays a stock and flow diagram for the use of bentonite. In this model, the stocks are *stBentonite* and *stTotalBentoniteUsed*, and the flow between them is *outflow*, which is defined as the quantity of bentonite used per time unit, e.g. per minute. When the system is run, the stock values change over time. For example, the quantity of *stTotalBentoniteUsed* grows and the *stBentonite* is reduced at the *outflow* rate.

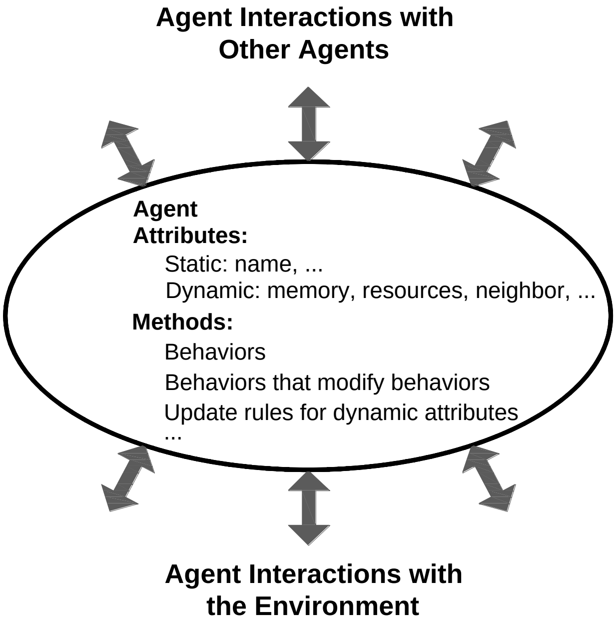


Figure 2.4: A typical agent. The behaviors and interaction of the agent with other agents and the environment (Macal and North, 2010)

2.2.3 Agent Based Modeling (ABM)

Agent based modeling is a more recent modeling method than discrete event modeling and system dynamics modeling. Since the early 2000s, agent based modeling has been introduced pretty much in academic topics. Many different developments have been going on under the slogan of agent based modeling in very different disciplines like artificial intelligence, complexity science, game theory, etc. People are still discussing what kind of properties an object should have to ”deserve” to be called an ”agent”: pro- and re-activeness, spatial awareness, ability to learn, social ability, intellect, etc (Schieritz and Milling, 2003). According to the point of view of Macal and North (2006) the agent based modeling simulates individuals and may be defined as a class of computational models for simulating the actions and interactions of autonomous agents. Agents also have behaviors, which are often defined by simple rules. Figure 2.4 shows a typical agent, agents interact with and influence each other, learn from their experiences, and adapt their behaviors so they are better suited to their environment (Macal and North, 2010).

2.3 The application of simulation in construction

Considerable efforts have been made to model construction operations utilizing simulation methodology. Many authors have attempted to use the different simulation implementations for the analysis of earth-moving operations. Alshibani and Moselhi (2007) present the simulation model designed for planning, tracking and control of earth-moving operations. The developed model was implemented in prototype software, using Visual C++ in Microsoft Windows' environment. Up to 2009, for optimization of earth-moving operations in heavy civil engineering projects, Moselhi and Alshibani (2009) built the simulation model assistant general contractor to optimize the planning of earth-moving operations. A genetic algorithm, linear programming, and geographic information systems were applied in the simulation model. Abduh et al. (2010) also use the CYCLONE model to develop the simulation model in order to optimize the resources of earth-moving operations. Recently, Fu (2012) has attempted to demonstrate the applicability of the simulation model for earth-moving operations. The author uses the CYCLONE modeling system to represent the logistics of the physical earth-moving system associated with the discrete-event simulation technique utilized to capture the interaction between the resources and the randomness of each of the activities.

As mentioned in section 2.1, the CYCLONE system provides a quantitative way of planning, analysis and control of the construction process and helped to make process simulation methodology popular. Therefore, several construction processes and operations have been modeled utilizing the CYCLONE system. Cheng and Feng (2003) presented an effective simulation mechanism for construction operations. They used CYCLONE with genetic algorithms with the Genetic Algorithms with Construction Operation Simulation Tool (GACOST) to find the best resource combination for the construction operation. Halpin et al. (2003) represented the method of integrating CYCLONE with Web CYCLONE service. They indicated that the CYCLONE model and Web CYCLONE are concepts designed to allow users at beginners, intermediate and advanced level of simulation expertise to study and analyze construction processes using computer based simulation systems. Abduh et al. (2010) attempted to improve the utilization of the simulation technique of construction operations by using the CYCLONE system.

Oloufa (1993a) proposed an object-oriented approach for the simulation of construction operations. In this approach, he developed a simulation module RESPEC (REsource SPECification Module) dedicated to predict the performance of the construction process. In the middle of 1993, he used the same approach for the modeling and simulation of earth-moving operations (Oloufa, 1993b). He also developed a simulation language (MODSIM) to analyze an earth-moving project. HSM is an hierarchical simulation model to be applied for planning construction projects developed by Sawhney and AbouRizk (1995a). In order to create the simulation model using HSM requires the user having to divide the project into the hierarchical structure (project, operations, and processes) and to identify the logistics of the activities of operations and links. The user also has to create the resources library for the projects. Finally, in order to run the simulation, the modeler has to perform and extend process modeling utilizing the CYCLONE system. In addition, numerous studies have attempted to develop simulation languages based on CYCLONE e.g. MicroCYCLONE (Halpin, 1990), COOPS (Liu and Ioannou, 1992), CIPROS (Odeh et al., 1992; Tommelein et al., 1994), STROBOSCOPE (Martinez, 1996) as mentioned in section 2.1.

Several researchers have used discrete event simulation to investigate differentiated aspects for scheduling problems. Koenig et al. (2012) applied of Building Information Modeling (BIM) in the planning of construction processes. They presented an intelligent concept to store interdependencies between activities in order to reuse them for handling modifications and different alternatives. Szczesny et al. (2012) applied of discrete-event simulation for the generation of valid schedules for construction projects. Beissert et al. (2007) used a constraint-based simulation model to detail construction tasks and their corresponding prerequisites such as constructional dependencie s between tasks, necessary resources or availability of working space to execute a given task. Koenig et al. (2007) developed a discrete-event simulation framework within the cooperation SIMoFIT (Simulation of Outfitting Processes in Shipbuilding and Civil Engineering) to support outfitting planning in shipbuilding and civil engineering.

This paragraph was an attempt to review simulation modeling approaches. There have been some efforts to apply simulation in construction. It also outlined the different aspects of applying simulation in construction:

1. Development of simulation languages, e.g. CYCLONE, COOPS, CIPROS, STROBOSCOPE, STEPS;
2. Application of simulation languages to solve the problems in construction operations, e.g. Cheng and Feng (2003); Koenig et al. (2012); Beissert et al. (2007); Koenig et al. (2007);
3. Integration of the simulation languages with another software, e.g. Halpin et al.

(2003) and Alshibani and Moselhi (2007).

2.4 Application of simulation in tunnelling construction

In this section, some literature reviews about the use of process simulation methodology for research and application in tunnelling construction will be represented. Subsequently, a table to summarize some of the results of the application of process simulation for TBM and MTBM will be established.

Various authors have used process simulation to analyze and evaluate the tunnel construction with TBMs. Salazar and Einstein (1986) used discrete event simulation techniques and FORTRAN programming language to develop a simulation program, named SIMSUPER5 (SIMulation SUPERvisor). The simulation program describes the tunnel construction process under conditions of uncertainty. The SIMSUPER5 helps engineers to estimate the overall time and cost needed to build a tunnel. Touran and Asai (1987) predicted the tunnel advance rate in the construction of a several kilometers long, small diameter (3-3,5 m) tunnel in soft rock. For this purpose, the CYCLONE modeling system is used. Several simulation models are developed to investigate the effect of difference variables on the tunnel advance rate. The impact of each major variable on the tunnel advance rate is studied by sensitivity analysis. These variables include the tunnel boring machine penetration rate, the train travel time, the number of muck trains, the type of rock, and the rock stand up time. Al-Jalil (1998) developed a decision support system called decision aids in tunnelling to predict the performance of tunnel boring machine excavation systems in hard rock geological condition. AbouRizk et al. (1999) described the special purpose tunneling simulation template developed based on the tunneling operations performed at the City of Edmonton Public Works Department for shielded TBM's. The results generated from the template using the historical data to test the template and to analyze the potential construction processes are presented. Donghai et al. (2010) estimated the penetration rate of the tunnel excavation with TBM based on the rock mass classification. Using the rate, a CYCLONE model of tunnel boring machine system has been established and the advance rates under different geological conditions have been determined. Then, the impact of different cutter head thrust, which has been chosen in a reasonable range according to previous experiences, on the project schedule is analyzed. Moreover, the simulation model of a mucking system is built to determine the number of muck trains and rail intersections that are reasonable, regarding the efficiency of muck loading and material transporting. Based on the interaction and interrelation between the TBM boring system and the mucking system, the combined CYCLONE model for the entire tunneling process is established. After that, a reasonable construction schedule, the utilization rate of work resources, and the probability of project completion are obtained through the model programming. At last, a project application shows the feasibility of the presented method.

Recently, numerous studies (Rahm et al., 2012; Sadri et al., 2013; Duhme et al., 2013) have attempted to analyze the earth pressure balance (EPB) shield tunnelling machine by developing a simulation model tool by using the same process simulation techniques. In order to analyze the issues of the tunnel with a EPB shield tunnelling machine, the authors have integrated the SysML and AnyLogic simulation software to develop the simulation tool. Two methodologies, called discrete-event simulation (DES), system dynamics (SD) are applied inside the AnyLogic simulation software to develop the simulation tool. They use the same simulation techniques but the focus on each study is different. Rahm et al. (2012) developed the simulation tool in order to analyze the relationship between productivity and supply chains under consideration of typical disturbances of tunnel construction with the EPB. The simulation tool is able to investigate the advancement rate of the TBM as well. By using the same methodology, Sadri et al. (2013) presented the simulation of a TBM supply chain. The task of the study is to develop the simulation tool for evaluating the effect of disturbances, e.g. damaged train, segments transport to the job site, on productivity of the TBM supply chain. Duhme et al. (2013) developed a generalized function model based on a functional analysis of different projects as well. The model may analyze logistical processes, interdependencies and downtime of the whole construction operations with TBM. The simulation tool is able to visualize the process interruptions and disturbances within the system and to test possible countermeasures virtually for their efficiency.

So far, however, there have several studies been published about the application of the process simulation in tunnel construction with MTBM by using the same simulation methodology, called CYCLic Operation NEtwork (CYCLONE). Nido et al. (1999) attempted to provide a template CYCLONE model for simulating an actual project, namely, the Holes Creek Tunnel Project site in Montgomery County, Ohio. The objective of this research is to evaluate and analyze the factors that affect the productivity of the projects. The performed simulation runs, using PROSIDYC (Purdue University, 2013a), a PC-based simulation program that is based on the CYCLONE methodology. The validation of the simulation is executed by comparing the actual production measured in the field with the simulation results. After validation, the simulation model is expanded with considering different soil compositions and used in order to evaluate the impact of the soil. As a result, the efficiency of microtunnelling is assessed by help of the developed simulation model for different ground conditions. A sensitivity analysis is also carried out with consideration of various combinations of resources. The results highlight the identification and analysis of the various resources that affect the productivity in microtunnelling operations. In addition, the simulation model can be used to estimate the productivity of the project. Further, the cost of the tunnel project may be estimated by the use of the model as well.

Roy and Mohammad (2007) have also suggested the CYCLONE simulation model for application in an actual microtunnelling field study conducted at Louisiana Tech University. The CYCLONE model of Roy and Mohammad (2007) is enhanced based on research by Nido et al. (1999). The simulation is validated by comparing the actual production observed in the field with the results of the simulation model. The core of this study is to evaluate the effect of the different soil conditions on the productivity in microtunnelling operations. A linear regression is conducted in order to find the correlations between productivity of MTBM in the project and different soil conditions. The result also shows that the general knowledge of microtunnelling productivity can be predicted for the actual project which was chosen. Moreover, the resource limitations have been found by using sensitivity analysis. The entire of the simulation results has been achieved through WebCYCLONE (Purdue University, 2013b), a web-based construction simulation program based on the CYCLONE methodology.

Marzouk et al. (2010) has developed a simulation module tool for planning microtunnelling projects using computer simulation. The objective of this research is to develop a simulation tool for planning microtunnel projects. For this purpose, a CYCLONE simulation model describing the microtunnelling and shafts processes was developed in the first step. Subsequently, a simulation tool was developed by utilizing Microsoft Visual Basic 6.0 to control and facilitate the data flow from/to the simulation software STROBOSCOPE (Martinez and Ioannou, 1994; University of Michigan, 2013). There are six sub-modules coded in the simulation tool in order to describe the construction of microtunnelling and shafts. An application example is presented to demonstrate the features of the simulation tool. As a result, by using the simulation tool, the productivity and the cost required in the tunnel construction with MTBM is estimated. In addition, the simulation tool is responsible for estimating productivity and utilization of resources in each shaft and microtunnel segment in the project.

Due to the review of literatures discussed above, the simulation methodology has been used for the analysis of tunnelling construction operations with both TBM and MTBM, and has had many contributions. So far, most applications of process simulation in tunnelling construction have used the CYCLONE modeling system (discrete event simulation) to develop the simulation model and have used the sensitivity analysis methodology in order to analyze the tunnelling construction processes. Thereby, the effects of bottleneck and soil conditions on productivity can be determined. However, the use of the CYCLONE methodology to build the simulation model have some disadvantages (illustrated in section 2.1). In addition, there has been little discussion about the impacts of disturbances leading to a reduction of productivity in the tunnel construction, e.g. Sadri et al. (2013) and Rahm et al. (2012), but only applied on large tunnel cross-sections with the Earth Pressure Balance Shield machine. And up to now no research has found the effect of disturbances on productivity of tunnel construction with MTBM by using process simulation. Furthermore, no research has used Systems Modeling Language (SysML) modeling language for the tunnel construction with MTBM. Therefore, in this study a new approach to analyze the tunnel construction with MTBM is presented. In order to analyze the operation of microtunnelling, a simulation module using the SysML modeling language combined with the commercial simulation software AnyLogic will be developed. The simulation module will be applied to analyze the processes and identify the main factors influencing the operations of the construction process productivity such as: soil compositions, disturbances, resources and geometry of the job site.

Such as a conclusion for this chapter, in table 2.1, the results of the application of process simulation for TBM and MTBM are summarized and compared. The table 2.1 is aids to easy visualization the different objective of this research with other.

2.5 Advantages and disadvantages of the use of process simulation

The use of process simulation has a number of advantages over analytical or mathematical models for analyzing systems. The advantages of the method is discussed at length by many authors and go much further than just the ability to simulate forward in time (Concannon et al., 2007). The following provides a summary of the advantages, as described by other authors, such as: Oloufa (1993a), Shannon (1998), Concannon et al. (2007) and Law and Kelton (2000):

- Determining the ”best” alternative: by simulating with new design, layouts, resources etc., it is possible to select the best alternative for change before implementing it.

- Understanding systems: by implementing the simulation model, the managers can predict the future behaviour. Thereby, the managers can reorganize the system and view the operation in its entirety to gain insight and understanding of the interaction of each intrinsic element in the system.

- Bottleneck analysis: simulation allows to identify bottlenecks of the system. Therefore, it is possible to test options for increasing the flow rates in the operations of the system.

Table 2.1: Some results of the comparison

Name of Author	Ali Touran (1987)	Nido (1999)	Roy Yu Luo (2007)	Liu DongHai (2010)	M. Marzouk (2010)	T. Rahm (2012)	**T. T. Dang** (2013)
Type of machine	TBM	MTBM	MTBM	TBM	MTBM	TBM	MTBM
Methodology							
DES	Y	Y	Y	Y	Y	Y	Y
SysML	N	N	N	N	N	Y	Y
Sensitivity Analysis	Y	Y	Y	Y	Y	N	Y
Consideration							
Soil Conditions	Y	Y	Y	Y	Y	Y	Y
Disturbances	N	N	N	N	N	Y	Y
Geometry	N	N	N	N	N	N	Y
Cost Estimation	N	Y	N	N	Y	N	N

Legend:

- MTBM: Microtunnelling Boring Machine
- TBM: Tunnel Boring Machine DES
- DES: Discrete-Event Simulation
- SysML: Systems Modelling Language
- Y: Yes
- N: No

- Problem identification: simulation allows to identify problems that can occur in the system as well. Thereby, manager can recognize all the symptoms and causes of problems. These results are helpful to repair the symptoms of a problem instead of solving the problem itself.
- Exploration: by testing new initiatives, designs, resources, and so forth, the simulation model can be used to evaluate and investigate the suggestions without putting the current system at risk.
- Control time: simulation provides the ability to increase or decrease the pace of a system for evaluation purposes e.g. when a problem occurs, the manager can slow down the system for investigating the issue. Simulation can perform the system for several months or years of production within a few minutes, giving the manager access to a large simulation period quickly.
- Visualizing the plan: in fact, when designing a completely new alternative construction, many flaws can not be anticipated through evaluation of a real job site. By using a simulation model, the manager is able to find inherent flaws and to eliminate them.
- Ability to seek optimal solutions: by using sensitivity analysis with different variations basic assumptions are expected. It helps to find the optimal solutions for inputs (e.g. number of workers, productivity, the cost of the tunnel.)

There are also some disadvantages in using process simulation. Among these are:

- Special knowledge is required: Simulation modeling is an art that requires specialized training and therefore the skill levels of modelers vary widely. The utility or functionality of the simulation model developed depends on the skills of the modeler.
- Time consuming: Development of the simulation requires significant amounts of time. It has already been stated that simulation is a time consuming approach.
- Optimization issue: Simulation can not provide optimal solutions for a system; instead it is useful for selecting the best alternatives from several scenarios.
- Massive data is required: The large amount of data requires an informed analysis for accurate conclusions regarding the simulated system and the validity of its model.

2.6 Process simulation software

2.6.1 Commercial simulation software

Nowadays, there are many companies producing specialist simulation software. Currently, any simulation software having been developed and being developed is based on the most common simulation methodologies today: discrete-event simulation (DES), system dynamics (SD) and agent based modelling (ABM). According to the author's opinion, almost all software has been developed based on DES e.g. Arena (Rockwell Automation, 2013), STROBOSCOPE (Martinez and Ioannou, 1994; University of Michigan, 2013), PROSIDYC (Purdue University, 2013a), EZStrobe (Martinez, 2001), Plant Simulation (Siemens, 2013). So far, the AnyLogic simulation software is the only simulation tool that supports all main simulation methodologies DES, SD and ABM (AnyLogic Company, 2012). In this section, a few of the simulation software tools will be highlighted.

Arena simulation software is a discrete event simulation software simulation and simulation software developed by Rockwell Automation and the former Systems Modeling Corporation, which was acquired by Rockwell in 2000 (Rockwell Automation, 2013). The software is widely used to model and simulate industrial processes and supply chains (Neubauer and Stewart, 2012). The development of Arena consists of three different core steps:

1. Analysis and identification of the operation processes;
2. Creation of a basic model by using window flowchart view;
3. Adding parameters to the model elements, e.g. processing times, resources and others to the model;

SIMUL8 simulation software has been developed by SIMUL8 Corporation and is used for simulating systems that involve the processing of discrete entities at discrete times (SIMUL8 Corporation, 2013). This program is a tool for planning, design, optimization and engineering of real production, manufacturing, logistics or service providing systems. The use of SIMUL8 involves of three different main steps:

1. Analysis and identification of the operation processes;
2. Addition of objects to SIMUL8;
3. Moving, linking, unlinking and defining the properties of objects;

Martinez (2001) has introduced EZStrobe, the general purpose simulation system based on activity cycle diagrams. EZStrobe is defined as *"a simpler discrete-event* *simulation system suitable for learning and modeling processes and operations that do not require the explicit identification of resources.”* (Martinez, 2011). The developer uses EZStrobe to develop simulations involving four main steps:

1. Identification of the activities, the flow and the condition of the construction operations;
2. The use of an activity cycle diagram to present the active, inactive resources and their intrinsic interaction of the flow of operations;
3. Drawing links to connect the activities;
4. Defining the properties of the resources.

The AnyLogic simulation software was first presented at the winter simulation conference in the year 2000 (AnyLogic Company, 2012). It is a general simulation system designed for capturing the complexity of engineering, business, economic and social systems. The developer uses the AnyLogic software to develop a simulation tool involving three different core stages:

1. Analysis and identification of the structures within the model;
2. Creation of the basic simulation tool by drag, drop and integrating simulation elements of pre-configured simulation elements with the comprehensive object libraries;
3. Expansion of the basic simulation tool by adding code in Java, Eclipse.

In this study, the AnyLogic software will be used. Therefore, the more detailed introduction of this software will be illustrated in the section 2.6.3.

Plant Simulation is a standard software developed by Siemens PLM (Product Lifecycle Management) Software. It is used for discrete event simulation methodology that may be used for modeling, simulating, analyzing, visualizing and optimizing production systems and processes, the flow of materials and logistic operations. The application of Plant Simulation to develop the simulation tool consists of four different main steps (Simplan, 2013). These include:

1. Identification and analysis of the factors, logistics of the system;
2. Development of the simulation model by integrating neuronal networks;
3. Automated optimisation of system parameters;
4. Batch size and sequence planning (sequencing)

2.6.2 Choosing simulation software

Like most software today, simulation software packages are adding features and capabilities very quickly due to competition and customer expectations. There are many companies producing specialist simulation software, e.g. AnyLogic, Arena, SIMUL8, EZStrobe as mentioned in section 2.6.1. Since microtunnelling operations involve a complex interaction of processes that require a variety of supporting equipment and personal experience, the simulation software chosen must therefore meet four core requirements:

1. Capturing the large and complex operations of the system with different levels of detail;
2. The developer can implement custom control logic in the code;
3. Automatically collects statistics and the data or graphs for the report can be obtained easily;
4. And the use of an industry standard operation system e.g. Microsoft Windows.

For this research the applied simulation environment is AnyLogic simulation software by XJ Technologies (2012), as AnyLogic meets all of the requirements mentioned above. The AnyLogic simulation tool can integrate three common simulation methodologies in place today: the discrete event, agent based and system dynamics simulation in one model (Rahm et al., 2012). Therefore, the AnyLogic simulation software is especially useful in order to simulate large and complex operations. In addition, AnyLogic supports a system of libraries, which are very helpful to capture most of the logic with different degrees of detail in one model and to easily collect statistics on the results of the performance of the simulated system. It can be run on Microsoft Windows, which is the common operating systems nowadays. This simulation software is based on Java platforms and allows to control the logic of the system by coding.

Furthermore, AnyLogic is suitable for educational purposes. A lot of academic models are included in the tool and every release provides new sample models and case studies.

2.6.3 AnyLogic simulation software

The most common simulation methodologies (mentioned in section 2.2) in place today: Discrete Event Simulation (DES), System Dynamics (SD) and Agent Based Modeling (ABM) have been integrated in AnyLogic software (Figure 2.5). The AnyLogic simulation software is especially useful regarding the simulation of large and complex operations. With this software, almost all corporate fields of application can be represented, e.g. production, logistics, business processes, market and competitors, supply chain and construction sequences (AnyLogic Company, 2012). The AnyLogic simulation software is able to break the simulation model down into different parts, and analyze them individually. Dividing the entire 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. Thereby, modelers can combine different simulation approaches within the same model.

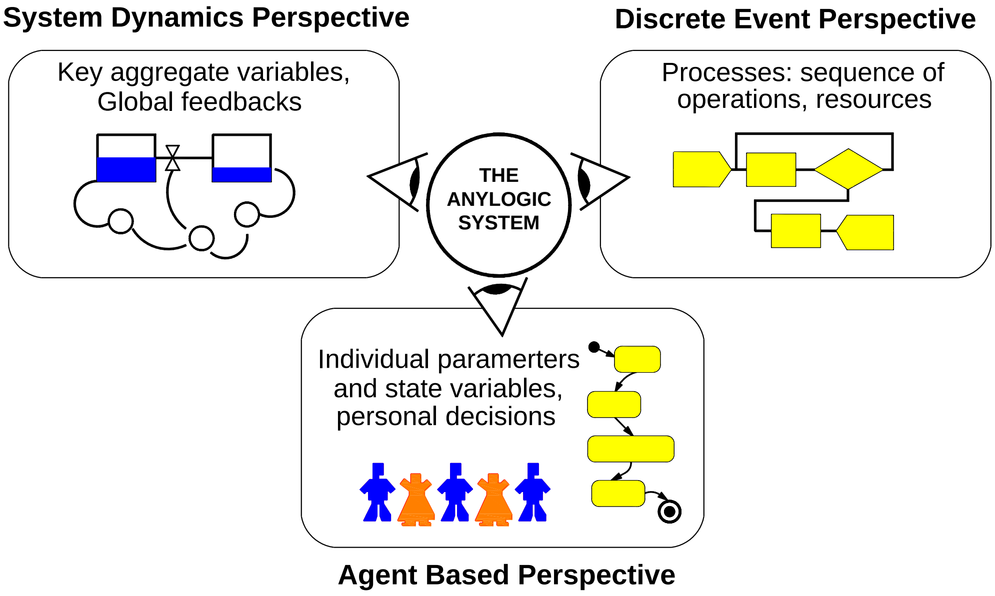


Figure 2.5: The three methodologies applied in AnyLogic (AnyLogic Company, 2012)

The AnyLogic also includes libraries, namely: The enterprise library, the pedestrian library and the rail library. The aim of each library is (AnyLogic Company, 2012):

- **The enterprise library** is a library designed to support the discrete event modeling. Using the enterprise library, modelers can for example simulate the manufacturing, logistics or supply chain. The user can use the enterprise library in order to model real world systems or the operation processes of systems or construction.
- **The pedestrian library** is a library to support the simulation of pedestrian flows in a ”physical” environment. For example, using the pedestrian library, the developer can create the model of pedestrian intensive buildings (e.g. subway stations, security checks, etc.).
- **The rail library** is a library developed for modeling, simulating and visualizing operations of a rail yard of any complexity and scale. The rail yard model can be merged with multi- method simulation modeling such as: discrete event or agent-based in order to model e.g. loading, unloading, resources, maintenance etc.

Furthermore, 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. AnyLogic includes an important function for the modeler, which enables him to debug the simulation model in order to find and remove the defect in the model. The user can use debugging at different stages of the simulation model, which has been developed by AnyLogic software.

Chapter 3

Microtunnelling process analysis

3.1 Definition

The tunnel construction with microtunnelling boring machine (MTBM) has originally been defined as mechanised pipe jacking for non man entry size tunnels. As the process has been developed further and more sophistications have been applied, it now is perhaps more correctly defined as pipe jacking employing a remotely controlled tunnelling machine.

According to Stein (2005b) the definition of MTBM is: *"In microtunnelling methods, jacking pipes are jacked from a starting shaft with the aid of a jacking station up to a target shaft. At the same time an unmanned, remote-controlled microtunnelling machine carries out the displacement or full faced excavation of the working face. In the latter variant, the spoil is transported though the jacked pipe string"*. The North American definition of microtunnelling: *"The MTBM is remote controlled, a laser guidance system is employed, a jacking system is used for thrust, and continuous pressure is provided to the face of the excavation to balance groundwater and earth pressures"* (American Society of Civil Engineers, 2001). As the name implies, the use of microtunnelling is applied to construct small tunnels. The application of this technique is suitable for inaccessible pipelines of 0.3m diameter to accessible diameters of 4.2m (Herrenknecht AG, 2013a).

3.2 Fundamental principles of microtunnelling

The basic principles of microtunnelling (shown in Figure 3.1) are similar to other kinds of TBMs. The fundamental principle of the tunnel construction with MTBM is briefly as

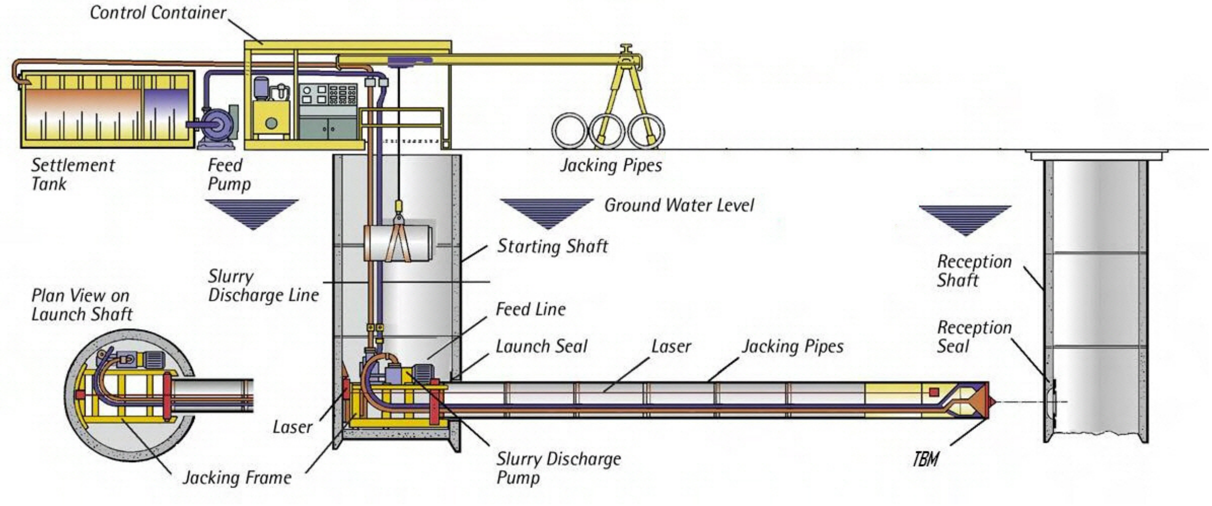


Figure 3.1: Microtunnelling principles (source: Herrenknecht AG (2013a))

follows (Stein, 2005b; French Society for Trenchless Technology, 2004): In microtunnelling methodologies, the pipe sections are installed one after the other on the launch skid from the starting shaft (or driving shaft). They are jacked from a starting shaft with the help of a jacking station (or thrust frame) located in the start shaft up to a reception shaft (or target shaft). At the same time, the MTBM is driven into the ground with the aid of a jacking station as well. The operator operates the various systems of the machine from the surface. The MTBM carries out the displacement or full faced excavation of the working face. At the working face, the spoil is excavated mechanically by a rotating cutting head and it is transported through the jacked pipe string. There are three types of spoil removal system in microtunnelling: the auger transportation system, the slurry transportation system and the pneumatic transportation system. The transportation system of the spoil for each type of MTBM is described in section 3.3. For microtunnelling, navigation systems such as laser are used as a guidance system. The navigation system gives the line and grade information for the pipe installation. In order to control and record jacking length, jacking force, cutting torque, steering and directional tendency, a control panel is required in microtunnelling as well. It is installed in the near of the starting shaft with steering desk and hydraulic power plant. The intermediate jacking stations are used to increase the overall jacking distance and to reduce the forces on the main jacks in cases of exception. For details of small tunnel construction using microtunnelling theory, the book of Stein (2005b) and (French Society for Trenchless Technology, 2004) is recommended for further reading.

3.3 Types of MTBM

According to Stein (2005b), microtunnelling methods can, depending on the way of conveying the spoil, be divided into three types of MTBM: 1. microtunnelling with

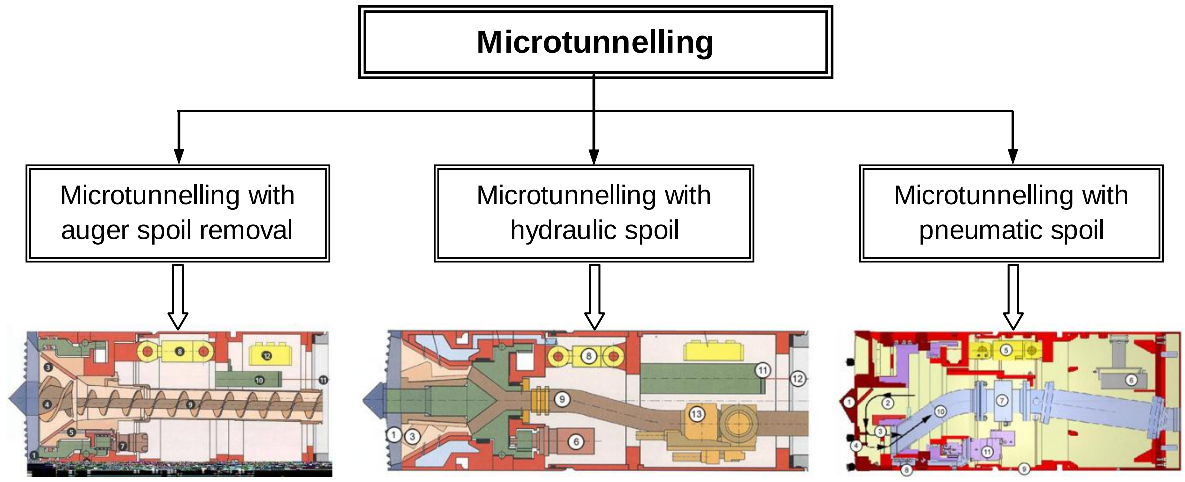


Figure 3.2: Basic classification of microtunnelling technologies (source: Herrenknecht AG (2013a))

auger spoil removal; 2. microtunnelling with pneumatic spoil removal; 3. microtunnelling with hydraulic spoil removal. The basic classification of microtunnelling technologies is shown in Figure 3.2. For MTBM with the auger type method, excavated materials are transported by a spiral conveyor or auger casing placed through the jacking pipes. The spiral conveyor or auger feeds the excavated materials to a spoil bucket positioned beneath the jacking frame in the starting shaft. When full, the spoil bucket is lifted to the surface, emptied and returned before the drive is continued. In the pneumatic system, the spoil is extracted from the face into an air-tight vacuum container. The suction of the spoil is possible thanks to suction generating equipment positioned on the surface (French Society for Trenchless Technology, 2004). For MTBM with hydraulic spoil removal,lubricants such as bentonite are used to reduce jacking loads. The spoil materials are excavated mechanically by a rotating cutting head. After that, the spoil is mixed with the slurry in a pressure chamber located behind the cutter head of the MTBM. This mixed material is transported through the slurry discharge pipes and discharged into a separation plant above the ground (Stein, 2005a). The task of the separation plant is to separate the slurry from the mixed material. The slurry is recycled, therefore the separation plant is a closed-loop system (Akkaya, 2008).

3.4 Choosing the type of MTBM for analysis

According to the French Society for Trenchless Technology (2004), the area of application for different types of MTBM depends on the type of the ground as suggested in table 3.1. Table 3.1 indicates that the types of MTBM are available for almost every type of soil composition. And it is also shown that the microtunnelling with hydraulic spoil removal is more suitable for the most types of soil, and is especially well suited for granular soils. Rock excavation can be achieved with especially designed hydraulic type machines with appropriate disc cutter heads.

Table 3.1: The fields of application of MTBM according to the type of ground to be excavated (French Society for Trenchless Technology, 2004)

Machines for mucking	**Clay**	**Pebbles**	**Gravel**	**Sand**	**Silt**	
					Not very plastic (IP<30)	Plastic (IP>30)
Hydraulic	**	**	**	**	**	*
Auger	O	*	**	**	*	O
Pneumatic	O	**	**	**	*	*

**: machine well suited; *: machine that can be convenient; O: machine not recommended; IP: plasticity index

The ground-water level is one of the reasons that is also used to select the type of MTBM. Due to the fact that the use of pneumatic MTBM is limited and rare, table 3.2 shows the choices between hydraulic and auger based on the ground-water level (according to Masashi et al. (1999)). In case 1, where there are more than 3 m of water of above the top of the pipe, auger types can not be selected, the hydraulic types are appropriate. In case 2, both auger and hydraulic could be used but hydraulic types are more suitable. In case 3, with no water above the invert of the pipe, auger might be feasible depending on the soil types.

Table 3.2: The fields of application of MTBM according to ground water level classification (Masashi et al., 1999)

Case	**Description**	**Machine selection**
1	Water table is more than 3 m above pipe.	Auger types cannot be used. The hydraulic types can be selected.
2	Water table is above invert and no more than 3 m above pipe	Auger types could be used but slurry types are more appropriate.
3	Water table is below invert of pipe.	Desirable condition for auger types.

The selected type of MTBM is also considered to be based on the size of boulders and pipe diameters. The rules for selecting the type of MTBM depends on the existence of boulders as described in table 3.3. Table 3.3 indicates that the most types of MTBM have the capability of crushing boulders of up to 1/3 of the machine's outside diameter. If such boulders are available, the machine head type should be a sand/silt type cutter head with crushers, and both hydraulic and auger types can be selected. In the cases that the size of the boulders are expected to be larger than 1/3 of the machine outside

Table 3.3: The fields of application of MTBM according to the existence of boulders (Masashi et al., 1999)

Classification	Description	Machine types
1	No boulders	Clay or sand/silt type cutter head can be used. Both hydraulic and auger types can be selected.
2	Small boulders (up to 1/3 of machine outer diameter)	Auger types could be used but hydraulic types are more appropriate.
3	Large boulders (larger than 1/3 of machine diameter).	Rock type cutter head is required. Not suitable for auger machines.

diameter, rock products that are equipped with disc cutters are required. However, a mixture of large boulders and soft soils will result in difficult drives, because machine control will require significant steering that causes eccentric jacking forces to pipes. In these cases, auger types cannot be used. While hydraulic types cover the most ranges of diameters, auger types are limited to no more than 1.2 m (Masashi et al., 1999). For larger diameters, type of hydraulic machines are selected instead of auger types.

The characteristics of the three types of microtunnelling are summarized and compared in table 3.4. Table 3.4 indicates that the tunnel construction with the type of microtunnelling hydraulic spoil removal is more versatile.

Several discussions with managers in the construction sites have been performed by the author. According to the point of view of the managers, nowadays for almost all of the small tunnel construction with microtunnelling, the MTBM with hydraulic spoil removal is used.

Due to the analyses mentioned above it may be concluded that: until now, the MTBM with hydraulic spoil removal method is almost always used in small tunnel construction with microtunnelling. Therefore, in this research only the MTBM with hydraulic spoil removal will be considered.

3.5 Microtunnelling with hydraulic spoil removal process analysis

Before the simulation model for microtunnelling is established, the resources, equipment and construction processes required during tunnel construction with MTBM must be analyzed. In this thesis, the analysis of the process of MTBM is divided into two parts: The first part will focus on the analysis of the core of construction by MTBM in the next sub-sections. Within the first part, the fundamental principles and important construction sequences of MTBM with hydraulic spoil removal will be portrayed at the

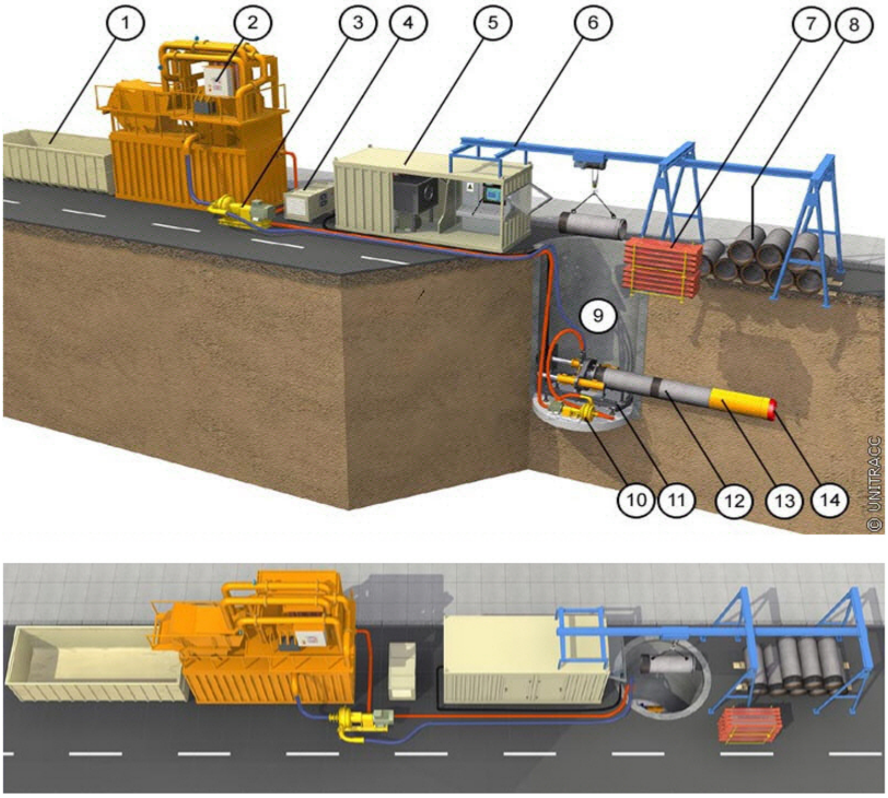
Table 3.4: Basic advantages and disadvantages of the three types of MTBM (Masashi et al., 1999; Stein, 2005a)

Characteristics	Hydraulic	Auger	Pneumatic
Advantages	• Available for wider range of soils, and diameters • Can be chosen from various types • Tunnelling more than 3m below groundwater table can be achieved • Application in soil and rock with and without ground water • Longer drives can be achieved • Driving pits can be cleaner, because material is automatically sent to separation plants.	• Whole system is simpler, and less expensive than slurry systems. Fewer troubles could occur • Effective for smaller diameters and shallow installations • More effective for cohesive soils and low water level sites	• Possible high jacking lengths can be achieved. • Application in temperatures below 0 degree.
Disadvantages	• System is more complicated and costly than other types. • There may be problems on driving through cohesive soils when installation depth is shallow.	• Tunneling below water table is limited. • Limited diameter variations. Usually available for less than 120 cm pipes. • Drive length is limited to typically around 90 m due to cutter torque. • Application in rock usually impossible	• In non-cohesive soils the jacking performance reduces remarkably

beginning. Subsequently, the resources required in microtunnelling will also be identified. After that, the disturbances in microtunnelling will be analyzed. In the second part, the detailed description of construction sequences and the interaction between elements in tunnel construction with MTBM will be represented in sub-section 4.2 (Chapter 4). Within sub-section 4.2 (Chapter 4), the development of the SysML simulation model will be explained in parallel with the description of construction sequences in order to understand more easily how to apply the SysML methodology into tunnel construction with MTBM.

3.5.1 Fundamental principle of MTBM with hydraulic spoil removal

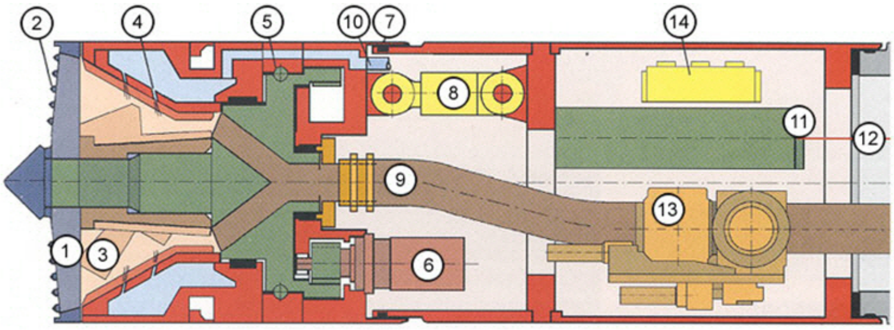
The principle of microtunnelling with hydraulic spoil removal (see Figure 3.3) is also called slurry shield microtunnelling. The fundamental principle in the slurry system can be illustrated as follows (according to Stein (2005b)):



1. Spoil container
2. Separation plant
3. Supply pump
4. Power generator
5. Container with steering desk and hydraulic power plant
6. Craneway
7. Conveyor lines
8. Jacking pipes
9. Starting shaft
10. Discharge pump
11. Jacking station
12. Jacking pipe string
13. MTBM
14. Cutting wheel

Figure 3.3: Microtunnelling with hydraulic removal principles (source: Stein (2005a))

The slurry shield microtunnelling is characterized by jacking with simultaneous full face excavation of the mechanically and liquid-pressure balanced working face. Further features are a cutting head and continuous hydraulic conveying of the soil (also called wet, flushing or slurry conveying in the literature) from a crusher, excavation and/or suspension chamber situated immediately behind the boring and steering head. The drive assemblies for the cutting head and the steering cylinder are arranged immediately inside the microtunnelling machine. The cutting head is designed differently according



1. Cutting wheel
2. Tools
3. Crusher room
4. Injection nozzle
5. Main bearing
6. Cutting wheel drive
7. Coupling
8. Thrust jack
9. Mucking pipe
10. Supply pipe
11. Target
12. Laser beam
13. Bypass
14. Valve block

Figure 3.4: Principle of a hydraulic mucking boring machine (source: Herrenknecht AG (2013a))

to the grounds. The cutting head of the MTBM has the option of a soft, mixed or rock head, depending on the ground conditions (see Figures 3.5 a, b and c). The selection of the cutting heads is made based on the ease of excavation and the pressure balancing of the working face. Normally, for flowing soil, the cutting heads fitted with scrappers are used (see Figures 3.5 a). The use of mixed drill heads (see Figures 3.5 b), which are fitted with knives and cutters for cohesive soils, as well as chisels and discs that can crush erratic blocks or rock layers, means that even the most difficult of soils can be drilled. When the tunnel drilling through rocks with high degrees of hardness, e.g. rocky grounds, cutting heads with disc cutters are used (see Figures 3.5 c).

Within the range of boring or drilling technology, the slurry shield microtunnelling generally belongs to the category of fluid flushing directional drilling that requires a circulating flushing medium to transport the excavated spoil to the surface. It is immaterial to the general principle of operation whether the flushing medium consists of clear water, whether it is water enriched with solids, whether it is gaseous or a mixture of gas and liquids or liquids mixed with gas. In the slurry shield microtunnelling, the flushing medium is circulated with the aid of pumps through an enclosed piping system inside the jacking pipe string that is successively increased in length with the installation of a new jacking pipe.

The pumped solid-fluid mixture (slurry) must usually be separated in order, on the one hand, to make the flushing medium available to the conveying circuit again, and on the other hand, to prepare the solids for disposal.

3.5.2 Construction sequences

The sequential concept of microtunnelling is schematically illustrated in Figure 3.6. In this process, the pipe sections are brought to the construction site from the manufacturing company. At the construction site, they are unloaded from the truck by crane

(a) Soft head (b) Mixed head (c) Rock head

Figure 3.5: Examples of cutting heads (source: Herrenknecht AG (2013a))

(or forklift) and stockpiled at a pipe storage near the top of the starting shaft. When the pipe is available, the Operator and Crew 2 (see sub-section 3.5.3) receive the signal from the shaft bottom, the crane is maneuvered, picks up a new pipe and lowers the pipe into the launch cradle. When the pipe is positioned on the launch cradle, the jack collar, cables and pipelines may be replaced and connected by Crew 1 (see sub-section 3.5.3) in order to prepare them for further operation. Subsequently, the pipe section may be jacked forwards. When the forwards pipe jacking is finished, the jack collar is retracted, cables and pipelines are disconnected. When the process is completed, the preparation for the next pipe is started and the sequence is repeated. The cycles repeat as required until the length of the tunnel is excavated.

As shown in Figure 3.6, the microtunnelling method includes 8 activity steps, which can be summarized as follows:

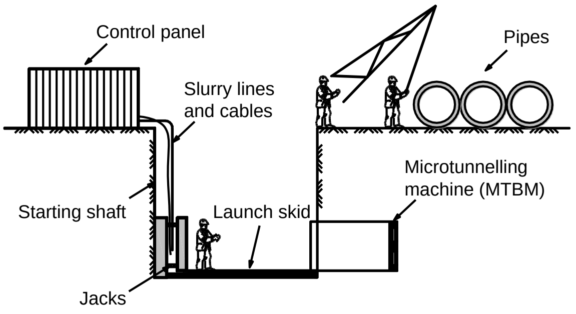
- Step 1 - Attach and transport pipe: represents the entire activities required to attach the pipe section to the crane and transport pipe section to the shaft collar;

- Step 2 - Lower pipe: represents all activities required to prepare the jacking system for pipe section placement, lower pipe section to the jacking frame, place the pipe on the launch skid;

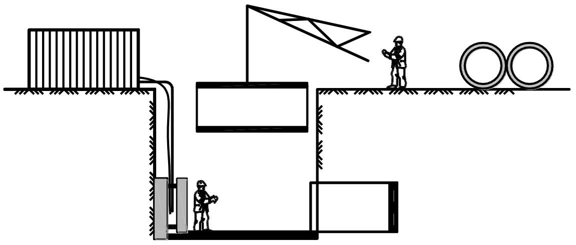
- Step 3 - Replace jacking collar: accounts for the entire activities involved for the jacking collar replace and re-engage the jacking system;

- Step 4 - Connect cables and pipelines: represents all activities related to connect cables and pipelines;

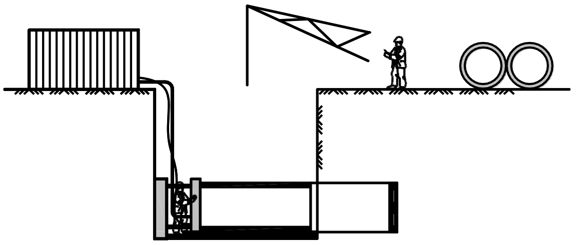
- Step 5 - Jacking processes: represents the entire activities involved in the pipe driving operation which actually advances the tunnel. Also consideration for all activities related to handling and separate the materials spoil, which is transported from the working face of the tunnel to the separation plant;



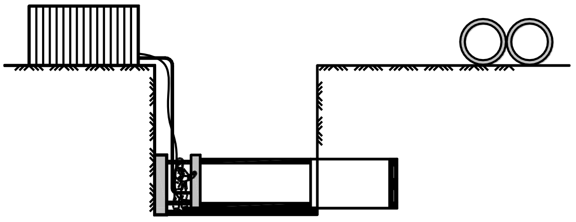
① Attach pipe and transport pipe to the starting shaft



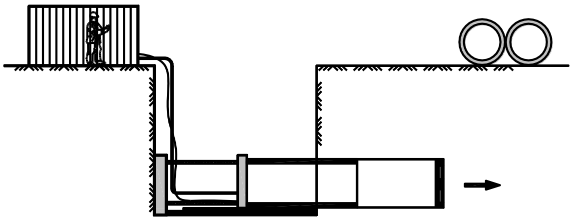
② Lower pipe



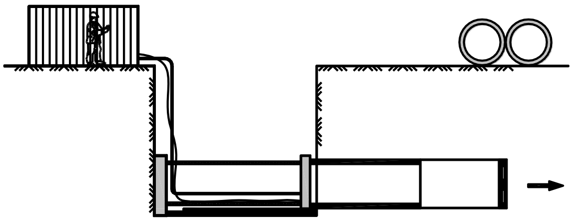
③ Replace jack collar



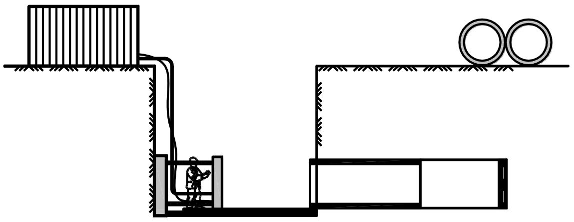
④ Connect cables and pipelines



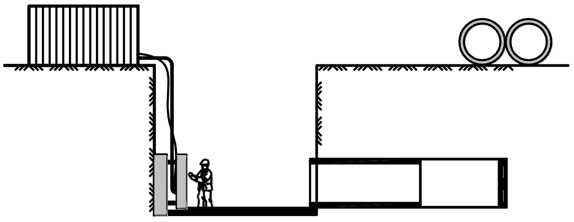
⑤ Jacking processes



⑥ Finished jacking processes



⑦ Retract jack collar



⑧ Disconnect cables and pipelines

Figure 3.6: Microtunnelling construction sequence

- Step 6 - Finished jacking processes;
- Step 7 - Retract jack collar: represents all activities required to retract the jack collar of the jacking system;
- Step 8 - Disconnect cables: represents the entire activities required to disconnect cables and reset the equipment for another cycle.

The summary of the tunnel construction with MTBM may be divided into two main processes, namely:

- **preparation processes:** represent all activities required in order to prepare the excavation phase: lower pipe, connect jack collar, cables, pipelines, mix bentonite, retract jack collar, disconnect cables and pipelines.
- **jacking processes:** in this procedure the entire activities involved in excavation processes occur simultaneously: control the thrust load of the jacking frame, control the MTB, control the navigation system, control the disturbances during excavation time.

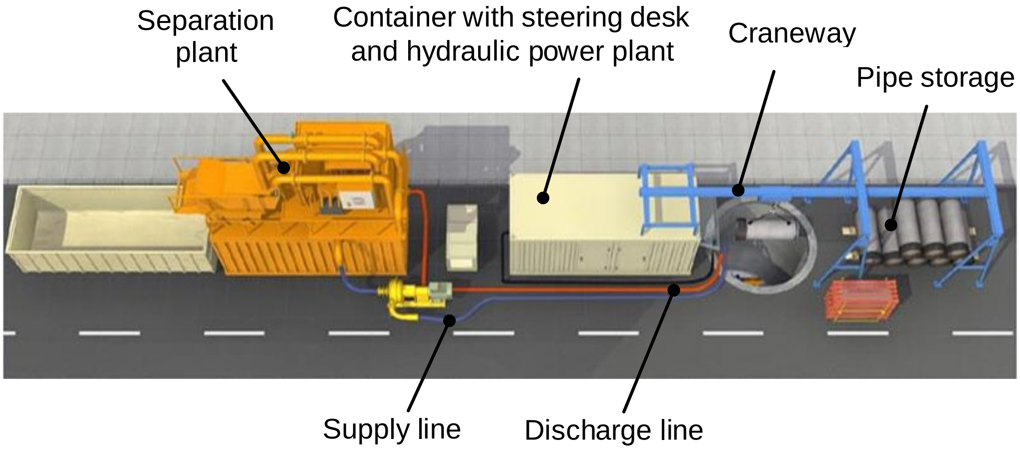


Figure 3.7: Basic equipment (longitudinal section and plan view) for microtunnelling with hydraulic spoil removal (source: Stein (2007))

3.5.3 The resources required in microtunnelling

An overview of the required basic equipment and resources for microtunnelling with hydraulic spoil removal is shown in Figure 3.7 and listed in Table 3.5.

The most important resources (main resources) have been identified in this study as the following (Stein, 2005b):

1. The microtunnelling machine with boring and steering head as well as trailing shield segment;

Table 3.5: Resources considered in simulation of MTBM

EQUIPMENT	CREW	MATERIALS
MTBM	Crew 1 - working on the surface	Pipe sections
Separation plant	Crew 2 - working in shaft	Slurry
Control container	Operator	MTBM energy use
Jacking station		Water
Lubrication mixture		
Pump system		
Crane		
Loader		
Navigation system		

2. The separation plant when using a bentonite suspension or settling tank when using water as a pressure balancing and transport fluid;
3. The control panel (or control container) with steering desk and hydraulic power plant when using a diesel-hydraulic drive for the jacking plant (a power generator is also required when using electric-hydraulic drive);
4. The jacking station system (or main jacking station system) consisting of jacking frame, jacking cylinder and thrust ring;
5. The lubrication mixture system for mixing the lubricant for lubricating the pipe string;
6. The pump system including discharge pump, charge pump and the injection pump.

The other resources have also been identified, but they are considered as secondary resources. These involve construction equipment e.g. loader, crane, navigation system, cables, hoses.

In tunnel construction operations with MTBM, three different classifications of the labor crew are normally required as follows:

1. The first is the Operator defined as one laborer. The Operator is involved in the task of job management and also operates the entire equipment in the job site e.g. control container, loader, crane;
2. The second crew is named Crew 1 and defined as one laborer working on the surface. Crew 1 is responsible for the mixing of the lubricant fluid, rigging the pipe section and preparing the pipe section before jacking pipe section forward;

3. The last crew is named Crew 2 defined as three labors working in the shaft. Crew 2 is involved in helping to replace the jack collar and to connect or disconnect cables or hoses.

The entire resources required for an tunnel construction with MTBM will be explained in more detail in block definition diagrams (Figure 4.7 in chapter 4).

3.6 Disturbances in microtunnelling

During tunnels construction with MTBM, a wide range of disturbances may occur. The disturbances can lead to delays in construction time and to conflicts regarding additional costs (Thewes and Burger, 2005). The motto of the tunnelling industry seems to be *“faster - larger - deeper - longer”* (Thewes, 2007). Therefore, one important part of this study is the analysis of the effect of the disturbances on advance rate *”faster”* of tunnel construction with MTBM. Therefore, the identification of disturbance causes will be analyzed. The disturbances are defined as: ”*unexpected occurrences causing an interruption or at least a delay in the execution of tasks; they cause a significant discrepancy between the target and actual data*” (REFA, 1991). In microtunnelling, there are many causes for disturbance e.g. traffic conditions, machine failure, missing of construction documents and material, blocking of the MTBM, bursting of hydraulic hoses, soil conditions, available space, etc. These factors are stochastic, hence creating great difficulties for construction operations management. They increase the project duration and consequently the project costs.

This section will focus on the disturbance causes and type of disturbances normally occurring in the tunnel construction with MTBM. Subsequently, the assumed disturbances affecting the logistics of construction processes will be established based on the type of the occurred disturbances. This assumption will be used to enhance the simulation module in order to evaluate the correlation between disturbances and productivity.

3.6.1 Identification of disturbance causes

The tunnel construction with microtunnelling involves operation processes that require a variety of supporting equipment, personal experience and the integration of different construction processes. Therefore, there are many reasons for occurring disturbances such as mechanical failure of system components, leakage of hydraulic hoses, blockage of slurry pipes, and waiting time for excavated materials hauling equipment during construction time.

Based on disturbance data collected from 35 microtunnelling projects, Mohamed and Gary (2007) have identified that ordinary disturbance causes were categorized

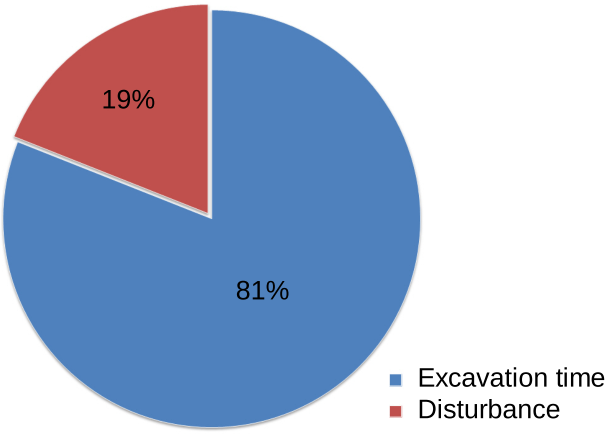


Figure 3.8: Percent of disturbance time in microtunnel projects (Mohamed and Gary, 2007)

into five main categories: slurry, operation, laser, mechanical problems, and surface management as shown in Table 3.6. The overall disturbance consumed about 19% of the total recorded excavation time as shown in Figure 3.8. The leading cause of delay was the blockage of slurry lines, and led to 39% of disturbance occurrences. Operational problems came next with 24% of disturbance time. The third maximum cause was the laser check with 20% of disturbance time. Mechanical problems and surface management are responsible for 17% of disturbance time as shown in Figure 3.9. The description of different disturbance causes for each category are shown in Table 3.6.

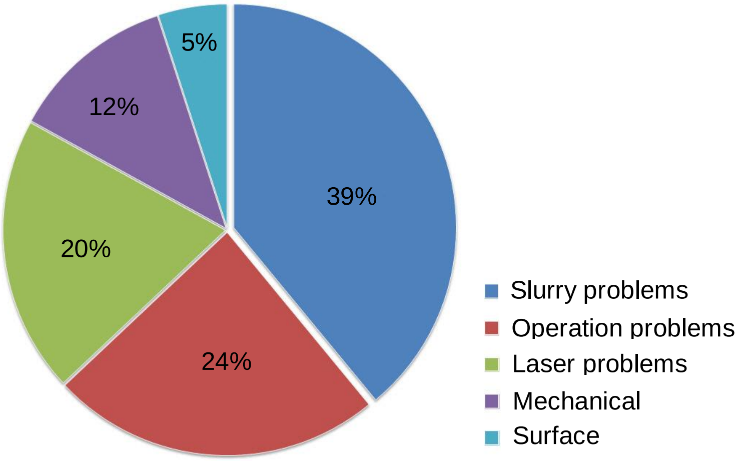


Figure 3.9: Disturbances registered at job site (Mohamed and Gary, 2007)

In the observation of Mohamed and Gary (2007), the obstructions are excluded from evaluation because they represent extraordinarily random disturbances that would stop the entire project for an exceptionally long duration. Meanwhile, almost all tunnel constructions with MTBM are done in urban sites and are mostly situated in the surface section of the ground, normally in between 3 and 15 meters depth, where MTBM may be immobilized due to the encountering of obstacles. The causes leading to the immobilization of MTBM are (French Society for Trenchless Technology, 2004):

Table 3.6: Disturbance causes for each disturbance category (Mohamed and Gary, 2007)

Disturbance category	Disturbance causes
Slurry problems	Blocking of slurry line; blocking of separation plant
Operation problems	Seepage through driving or exit eye; shifted break into the exit shaft
Laser problems	Periodical laser position check; hitting the laser gun accidentally by laborers
Mechanical problems	Burst of hydraulic hoses; breaking down of equipment
Surface management	Laborer delay in pipe segment preparation; shortage of materials supply during operation

- The boulders and obstacles whose diameter is too large to enter the crushing cone of the machine have to be broken by tools of the cutting wheel.
- The various blocks or debris that enter the cone have to be reduced to a size that is suitable for their removal by the mucking system
- Pieces of scrap metal, wood or PVC are difficult to crush by the crusher and the cutting wheel due to their flexibility.
- The pipe string is jammed due to the lack of overcut and pipe lubrication.

The main disturbance causes that can occur when constructing by MTBM are summarized with that. One of the aims of this study is to evaluate the affect of disturbance on the productivity of MTBM. Furthermore, the estimation of the influence of the disturbance on the resources in the construction site. Therefore, based on the disturbance causes, the need to analyze the effect of the disturbances when the disturbance occurs, e.g. when the disturbance effects resources that crews have to repair. The discussion of the relationship between disturbances and resources will be carried out in the next section.

3.6.2 Disturbance assumptions

First, the simulation module is enhanced to analyze the effect of the disturbance on productivity of tunnel construction with MTBM. The influence of disturbances on the sequences of construction processes of MTBM must be assumed. For instance, during jacking processes, the disturbance of the laser occurred. Due to the disturbance, the MTBM must be stopped (the jacking processes will be stopped). When the jacking processes are stopped, which equipment must be stopped after that and which resources are maneuvered in order to repair the disturbance. Within this study, based on

Table 3.7: Summary of penetration rates for each type of soil (French Society for Trenchless Technology, 2004)

Type of soil	Minimum time (min) for a pipe (2m)	Maximum time (min) for a pipe (2m)	Mode time (min) for a pipe (2m)
Fine sand	16 (2)	45	19
Sand & gravel	35 (3)	157	38
Clay/marl	69 (1)	292	74

Legend:

- (1) Calculated over a straight section of 507 meters;
- (2) Calculated over a straight section of 855 meters;
- (3) Calculated over a straight section of 476 meters.

the disturbance causes mentioned above and according to the results observed and surveyed from the construction site, the summary of the analysis of the influence of the disturbances on the sequences of construction processes of MTBM is established in Table 3.8. Table 3.8 describes the disturbance category, type of problems (or disturbances) of the equipment, the occurrence per cycle, which percentage of the potential disturbance may occur in one cycle and the influence of disturbances on the resources and crews.

3.7 Duration for jacking processes only

The rate of penetration and productivity in microtunnelling projects are depending on the type of soil condition, which are encountered by the MTBM. One important part of this study is analysis the effect of the different soil conditions on productivity of tunnel construction with MTBM. The encounter of such a soil variety would be probably rare in actual practice for a single microtunnelling operation. Therefore, the assumption that the results of the simulation module test could be used for simulation of impacts of similar types of soils and the tunnel will be encountered with different type of soils. In order to select a specific type of soil mostly encountered in real situations, three types of soil, marl/clay, fine sand, sand and gravel are chosen. According to French Society for Trenchless Technology (2004) the minimum, maximum and mode values of the durations of pipe jacking according to the nature of the soil are shown in Table 3.7. The penetration values are recorded on nine sections thanks to questionnaires filled in by several companies. The data based on a total 1838 meters of which 507 meters are for cohesive soil, 855 meters for fine sand and 476 meters for sand and gravel.

Table 3.8: Assumptions of the influences of disturbance on the construction sequences

Disturbance category	Type of problems	Influence of disturbance on the construction sequences
Slurry problems	- Block, burst of slurry line	The jacking processes must be stopped. Crew 1, Crew 2 and Operator will repair the problem.
	- Blocking of separation plant	The jacking processes must be stopped. Crew 1, Crew 2 and Operator will repair the problem.
Navigation	- Hitting the laser gun accidentally by laborer	The jacking processes must be stopped. Crew 2 will repair the problem.
Mechanical problems	- Crane problem	The crane will be repaired by Operator and Crew 1
	- Loader problem	The crane will be repaired by Operator and Crew 1
	- Pump problem	The jacking processes must be stopped. Crew 1, Crew 2 and Operator will repair the problem.
	- Microtunnelling problems	The jacking processes must be stopped. Crew 2 and Operator will repair the problem.
	- Maintenance of equipment	Crew 1, Crew 2 and Operator will maintain the equipment.
Operation problems	- Lowering pipe	The pipe must be lifted and lowered again, performed by Operator, Crew 2 and crane.
	- Connect pipe to pipe	The pipe will be fixed by Operator, Crew 2 and crane.

Table 3.8: Assumptions of the influences of disturbance on the construction sequences

Disturbance category	Type of problems	Influence of disturbance on the construction sequences
Operation problems	- Shortage of materials supply during operation	The construction operation must be stopped to wait for the materials supply.
	- Delay in supply chain of pipe	The preparation processes must be stopped to wait for the pipe section available.

Chapter 4

Process description methodology

4.1 SysML methodology

4.1.1 SysML introduction

The definition of SysML is *"a general purpose modeling language for systems engineering applications. It supports the specification, analysis, design, verification and validation of a broad range of systems and systems-of-systems. These systems may include hardware, software, information, processes, personnel, and facilities."* (SysML publications, 2013). The SysML methodology uses graphic objects with different types of diagrams in order to represent the system engineering. They are managed and developed by the Object Management Group (OMG), which is a consortium that concentrates on modelling software, systems and business processes and the standards that support them. The SysML is a young modelling language, a first draft of the language was established in May, 2003 and the last version 1.3 SysML has been submitted on June 8, 2012 (Object Management Group, 2012). Nowadays, the SysML has a growing user base, largely in the aerospace and defense industry and is spreading to engineering (Batarseh and Mcginnis, 2012).

This section is by no means a full description of SysML, there are many books on this subject, but rather a short introduction describing the most important language elements, some of which will be referred to later during this research. More information concerning SysML methodology is provided in Jon and Simon (2008); Sanford et al. (2008).

4.1.2 SysML diagrams

SysML diagrams are the actual graphs that show how the different model elements are arranged and related. SysML includes four core diagrams: behavior diagram, structure diagram, requirement diagram and parametric diagram. The core *behavior diagram* is established by four sub-diagrams and the core *structure diagram* is formed by three sub-diagrams as shown in the diagram taxonomy in Figure 4.1. Each sub-diagram or core diagram is drawn to illustrate a particular aspect of the system and a system is usually described by several types of sub-diagrams. The definition of each sub-diagram type is described below (according to Friedenthal et al. (2009)):

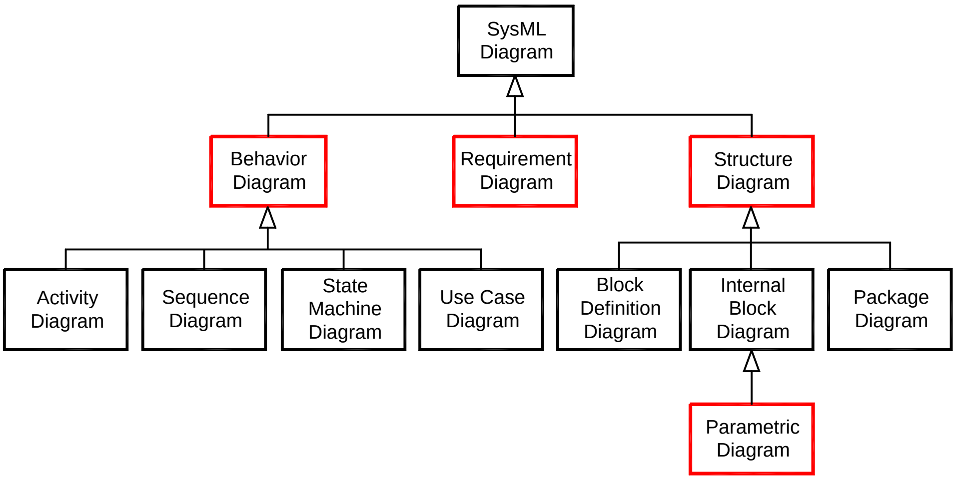


Figure 4.1: SysML diagram taxonomy (Sanford et al., 2008)

- **Behavior diagram** includes the activity diagram, sequence diagram, state diagram and use case diagram:

  Activity diagram represents behavior in terms of the order of actions based on the availability of inputs, outputs, and control, and how the actions transform the inputs to outputs.

  Sequence diagram represents behavior in terms of a sequence of messages exchanged between parts.

  State machine diagram represents behavior of an entity in terms of its transitions between states triggered by events.

  Use case diagram represents functionality in terms of how a system or other entity is used by external entities (i.e., actors) to accomplish a set of goals.

- **Requirement diagram** represents text-based requirements and their relationship with other requirements, design elements, and test cases to support requirements traceability.

- **Structure diagrams** includes the block definition diagram, internal block diagram, and package diagram:

  Block definition diagram represents structural elements called blocks, and their composition and classification.

  Internal block diagram represents interconnection and interfaces between the parts of a block.

  Package diagram represents the organization of a model in terms of packages that contain model elements.

- **Parametric diagram** represents constraints on property values, such as v = s/t, used to support engineering analysis.

Within this study, the SysML simulation models will be constructed. Based on SysML methodology, the simulation models representing the tunnel construction process with microtunnelling will be developed. The SysML simulation model consists of three types of diagrams: block definition diagram (bdd), state machine diagram (stm) and sequence diagram (sd). Therefore, the introduction will describe the concepts behind each of the three types of diagrams in detail, which will be used later in the research described in the next paragraph.

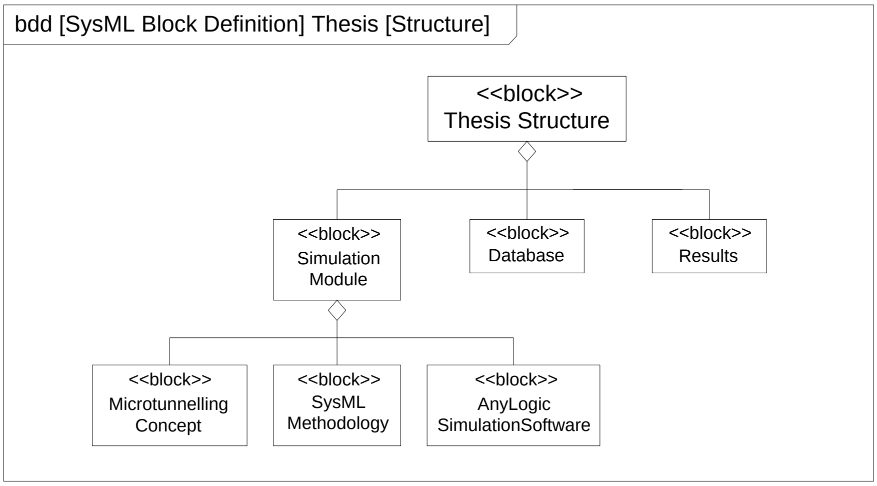


Figure 4.2: A simple example of a block definition diagram

4.1.2.1 Block definition diagram

The block definition diagram (bdd) is used in order to show the structure elements called blocks in any system. Each element in the bdd is considered a stand-alone block, which can have a specific behavior, attributes, constraints and requirements (Rahm et al., 2012). The bdd is very useful for the analysis and design of the system (Weilkiens, 2008). Figure 4.2 shows a simple example of bdd applied for the structure of this *Thesis*. The SysML bdd describes the *Thesis* as a system composition. In the example model, the *Thesis* is defined as a SysML system containing other subsystems. The *Thesis* contains subsystems that define the *Simulation Module*, *Database*, and the *Results*. The subsystem *Simulation Module* involves the three small subsystems *Microtunnelling Concept*, *SysML Methodology*, and *AnyLogic Simulation Software*.

4.1.2.2 Sequence diagram

The sequence diagram (sq) represents behavior in terms of a sequence of messages exchanged between parts (Weilkiens, 2008). The sequence diagram is useful for system analysis and design.

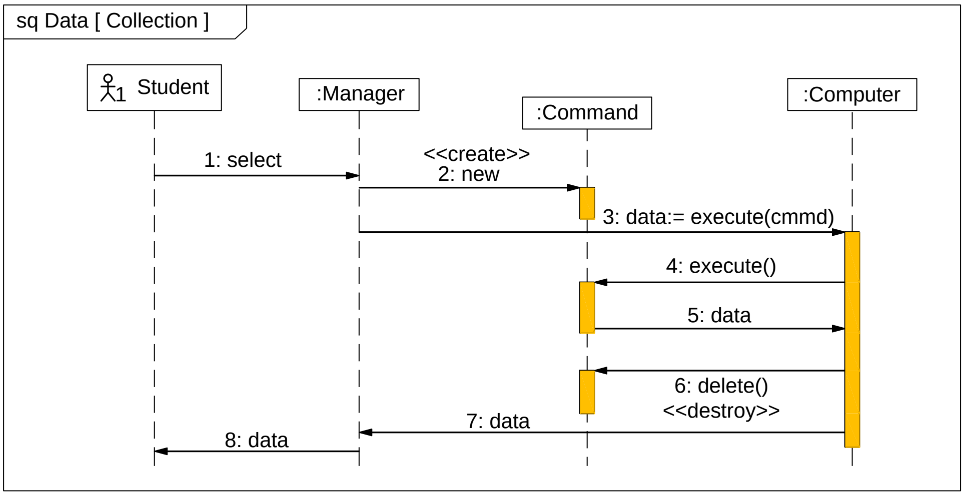


Figure 4.3: A simple example of a sequence diagram

Figure 4.3 represents a simple example of sq for *Collecting the data* from job site, which are stored in the computer. In the example model, a *Student* tells the *Manager* what type of data he wants to select in the job site. In response, the *Manager* creates a *Command* and tells the *Computer* to execute it. Subsequently, the *Computer* asks the *Command* to execute it itself, stores the data, deletes the command, then the *Manager* saves the data and gives it to the *Student*.

4.1.2.3 State machine diagram

The state machine diagram (stm) is also called state diagram or statechart diagram, representing the behavior of an entity in terms of it transitions between states triggered by events (Weilkiens, 2008). The stm is useful for system design and simulation/code generation. Figure 2.2 in Chapter 2.1 shows and describes a simple example of a state machine diagram.

4.1.3 SysML frames

In SysML methodology, every SysML diagram must have a **"frame"**, as shown in Figure 4.4. The frame provides a visible context for the diagram. Diagram frames describe a model element that provides the context for the diagram content. In addition, certain diagrams explicitly draw symbols on or to the frame boundary to indicate external interfaces of the model element owning the diagram (Friedenthal et al., 2009).

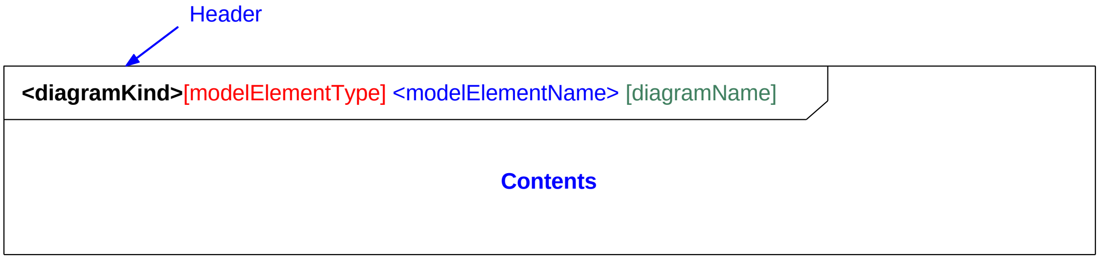


Figure 4.4: A diagram frame

The diagram frame is a rectangle with a diagram header, which is a rectangle with its lower right corner cut off. The **diagram header** in the diagram frame describes the type of diagram, the diagram name, and gives some additional information that provides context for the diagram content. It includes the following information (Friedenthal et al., 2009):

- **diagramKind** is used to indicate the type of the diagrams such as block definition diagram (bdd), sequence diagram (sd) or state machine diagram (stm).

- **modelElementType** is applied to indicate the type of model elements that the diagram represents.

- **modelElementName** is utilized to identify the name of the represented model element

- **diagramName** is employed to give the the name of the diagram, which is often used to say something about its purpose.

4.1.4 SysML model elements

There are a great number of building elements in SysML, structural, behavioral, requirement and parametric elements. It is difficult to classify them, since many of them can be part of all structural, behavioral, requirement and parametric diagrams. The elements used in this study are shown in Figure 4.5 (Sanford et al., 2008).

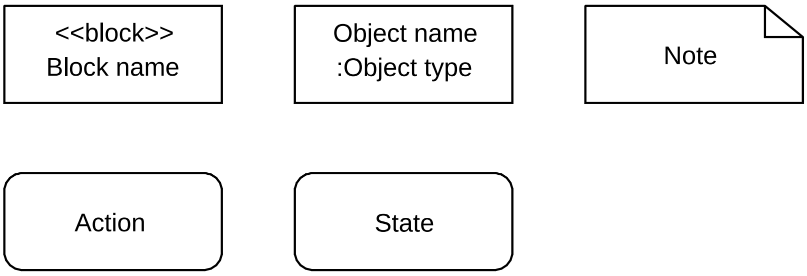


Figure 4.5: SysML elements

- A ”**block**” is used to represents a type of ’thing’ that exists in the real world and, hence should have a very close connection to reality. Blocks are almost always given names that are nouns, since nouns are ’things’ and so are blocks.

- An ”**object name**” is applied to represent information that has been represented elsewhere in the model by a block and is forming an input to or an output from an activity.

- A ”**note**” is utilized to represent an annotation element, usually used as a short explanation of a diagram.

- An ”**action**” is employed to represent behavioral elements used in activity diagrams to represent a physical or logical activity.

- A ”**state**” is used to represent behavioral elements used in state diagrams to represent the different states the model can have.

4.1.5 SysML relationships

The elements are connected by SysML relationships to create complete diagrams. There are about 20 relationships defined for the connection between model elements by adding semantics to the model. Figure 4.6 shows the relationships used in this study (Sanford et al., 2008).

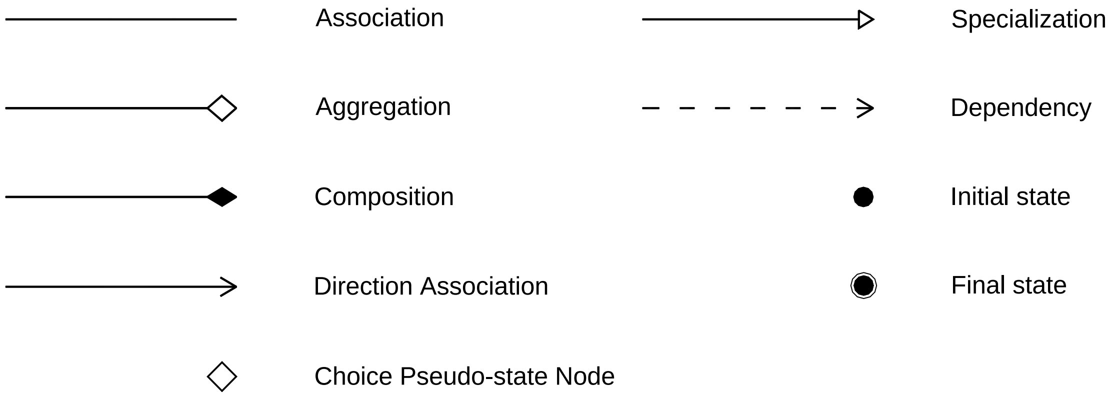


Figure 4.6: SysML relationships

- An ”**association**” relationship is employed to model structural relationships between elements, blocks. There are also two specializations of ”association”: a special type of ”association” known as ”aggregation” and one known as ”composition”.

- A ”**composition**” and ”**aggregation**” relationship is used to denote that one element is a part of another element. The difference in meaning between ”**aggregation**” and ”**composition**” relationship is subtle. In the SysML diagram, an ”aggregation” is read by saying ”is made up of” and a ”composition” is read by saying ”is composed of”.

- A ”**direction association**” relationship is a one way navigable association.

- A **”choice pseudo-state node”** relationship represents the outgoing transitions of a choice pseudo-state which are evaluated once it has been reached.

- A **”specialization”** relationship is employed to represent ”child” blocks, sometimes referred to as ”sub-blocks” of a ”parent” block. Typically one parent has multiple children.

A **”dependency”** relationship is used to represent that one block is dependent on another. This means that a change of the supplier model element may affect the client model element.

- An **”initial state”** is utilized to represent the creation of an instance of the block.

- A **”final state”** is applied to represent the destruction of the instance of the block.

4.2 SysML model development for MTBM

The SysML applied for developing the simulation model in this research is based on flow units and resources (discussed in Chapter 3). As mentioned in section 4.1.2, the SysML model developed for tunnel construction with MTBM consist of three types of diagrams: ”block definition diagram (bdd)”, ”state machine diagram (stm)” and ”sequence diagram (sd)”. Therefore, in this section it will be explained how to develop the SysML model of MTBM operations through the three kinds of these diagrams.

4.2.1 Block definition diagram (bdd) for microtunnelling

The objective of the use of bdd is to show the structure elements in the microtunnelling construction. Each element in the bdd is considered as a stand-alone block, which can have a specific behavior, attributes, constraints and requirements (Rahm et al., 2012). Applied on the microtunnelling construction, a first hierarchical order is established by the distinction between some of the main resources. The next level of hierarchy is provided by the secondary resources. The classification of the main and secondary resources will be analyzed in section 3.5.3 of Chapter 3. The main blocks of an MTBM are illustrated in Figure 4.7.

4.2.2 State machine diagrams (stm)

In order to capture the processes of the microtunnelling construction elements, the technique of state machine is applied. The intrinsic processes of every block represented in the bdd is described within a separate stm. Each stm explains the behavior of an activity in terms of transitions between states triggered by events. The following section gives the description of the applied stm to microtunnelling.

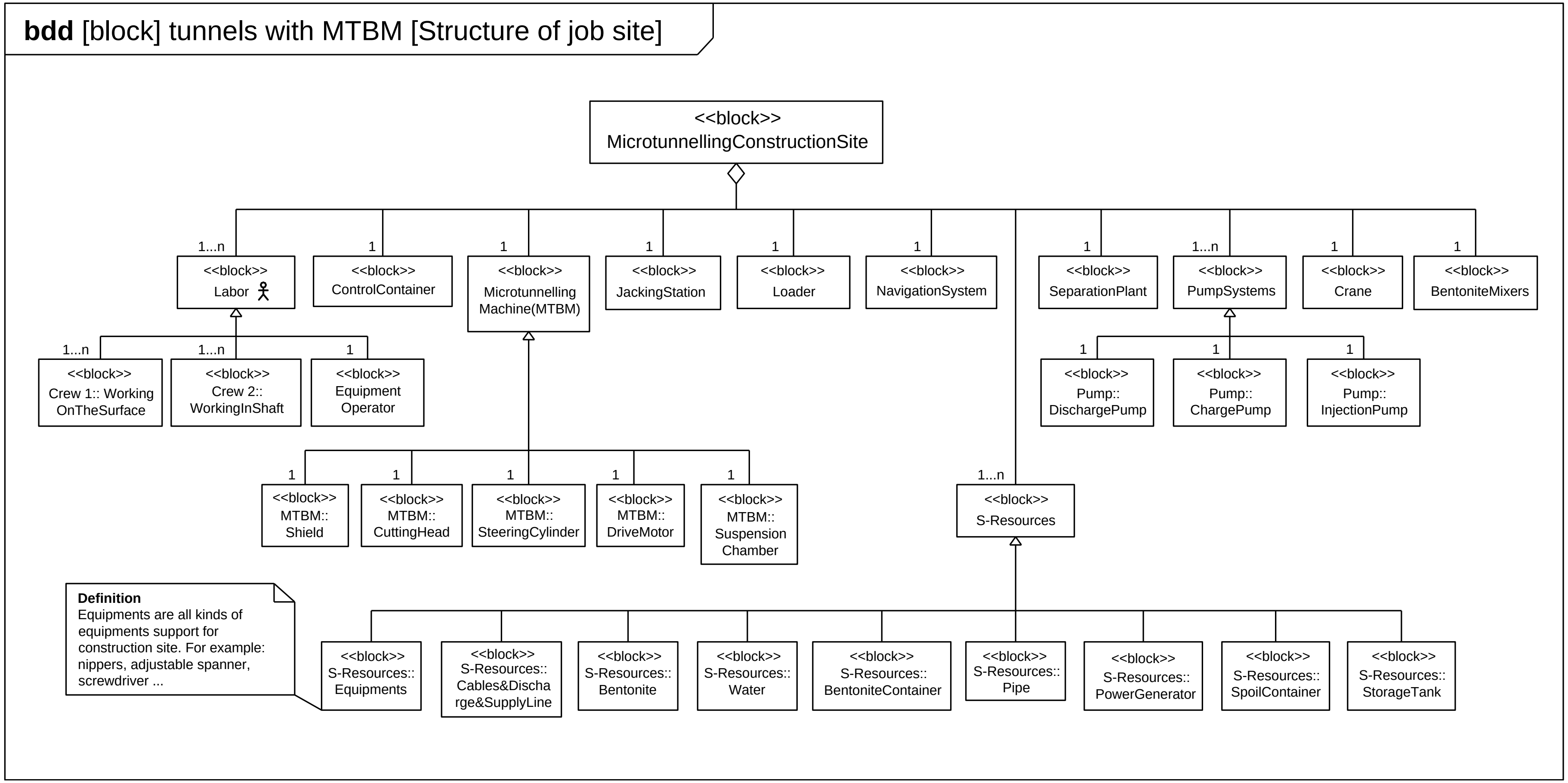


Figure 4.7: Block definition diagram for MTBM

4.2.2.1 State machine diagrams for Crew 1

Such as mentioned in Chapter 3, in tunnel construction operations with MTBM, three different classifications of the labor crew (called Crew 1 - working on the surface and Crew 2 - working in shaft and one equipments operator) are normally required. In this sub-section, the development of the stm for each crew is established.

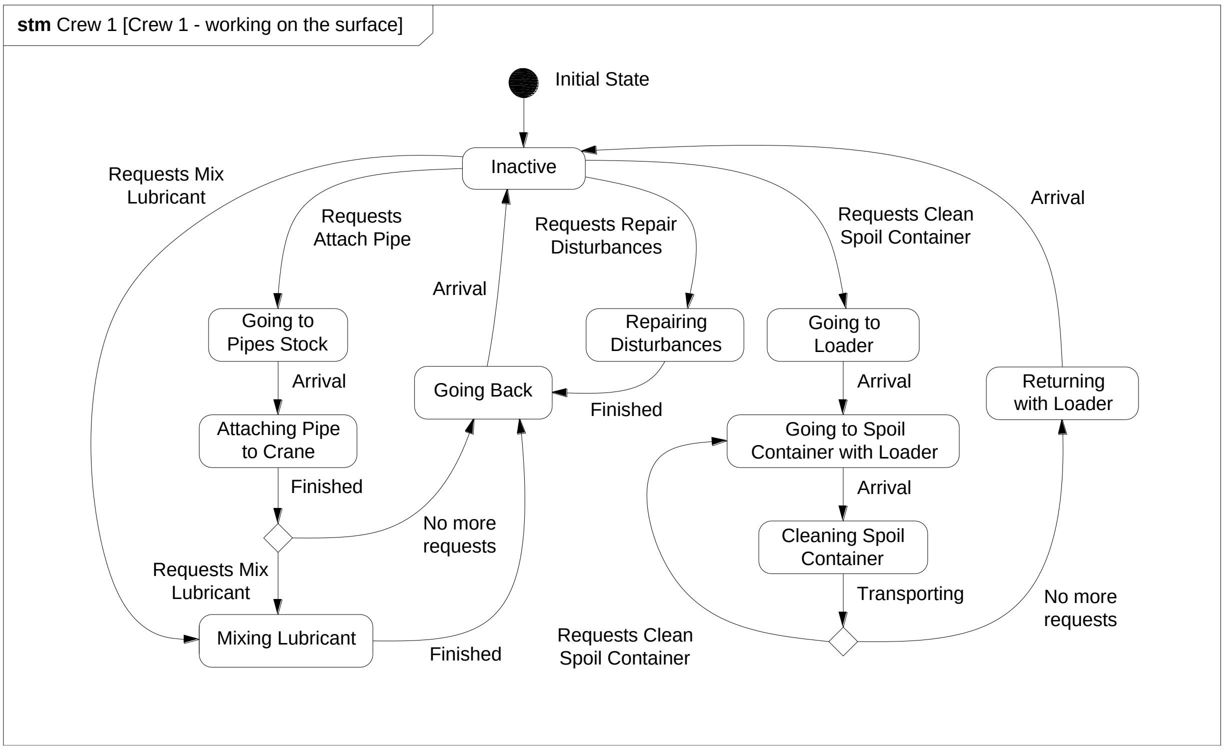


Figure 4.8: State machine diagram for Crew 1 - working on the surface

The first crew is named Crew 1 and the quantity of the laborers in Crew 1 is changed from one to three laborers. Crew 1 works on the surface. Crew 1 accomplishes the task of mixing the lubricant, cleaning the spoil container, if necessary. Crew 1 does the entire work only on the surface, does not directly interact with the jacking system cycle since they do not perform any jacking related activity.

The stm of Crew 1 is described in Figure 4.8. Initially, it is assumed that Crew 1 is in *Inactive* state. The transition from *Inactive* to *Go to Pipes Stock* state is triggered by the receipt of the event *Requests Attach Pipe*. Subsequently, when Crew 1 arrives at the pipes stock the state changes to pipe being attached to the Crane in the *Attaching Pipe to Crane* state. After that, the state either changes to *Mixing Lubricant* if there are *Requests Mix Lubricant* or to the *Going Back* status and returns to the *Inactive* state if the mixing of the lubricant is not requested. In case the volume of lubricant in the storage tank is warning not to be enough for jacking processes, the mixing of the lubricant is due. Crew 1 is switched to the state *Mixing Lubricant*. When the mixing of the lubricant is finished (the bentonite container is full), Crew 1 transfers to the status *Going Back* and re-enters the *Inactive* state.

In case any disturbances occur and Crew 1 is maneuvered to repair, the state changes from *Inactive* to *Repairing Disturbances* by the reception of the message *Request Repair Disturbances*. When the disturbances are repaired, Crew 1 transfers to *Going Back* state and returns to *Inactive* state again. The transfer from *Inactive* to *Going To Loader* state is triggered by the requests event *Requests Clean Spoil Container*. After the loader arrives at the spoil container, Crew 1 is steered to the Loader to clean the spoil in the *Cleaning Spoil Container* state. When the spoil container is empty or no more requests to clean the spoil container exist, Crew 1 returns with loader and switches to initial *Inactive* state.

4.2.2.2 State machine diagrams for Crew 2

The second crew is Crew 2 - defined as three to five laborers working in the shaft. This crew are assigned mainly jacking related activities in the shaft such as rigging the pipe in the starting shaft, helping to lower, fix and lay the pipe on the jacking frame, connecting and disconnecting the cables and pipelines. Due to the tight working space in the shaft bottom, in this study it is assumed that the laborers in Crew 2 have to work together.

Figure 4.9 displays the stm of Crew 2. The initial state of Crew 2 is state *Inactive*. In the event that *Requests Prepare For Jacking Processes* is triggered, the transitions from *Inactive* to *Going to Shaft Bottom* state is turned. When Crew 2 reaches the shaft bottom, the state will either change to *Rigging The Pipe*, if the event *Requests Setup Pipe and Connect Cables* occurs or to *Retracting Jack Collar*, if the event *Requests Retract And Disconnect Cables* appears.

In the case that the event *Requests Setup Pipe and Connect Cables* occurs, Crew 2 sends the message to the surface of the construction site to confirm that the starting shaft is ready to set-up the pipe. After the new pipe section is lowered by Crew 1 and the Operator, the pipe, hoses and cables installation processes are started. At first, the system switches to *Rigging The Pipe* state triggered by the *Requests Setup Pipe and Connect Cables*. After the rigging pipe processes are finished, the state switches from the *Rigging The Pipe* situation to the *Replacing Jack Collar* state. The transition from *Replacing Jack Collar* state to *Connecting Cables and Hoses* takes place when the process *Replacing Jack Collar* is completed. After the state *Connecting Cables And Hoses* is finished, Crew 2 is switched to *Going Back* state and re-enters *Inactive* state again when the Crew arrives at the initial position.

In case that the message *Requests Retract And Disconnect Cables* state is received, Crew 2 transitions into *Retracting Jack Collar* status. When this is completed, Crew 2 switches to state *Disconnecting Cables And Hoses*. After this task is finished, the state will either change to *Rigging The Pipe*, if the event *Requests Setup Pipe and*

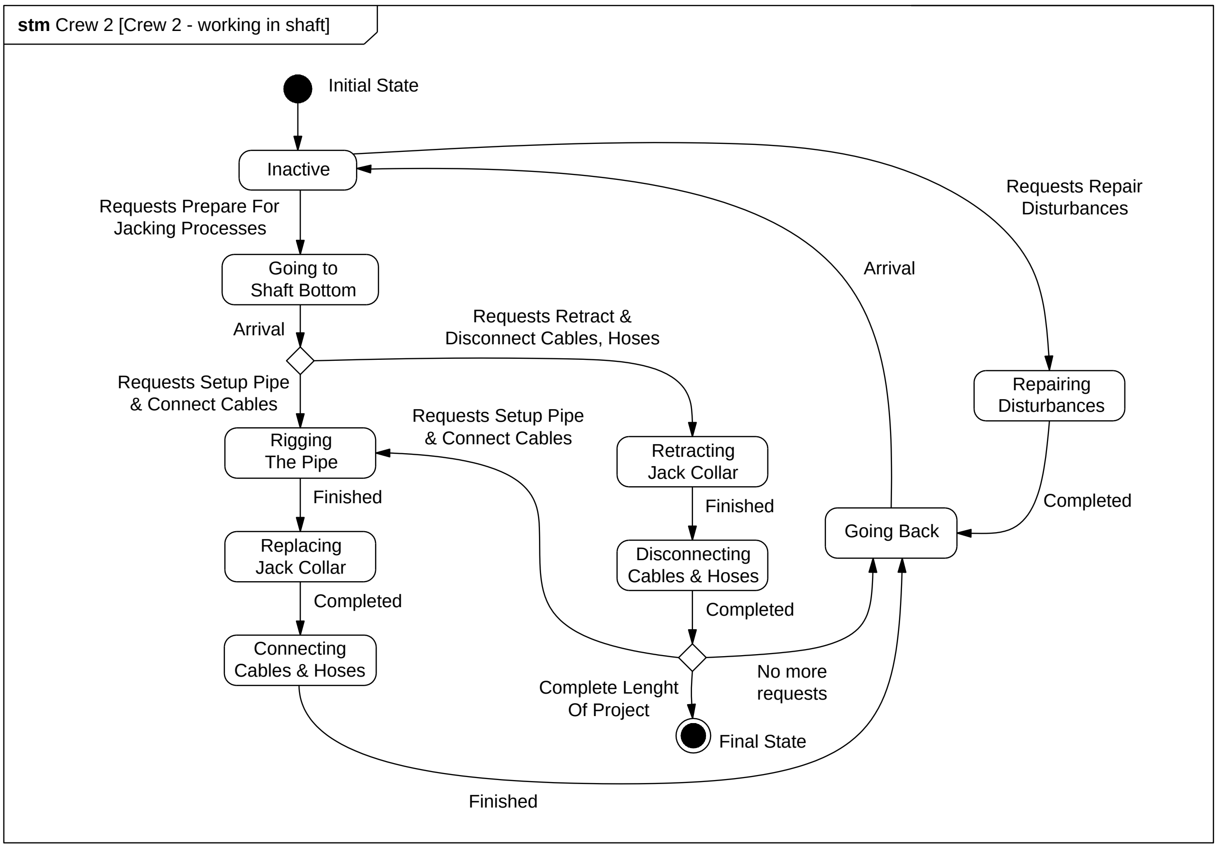


Figure 4.9: State machine diagram for Crew 2 - working in shaft

Connect Cables occurs (repeat the processes mentioned in last case) or returns to *Going Back* state if there are no more requests or switches to *Final State*, if the length of the project is completed.

In case any disturbances occur and Crew 2 is needed for repair, the state changes from *Inactive* to *Repairing Disturbances* after the message *Request Repair Disturbances* is received. The disturbances are repaired, Crew 2 switches to *Going Back* state and after that returns again to the initial *Inactive* position.

4.2.2.3 State machine diagrams for the Operator

The last crew required on the job site is the Operator. It is defined as one laborer - The Operator is involved in the task of job management and also operates the most of the devices on the job site e.g. control container (CC), loader. In addition, the Operator is also involved in the duty of detecting disturbances that appear on the job site. This crew is also the leader to fix any disturbances during the excavation time. The stm for the Operator is illustrated in Figure 4.10. Initially, the Operator is in the *Inactive* state. The transition from *Inactive* to *Going To Crane* state is performed by receiving a message from bottom shaft *Requests New Pipe Section*. After the Operator arrives at the Crane, the Operator switches either to *Time For Repairing* state if there are problems with the Crane or to *Driving To Pipes Stock* state (drives the crane to pipes stock in order to pick up one pipe section). If the state changes to *Time For Repairing* state, the problems of the Crane will be fixed. After the problems have been repaired, the state returns to *Driving To Pipes Stock* state. At the pipes stock, the Operator turns to the *Waiting For Attaching Pipe To Crane* state. After receiving the message *Attached Pipe* from Crew 1, the Operator steers the crane to lift the pipe (*Lifting Pipe* state) and drives the crane with the pipe to the shaft (*Driving Go To Shaft With Pipe* state). When the crane arrives the shaft, the Operator steers the crane to lower the pipe and to rig the pipe on the jacking frame (*Steering The Crane* state). When this is completed, the Operator drives the Crane back to the initial parking, the Operator system turns to *Going Back* state and then switches to *Inactive* state after arrival.

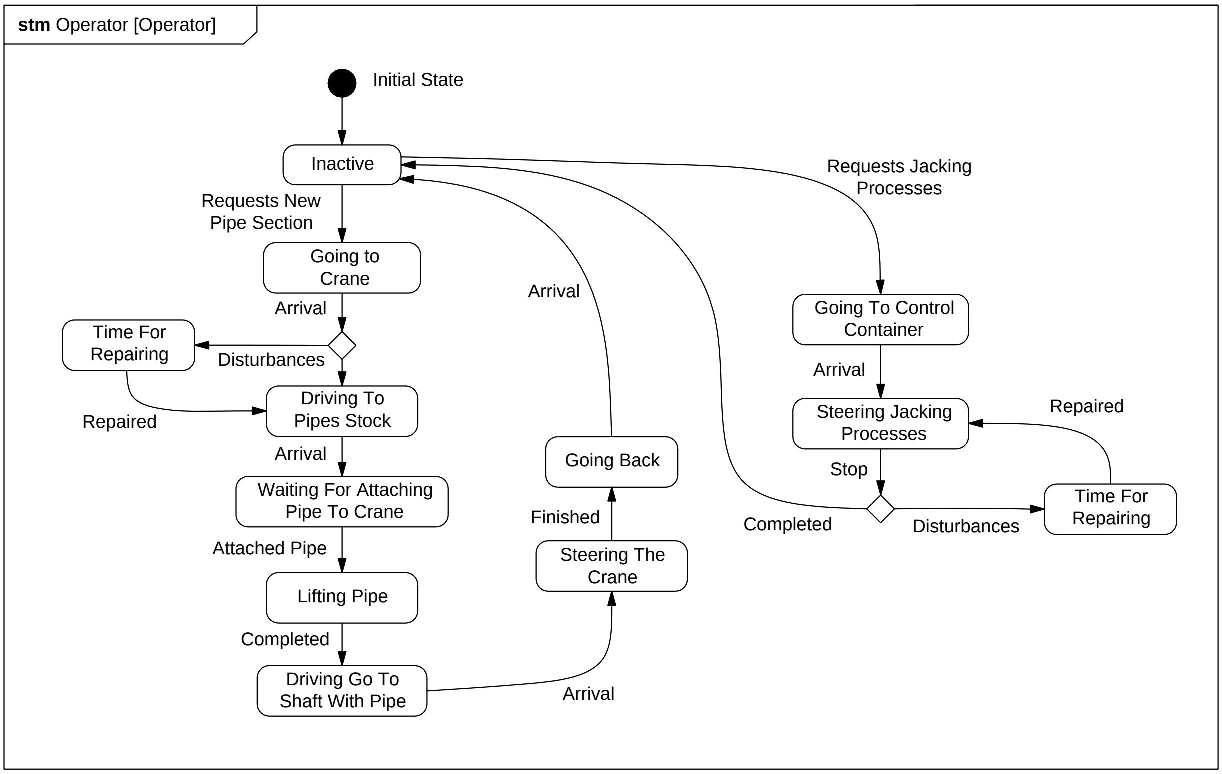


Figure 4.10: State machine diagram for the Operator

In case the event *Requests Jacking Processes* is triggered, the Operator turns to *Going To Control Container* state. After the Operator arrives the CC, the state switches to *Steering Jacking Processes* state. During jacking processes, if the Operator receives the message *Stop*, the Operator will stop temporarily the jacking processes for steering the CC. The state changes either to *Time For Repairing* state if any disturbances occur or to *Inactive* state when the jacking processes are completed. If the state changes to *Time For Repairing* state, the disturbances will be fixed. After the disturbances are repaired, the state re-turns to *Steering Jacking Processes* state.

4.2.2.4 State machine diagrams for the control container (CC)

The MTBM are designed as automatic, remotely controlled tunnelling machines. The entire jacking processes are handled via the CC, which is located on the surface and near the starting shaft. Normally, the CC is divided into two rooms, the machine room with electrical and hydraulic power pack components and the operation room with one steering desk. The steering desk consists of all facilities required for operation and controlling of the jacking processes. The data in the job site, such as: the location of the TBM, the force of the jacking system, the velocity of the TBM, the disturbance causes in the job site, etc are electronically transmitted via cable systems to the CC and shown on the monitor display. The operator can reasonably control the excavation process of the TBM via the monitor display. Through the CC system, most of the disturbances occurring during the jacking processes are reported via a warning message.

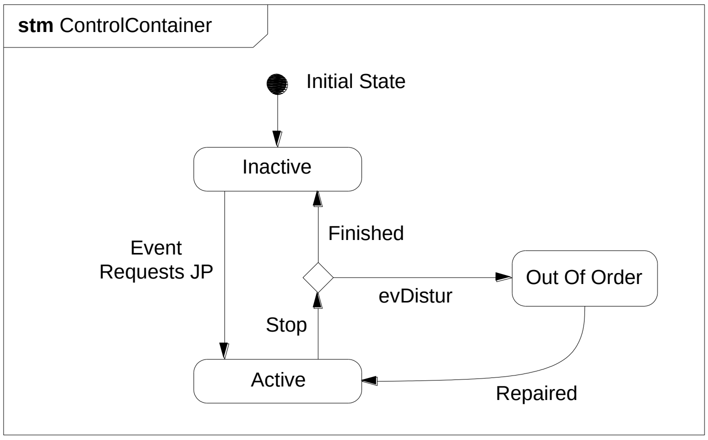


Figure 4.11: State machine diagram for control container (CC)

The stm for CC is shown in Figure 4.11. The state of the CC will be divided into three main states: *Inactive* state (the CC is not working), *Active* state (the CC is working) and *Out Of Order* state. Initially, the CC is defined in the *Inactive* state. The transitions from *Inactive* state to *Active* are performed when the CC receives the command *Event Requests JP* from the Operator. And due to that, the entire of the excavation system of microtunnelling will start jacking processes right after the CC started (right after the state switched to the *Active* state, the CC sends the commands (requests) to other devices to start the jacking processes). During the steering of jacking processes, the state may be changed either to state *Out Of Order* if the system warns of disturbances occuring or the system re-enters to *Inactive* state if the total length of the pipe section is jacked. In case the system warns of occurring disturbances, the jacking processes will send the message *Stop* to all devices. At this time, all devices supporting the jacking processes are changed to the state *Out Of Order*. The CC stays in out of order state or is not working until the disturbances are fixed. After the disturbances are repaired, the Operator controls the CC again and the state re-enters to *Active*, the jacking processes continue. In another case, the state returns again to *Inactive* state when the length of the pipe section is jacked.

4.2.2.5 State machine diagrams for microtunnelling boring machine

The stm for MTBM is displayed in Figure 4.12. The state of the MTBM in this study will be divided into three main states: *Inactive* state (MTBM not working), *Active* state (MTBM working) and *Out Of Order* state. Initially, the MTBM is in the *Inactive* state and due to that, the MTBM will start the excavation process after they received the command from CC. Therefore the transition from *Inactive* state to *Active* state is switched if the jacking processes or CC send the event to start jacking processes. During excavation processes, if the MTBM system receives the message *Stop*, the excavation processes will be stopped. The state changes either to state *Out Of Order* if any disturbances occur or returns to *Inactive* state if the jacking processes are completed. In case the MTBM system changes to *Out Of Order* state, the MTBM system is out of order or not working until the disturbances are fixed. After the disturbances are repaired, the state returns to *Active* state, the jacking processes keep working. Otherwise the state returns to *Inactive* state when the jacking processes are completed.

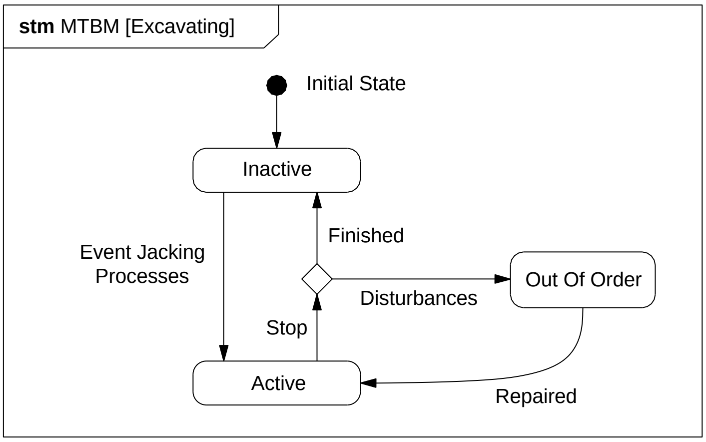


Figure 4.12: State machine diagram for MTBM

4.2.2.6 State machine diagrams for jacking system

The jacking system consists of the jacking frame and hydraulic jacks. A jacking system is installed inside the starting shaft (Figure 3.1). The main functions of the jacking station system involves three main tasks: 1) replace jack collar; 2) jacking forward; 3) retracting jack collar. Figure 4.13 describes the stm of the jacking system. The initial status of the jacking system is defined as *Inactive* state. After the pipe section is lowered into the starting shaft and laid on the jacking frame, the event *Requests Replace Jack Collar* switches the jacking system from *Initial* state to *Replacing Jack Collar* state. When this is completed, the status of the jacking system returns to *Inactive* state.

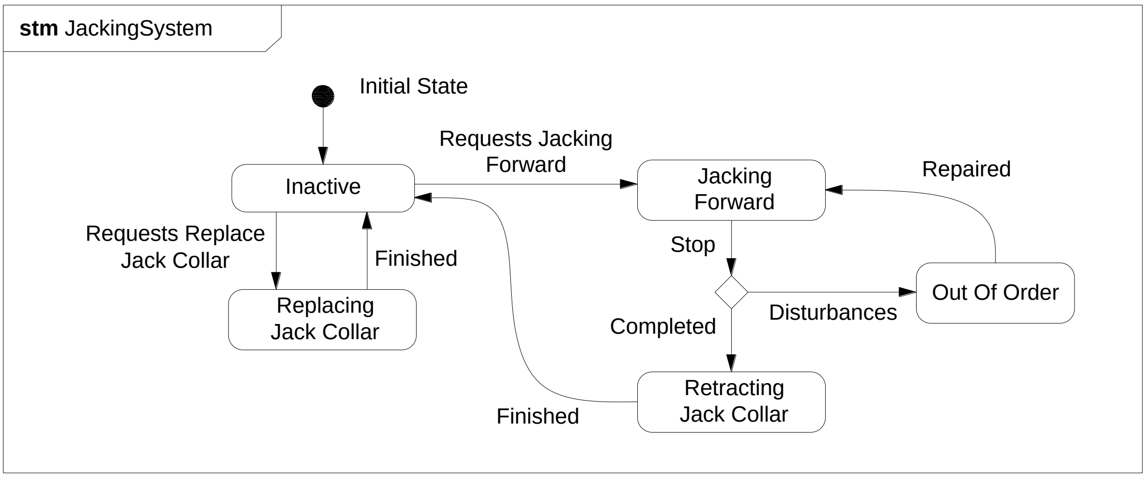


Figure 4.13: State machine diagram for jacking system

In case the event *Requests Jacking Forward* occurs, the jacking system turns to *Jacking Forward* state. During jacking forward, if the jacking system receives the message *Stop*, the jacking system will stop jacking forward. The state changes either to state *Out Of Order* if any disturbances occur or to *Retracting Jack Collar* state when the jacking forward is completed. In case the jacking system changes to *Out Of Order* state, the jacking forward is out of order or not working until the disturbances are fixed. When the disturbances are repaired, the state re-enters into *Jacking Forward* state. Otherwise, if the state changes to state *Retracting Jack Collar*, the jacking system retracts the jacking collar and turns to *Inactive* state when the task *Retracting Jack Collar* is finished.

4.2.2.7 State machine diagrams for loader

The loader is used to clean the spoil container. When the spoil container is full and needs to be cleaned, the loader is controlled by Crew 1. Crew 1 will steer the loader to go to the spoil container and to charge the spoil material onto the truck. The truck will bring the material to the dumping site. All of the activities of the loader are controlled by Crew 1. Therefore the stm developed for Crew 1 (mentioned in 4.2.2.1) also illustrates the activities of the loader.

4.2.2.8 State machine diagrams for the navigation system

The laser is the most commonly used navigation system in MTBM. The laser gives the line and grade information for the pipe installation. The navigation system is exclusively used through the entire jacking process. In this study it is only distinguished between three main states of the navigation system: *Inactive*, *Active* and *Out Of Order* state.

Figure 4.14 displays the stm of the navigation system. During the tunnel construction with MTBM, the navigation system is working at the same time as the jacking processes. That means, the transitions from state *Inactive* to *Active* state is done by

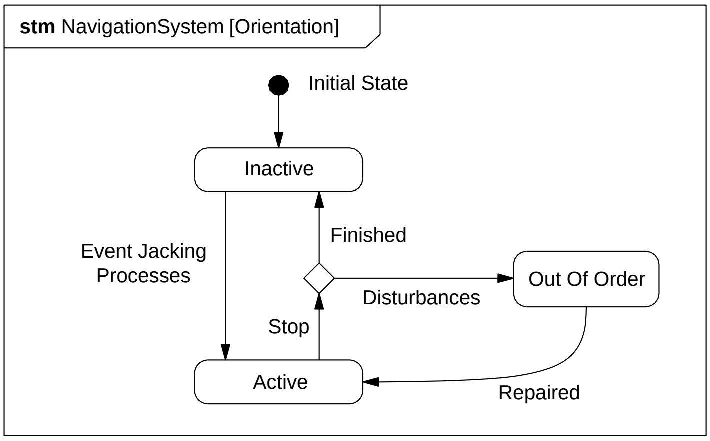


Figure 4.14: State machine diagram for navigation system

the message *Event Jacking Processes* from CC. During the *Active* phase, if the navigation system receives the message *Stop*, the navigation system will stop orientation. The state changes either to state *Out Of Order*, if any disturbances occur, or return to *Inactive* state when the jacking processes are completed. In case the navigation system changes to *Out Of Order* state, the navigation system is out of order or not working until the disturbances are fixed. After the disturbances are repaired, the state returns to *Active* state.

4.2.2.9 State machine diagrams for the separation plant

In tunnel construction with MTBM, the separation plant is an important device, being a sensitive and integral component of tunnelling systems. And according to the discussion with the manager from the construction site, the separation plant is the one which causes a lot of disturbances. A high tunnelling rate is completely reliant on a powerful separation system (Herrenknecht AG, 2013b). The objective of the separation plant is to separate the solid from the fluid components in the excavated material, so that the slurry water can be returned to the circuit after depositing the excavated soil (Overby et al., 2009). In this study it is only distinguished between three states of the separation plant: *Inactive*, *Active* and *Out Of Order* state.

Figure 4.15 describes the stm of the separation plant. The separation plant is working simultaneously with the jacking processes. Therefore, the transitions from state *Inactive* to *Active* state are done by the message *Event Jacking Processes* from CC. During *Active* state, if the separation plant receives the message *Stop*, it will stop to operate. The state switched either to state *Out Of Order*, if any disturbances occur, or turns to *Inactive* state when the jacking process is completed. In case the separation plant changes to state *Out Of Order*, the separation plant is out of order or not working until the disturbances are fixed. After the disturbances are repaired, the state returns to *Active* state.

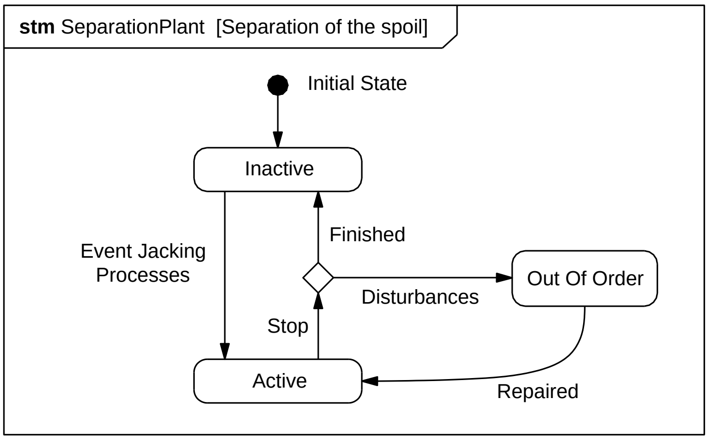


Figure 4.15: State machine diagram for separation plant

4.2.2.10 State machine diagrams for pump system

The pump system is used to perform two main tasks:

1. Due to the MTBM boring through the subsurface, it leaves an annulus of 20-30mm all around the pipe sections. The lubricant is pumped into the annular space. It fills the void around the pipe, temporarily supporting the surrounding soils and minimizing friction to lessen the required jacking forces.
2. The excavated material enters from the face of the MTBM into a crusher chamber located behind the cutting head of the MTBM. In order to create a slurry, water is pumped into the crusher chamber, so the mixture can be transported through the slurry discharge pipes and discharged into a separation system.

The pump system is required through the entire jacking process until the cables and hoses are disconnected. Figure 4.16 displays the stm of the pump system. The pump system works simultaneously with the jacking processes. Therefore, the transitions from state *Inactive* to *Active* state are done by the message *Event Jacking Processes* from CC. During the *Active* state, if the pump system receives the message *Stop*, it will stop pumping. The state switches either to state *Out Of Order*, if any disturbances occur, or turns to *Inactive* state when the jacking process is completed. In case the pump system changes to state *Out Of Order*, the pump system is out of order or not working until the disturbances are fixed. After the disturbances are repaired, the state returns to *Active* state.

4.2.2.11 State machine diagram for the crane

The crane is used to upload the pipe section from the truck and to store pipes in the pipe storage. It is also required to set up the pipe in the starting shaft. The crane goes to the pipe storage with the equipment operator and one laborer attaches the pipe section to the crane. The crane lifts and brings the pipe section to the starting

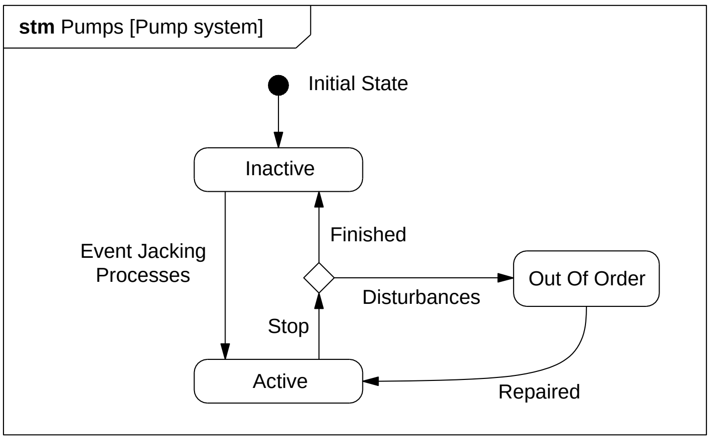


Figure 4.16: State machine diagram for pump system

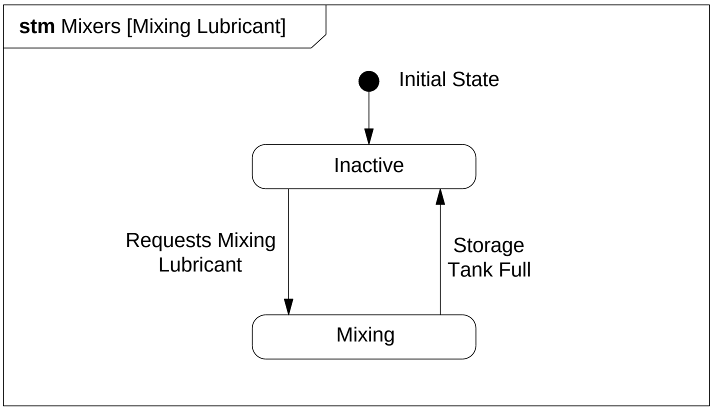


Figure 4.17: State machine diagram for mixer

shaft. After that, the pipe section is lowered into the starting shaft and laid on the jacking frame by the crane (Figure 3.6 a and b). The entire activities of the crane are controlled by the Operator. Therefore the stm developed for the Operator (mentioned in 4.2.2.3) also describes the activities of the crane.

4.2.2.12 State machine diagrams for the mixer

The mixer is operated when the volume of lubricant, which is stored in the storage tank, is not enough to support the jacking processes. These resources are required throughout the entire jacking process until the cables and hoses are disconnected. Figure 4.17 describes the stm for the mixer. The definition of the first state of the mixer is *Inactive*, the transitions from *Inactive* state to *Mixing* state is performed when the message *Requests Mixing Lubricant* is received (e.g. when the volume of the lubricant in the storage tank is not enough, the model will send the message: *Requests Mixing Lubricant*). During the mixing process, the lubricant is mixed in the mixing tank and stored in storage tank. When the storage tank is full, the state returns to *Inactive* state.

4.2.3 Sequence diagram for microtunnelling

The sq, in this study, is an auxiliary design document intended to identify the interaction between blocks as well as to understand the intrinsic processes of every block of the tunnel construction with MTBM. It is not used to develop the simulation module, it is not a part of the AnyLogic modeling language. As mentioned in Chapter 3 Section 3.5.2, normally, the tunnel construction with MTBM can be separated into two steps. The first step (named preparation step) and the second step (named excavation step). Therefore, the sq is established in a way to describe this basis of two steps as well.

4.2.3.1 Sequence diagram for preparation processes

The first step (named preparation step), representing the entire preparation process before the tunnel is excavated. Figure 4.18 displays the sequence diagram for preparation processes. In Figure 4.18 of the message sequence diagram, when *Crew 2 - Work in Shaft* receives the message *Request retract jack collar task* from the Operator, Crew 2 will go to the shaft bottom and retract the jack collar and disconnect cables and hoses. When this is completed, Crew 2 sends the message *Request new pipe section* to Operator and Crew 1. Immediately, the Operator goes to the crane and starts to drive the crane to the pipes stock. Crew 1 goes to pipes stock as well. When Crew 1 and Operator arrive, Crew 1 will attach the pipe section to the crane. The Operator controls the lifting of the crane, the lowering of the pipe section into the shaft and the placing on the jacking frame. When the pipe section is laid on the jacking frame, Crew 2 will set up the pipe section before the jacking processes. When this is completed, Crew 2 returns to the initial position and sends the message *Request jacking processes* to the Operator.

During preparation and jacking processes, the mixing of the lubricant or cleaning of the spoil container are requested. Crew 1 goes to the mixer in order to mix the lubricant in case there is a warning that the volume of the lubricant in the storage tank is not enough for jacking processes. Crew 1 goes to the spoil container to clean the spoil material if the spoil container is full.

4.2.3.2 Sequence diagram for jacking processes

The second step (named jacking processes) is performed by the Operator. The Operator controls the CC in order to steer the jacking pipe section process and excavate, while removing the spoil. Figure 4.19 depicts the sequence diagram that shows the progression of the message that is send to the other classes in order to perform the jacking processes.

In the sq diagram for jacking processes, when the *Operator* receives the message

Request jacking processes, the *Operator* starts *Go to control container* to steer the jacking processes. After the Operator arrives at the container (box across *ControlContainer*), the Operator will create the command by using the menu item on CC. In response, the box across *ControlContainer* creates a command sequence and requests the item of equipment such as MTBM, separation plant, jacking station, navigation system or pump system to execute it. The item of equipment asks the command to execute it itself. After the duration, the jacking processes finish all of the jacking processes, delete the commands, then return to the CC and send the message *Request retract jack collar* task.

4.2.4 Summary of tunnel construction with MTBM

In order to have an overview of the tunnel construction processes with MTBM, in this sub-section a summary of the tunnel construction with MTBM using SysML is given.

Figure 4.20 (a) shows the stm for the general view of the building operations by using MTBM. According to the summary in Chapter 3 Section 3.5.2, the tunnel construction with MTBM is divided into two main processes: **Preparation processes** and **Jacking processes**. Therefore, the initial state of the stm for microtunnelling system is the *Preparation processes* state. In case the preparatory work (*Preparation processes*) is completed, the transition from state *Preparation processes* to state *Jacking processes* is carried out. The *Jacking processes* state will switch to another state if the total length of the pipe section is jacked forward and the system completed one building operation cycle. When this process is completed, the state changes either to state *Final State*, if the total length of the project is finished (trigged: *LengthOfProject = true*), or returns to state *Preparation processes* (the system starts with the new operation cycle), if the total length of the project excavated is less than the designed length of the project (trigged: *LengthOfProject = false*).

Figure 4.20 (b) describes the sq for the general overview of the use of the resources during the tunnel construction with MTBM. In the sq diagram model, a box across *ItemsOfEquipment* represents the entire of the equipment, e.g. loader, crane, mixer, etc. in order to support the preparation and jacking processes. Another box across *ControlContainer* displays the CC device, which steers the system equipment in order to perform the jacking processes.

In the sq diagram, the *Laborers* select the equipment on a box across *ItemsOfEquipment*. In response, the box across *ItemsOfEquipment* will execute the preparation processes. After that duration, the preparation processes for the jacking processes are completed. The system returns to the *Laborers* box across. Subsequently, the *Laborers* create the commands and tell the *ControlContainer* to control the *ItemsOfEquipment* in order to perform the jacking processes. After that duration time, the jacking

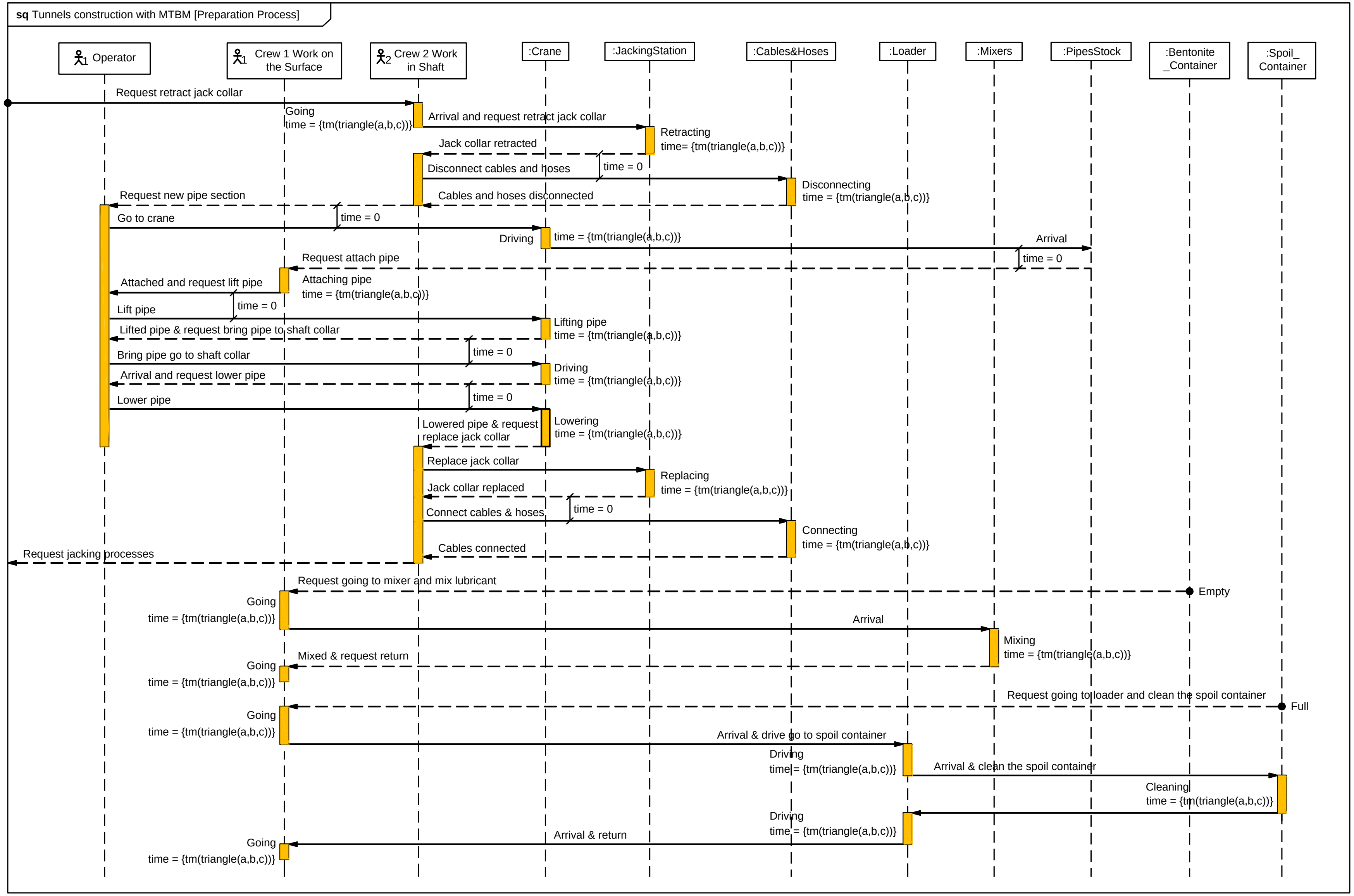


Figure 4.18: Sequence diagram for preparation processes

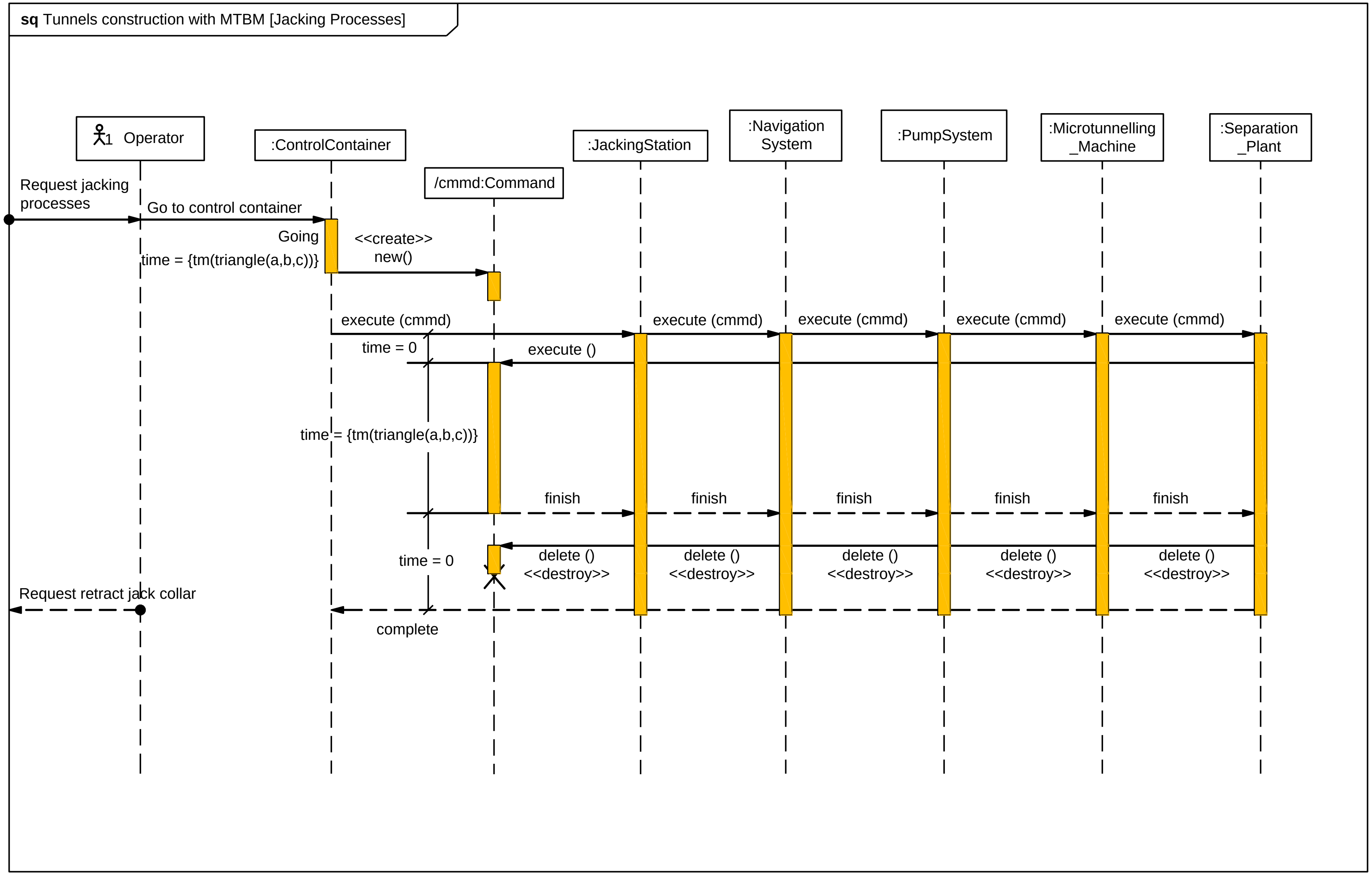
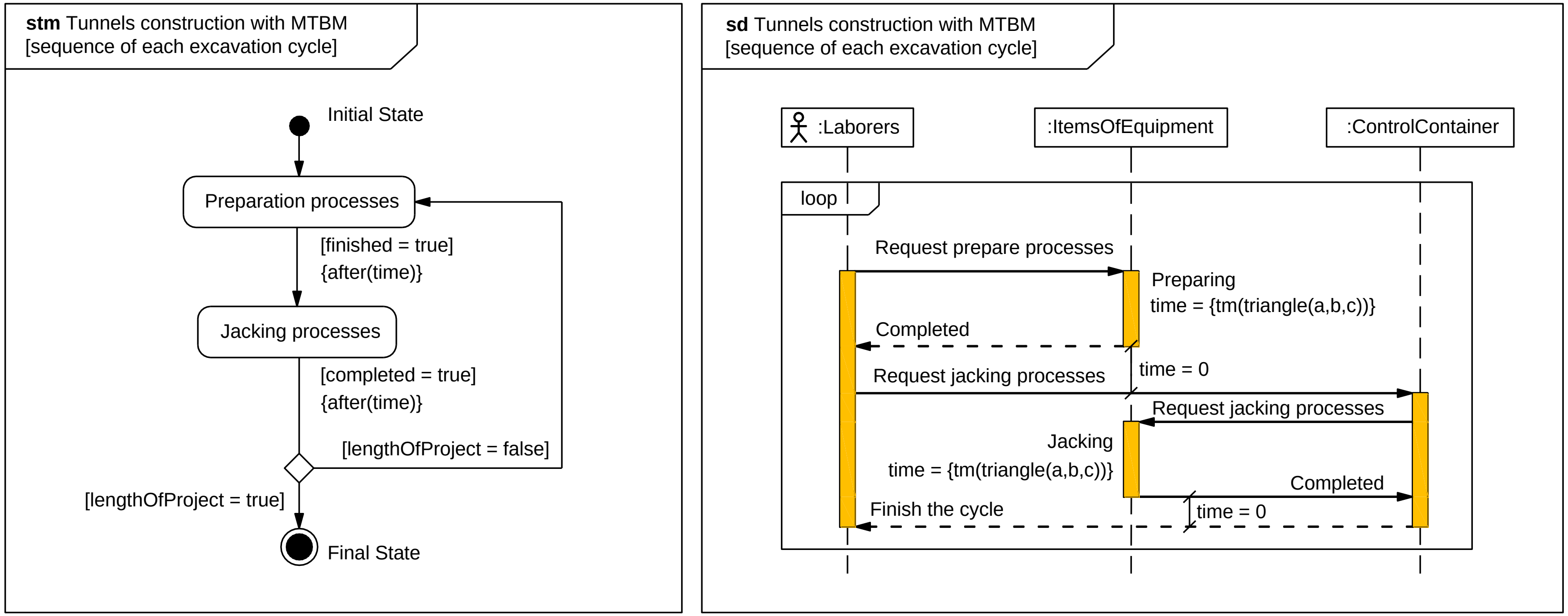


Figure 4.19: Sequence diagram for jacking processes

processes are completed, delete the commands, the system returns to *Laborers*. One cycle of tunnel construction with MTBM is finished, another cycle to be repeated until the total length of the tunnel is excavated.



(a) (b)

Figure 4.20: Summary of tunnel construction with MTBM

Chapter 5

Simulation of microtunnelling processes

This Chapter focuses on two components of the simulation module: 1) the application of simulation software to develop the simulation module will be presented and 2) the functions of the simulation module will be introduced.

First, the development of the simulation module named MiSAS (Microtunnelling: Statistics, Analysis and Simulation) will be highlighted. The applied simulation environment is AnyLogic simulation software by *XJ Technologies* XJ Technologies (2012). The MiSAS is based on Java and utilizes the discrete event, system dynamic method, which is supported by the AnyLogic simulation software. The enhancement of the functions to analyze different types of disturbances, the soil composition for the evaluation of progress or predicting the progress are integrated in the MiSAS and described as well. Subsequently, the description of the MiSAS module such as use, design and implementation stages benefit of the simulation module will be presented.

5.1 Development MiSAS module

The development of the MiSAS based on AnyLogic simulation software has been carried out in three main stages. These stages are:

- Stage 1: The standard MiSAS module is based on the SysML developed simulation model. The implementation and transcription of the element blocks (described in Chapter 4 section 4.2) into AnyLogic software is executed.
- Stage 2: The enhancement of the MiSAS with the consideration of the soil composition and disturbances is performed by using the system dynamic simulation

methodology after the standard MiSAS module validated.

- Stage 3: The design of the interfaces of the MiSAS module, e.g. interface for input, output data and the interface for the statistics and analysis of the results.

Following, the details of the implementation for developing the standard module MiSAS are presented.

5.1.1 Development standard module MiSAS

The standard module MiSAS is achieved by transcribing all of the element blocks within SysML model into the modules in AnyLogic based on *Active Object Classes (AOC)*. The process interaction inside of each block as well as the behavior between each element is rebuilt by using state charts, which are provided by *AnyLogic* simulation software. Due to that, the elements from the developed model SysML transcribed to AnyLogic software have the same properties and attributes. Therefore, in this sub-section only two element blocks of Mixer (one simple element block) and Crew 1 (one of the most complex element blocks) are highlighted and described as an example.

5.1.1.1 The AOC of Mixer in AnyLogic

In Figure 5.1 the simple internal composition of the *AOC Mixer* is displayed. The processes are modeled by using state charts in AnyLogic and transcribing the element block of Mixer (described in Chapter 4 sub-section 4.2.2.12). The same applies for the stm diagrams for the mixer (Figure 4.17), the state chart in AnyLogic software starts with the state *Inactive*, the transition event *evRequestsMix* transfers the element from *Inactive* state to *Mixing* state. In case the event *evStorTankFull* is triggered, the state returns to initial state *Inactive*.

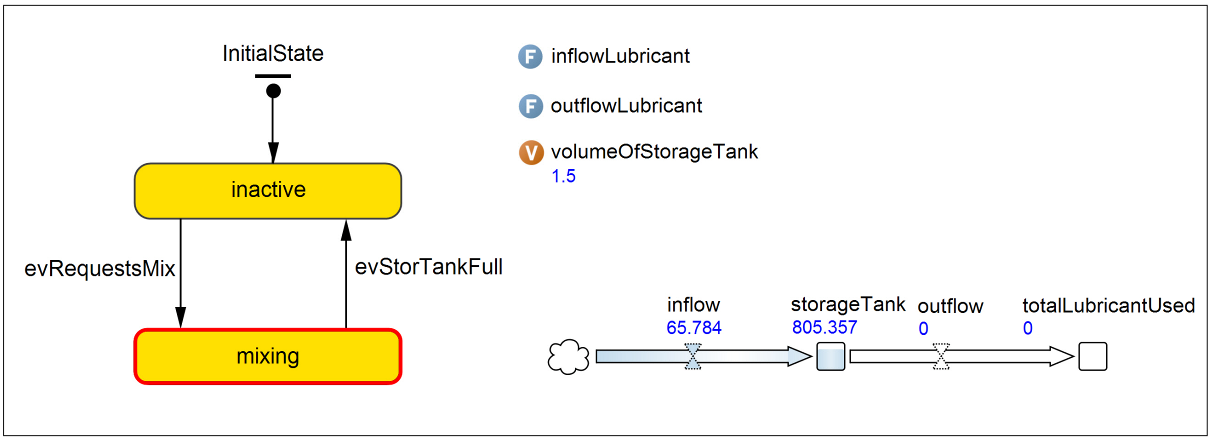


Figure 5.1: The *AOC Mixer* during the state *mixing*

In order to handle the flow rate of the lubricant, the stock-variable and flow-variable, which are supported by a system dynamic model that is used in AnyLogic software.

The stock-variable is employed to calculate the volume of lubricant, and the flow-variable is used to measure the rates of change of the volume of the lubricant. For the Mixer, two stock-variables and two flow-variables (named *inflow* and *outFlow*) and a variable (named *volumeOfStorageTank*) are used. The variable is used to input the cubic capacity of the storage tank. The first stock-variable represents the volume of the storage tank (named *storageTank*). The volume of *storageTank* is increased or decreased by the *inflow* or *outFlow* of the lubricant, respectively. The second stock-variable describes the total volume of the lubricant used (named *totalLubricantUsed*). The volume of *totalLubricantUsed* is increased by the *outFlow* of the lubricant. The flow rate of the *inflow* and *outFlow* are calculated by function *inFlowLubricant* and *outFlowLubricant*, respectively.

Figure 5.1 describes a print screen during a simulation run, where the Mixer is momentarily in the state *mixing* - shown with the thick red border. The volume of the storage tank (*storageTank*) can stock a setup equal to 1,5 cubic meter. Due to that the state *mixing* is active, the flow-variable *inflow* is active as well. The stock-variable *storageTank* increases with inflow value 0.065 cubic meter per minute. The stock-variable (*storageTank*) is increased up to 1,5 cubic meter, the system sends the message event *evStorTankFull*. After that the *Mixer* state diagrams will return to *Inactive* state. In case the lubricant is used, the flow-variable *outflow* is active, therefore, the stock-variable *storageTank* decreases. When the stock-variable *storageTank* is empty or inputs the information that less than 20% of the volume of the storage tank is used, the system sends the message event *evRequestsMix* to the *Mixer* state chart. The state chart will be switched to *Mixing* state.

5.1.1.2 The AOC of Crew 1 in AnyLogic

In Figure 5.2 the most complex internal composition of the *AOC Crew 1* is described. Figure 5.2 displays a capture during a simulation run, where Crew 1 is momentarily in the *liftingPipe* state - distinguishable with the thick red border. The processes are modeled by also using state charts in AnyLogic and transcribing the element block of Crew 1 (described in Chapter 4 sub-section 4.2.2.1).

The same goes for the state machine diagrams in SysML for Crew 1 (shown in Figure 4.8), initially the state of Crew 1 in AnyLogic is *Inactive* state. The transition from *Inactive* to *Go to Pipes Stock* state is triggered by the receipt of the event *evRequestsAttachPipe*. Subsequently, when Crew 1 arrives at the pipes stock the state changes to attaching pipe to the Crane in the *attachingPipeToCrane* state. After that, the state either changes to *mixingLubricant*, if there are *evRequestsMixLubricant* or to state *goingBack* and returns to *Inactive* state if the mixing of the lubricant is not requested. In case any disturbances occur and Crew 1 is maneuvered for repair, the

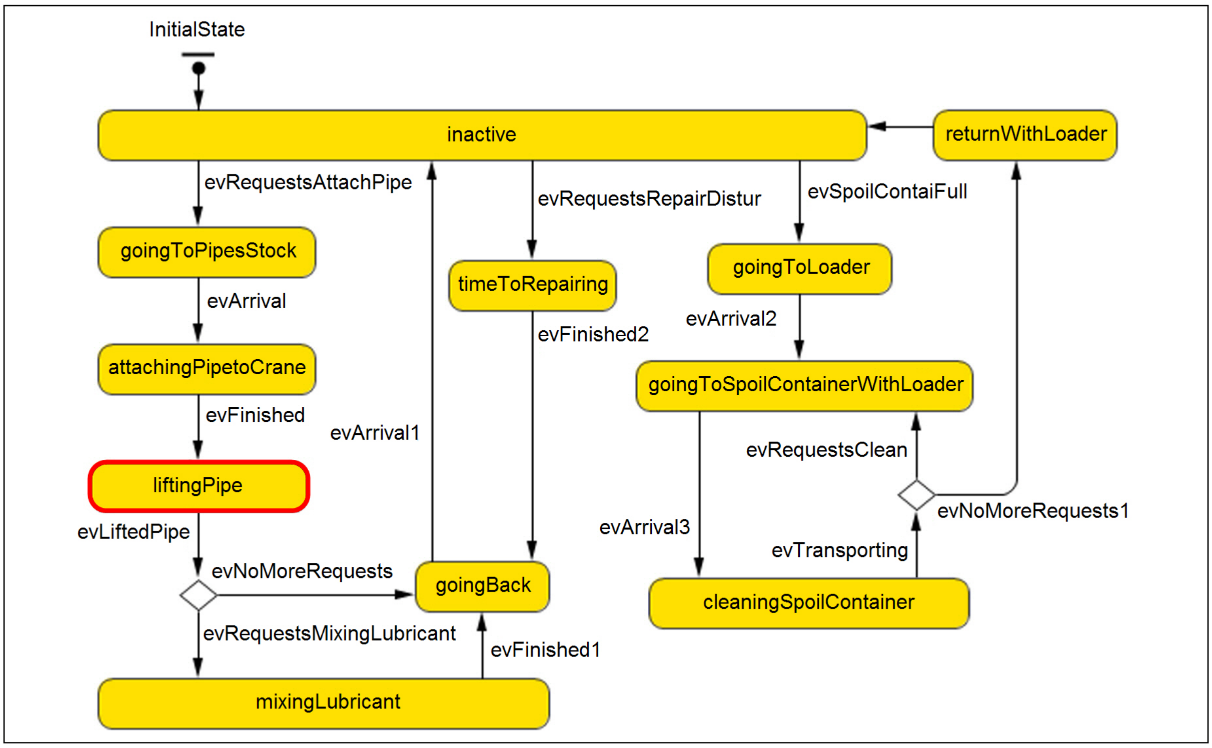


Figure 5.2: The *AOC Crew 1* during the state *liftingPipe*

change from *Inactive* to *timeTorepairing* state is carried out by the receipt of the message for event *evRequestRepairDistur*. When the disturbances are repaired, Crew 1 switches to *goingBack* state and returns to initial state *Inactive*. The transition from *Inactive* to *goingToLoader* state is triggered by the event *evSpoilContaiFull*. After the loader arrives at the spoil container, Crew 1 steers the Loader to clean the spoil in the *cleaningSpoilContainer* state. When the spoil container is empty or no more requests exist, Crew 1 returns to the initial parking with the loader and switches to *Inactive* state.

5.1.2 Enhancement MiSAS module

The last sub-section above mentioned the basis of the methodology (stage 1) in order to build the standard MiSAS module. After validation of the simulation module (mentioned in Chapter 7 section 7.1), the MiSAS module is enhanced with soil composition and disturbances.

5.1.2.1 Enhancement MiSAS module to consider disturbances

The effect of the disturbances on the rate of progress of the tunnel construction with MTBM is considered within the MiSAS module. According to Table 3.8 in Chapter 3 sub-section 3.6.2, the disturbance is enhanced in two cases: 1. Disturbances during jacking processes; 2. Disturbances during preparation processes.

5.1.2.1.1 Disturbances during jacking processes

Figure 5.3 shows the stm of the control container (CC) during the state *active*. The stm of CC is not only described as the states of CC but also as a Disturbances Processing Center *(DPC)* during jacking processes. The *DPC* is developed by a state chart as well. The main task of the *DPC* is to receive or collect the event disturbances from other devices, e.g. MTBM, separation plant, navigation system and after that the *DPC* processes the disturbances data. The specific of the microtunnelling is that if any category of disturbances occur during jacking processes, the jacking processes must be stopped and all devices, which are support the jacking processes must be stopped as well. Furthermore, the disturbances are stochastic, therefore during one jacking processes cycle may occur some disturbances from any devices. The *DPC* receives every event disturbance from other devices, and processes the information, plus (or adding) the whole Mean Time To Repair (MTTR) and sending the message to CC in order to stop working in time failure. For example, on Friday, June 29, 2012 at the pipe number 13, the disturbances occured two times because of the separation plant (according to the data recorded from project BV Recklinghausen V.15, shown in Appendix A.3). The MTTR for the first and second disturbances is 247 and 236 minutes, respectively. Due to that, the disturbance causes occurred not at the same time. Therefore, the correction of the disturbances was not carried out simultaneously, the *DPC* adds the MTTR of the first disturbance with the MTTR of the second disturbance for one MTTR value. That means that the total time for MTTR in this case is 247 min + 236 min = 483 min. 483 min is the MTTR value used for calculating the mean time between failure (MTBF). After the devices are repaired, the *DPC* sends the message request to resume the jacking processes.

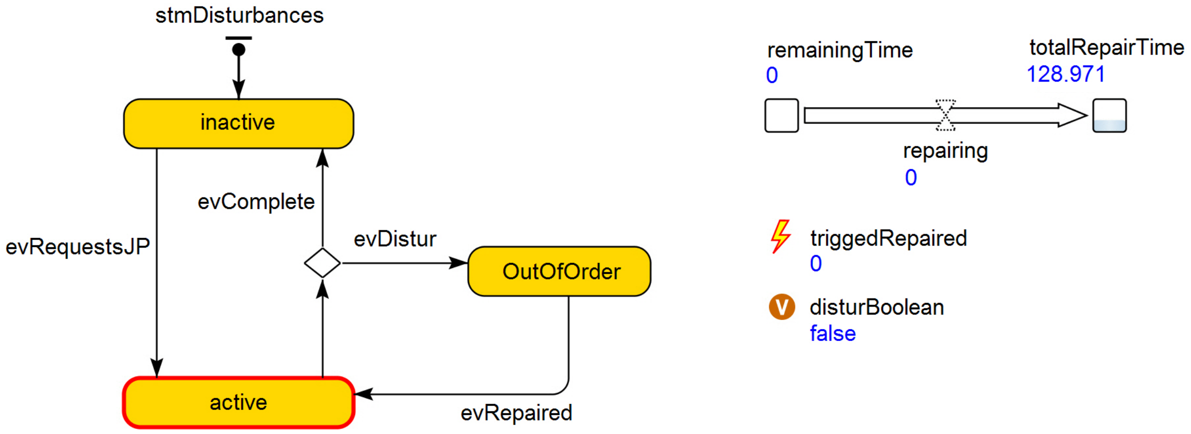


Figure 5.3: The *AOC control container (CC)* during the state *active*

The explanation of Figure 5.3 is as follows: The *DPC* works in parallel with the jacking processes. Therefore, the transition in Figure 5.3 from state *inactive* to state *active* is carried out when the *DPC* receives the event *evRequestsJP* from the Operator. In any case with or without disturbances, the state *active* returns to *inactive* state when the jacking processes are completed. In case there are no disturbances, the *DPC* does not run through *OutOfOrder* state. In case there are disturbances, the state *OutOfOrder* is used to alternate the jacking processes. After the disturbances are repaired, the transition *evRepair* is called and the *active* state is re-entered. The *DPC* sends the commands to other devices and the jacking processes is resumed.

In the *DPC* the ”loading bar”, supported by system dynamic model, is used to measure the repair time of the disturbed operation. In the ”loading bar” the *remainingTime* describes the remaining time to repair the disturbances. The flow-variable *repairing* reduces stock by one every-time unit. Consequently the stock-variable *totalRepairTime* is increased by one every-time unit of repairing operation.

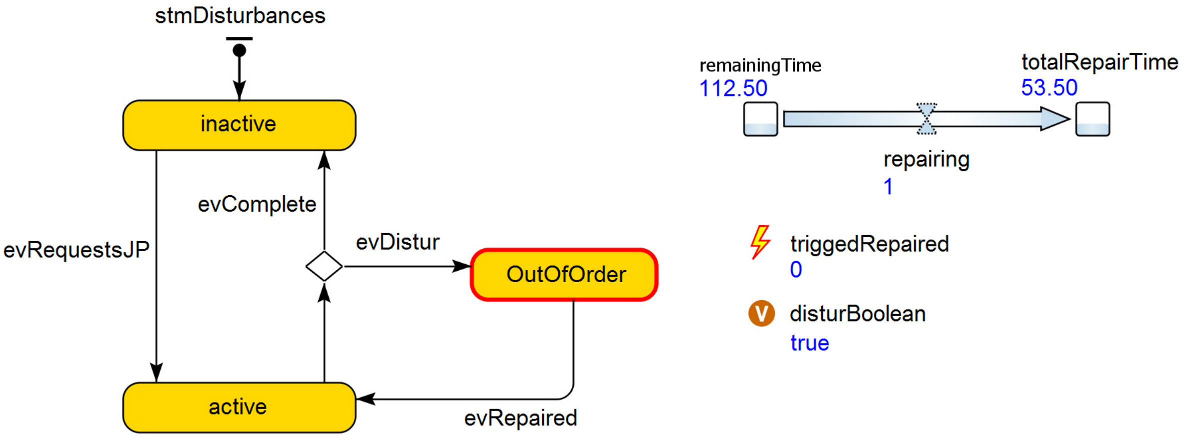


Figure 5.4: The *AOC control container (CC)* during the state *OutOfOrder*

Figure 5.3 is displays a snapshot during a simulation run without disturbances, the state of the *DPC* is momentarily in the state *active* - represented by the thick red border. When the *DPC* is in *active* state, the flow-variable *repairing* is not active (not working). The variable *disturBoolean* expresses the state of the system with or without disturbances. The variable *disturBoolean* is currently in the state *false*, that means no disturbances in this time. The objective of the event *triggedRepaired* sends the command in order to change the *disturBoolean* state. Figure 5.4 shows one screenshot during a simulation run with the disturbances data recorded from project BV Recklinghausen V.8. The disturbance occurred at pipe number 10 on Wednesday, June 01, 2011 and the MTTR of the disturbance is 166 min (shown in Appendix A.1). When the disturbances occur, the trigger *triggedDistubance* sends an event to *DPC*, the *DPC* sends the commands event *Stop* to other devices, which are related to jacking processes to stop the operation temporarily. Meanwhile, in the *DPC* system, the state switches to the *OutOfOrder* state as well. The flow-variable *repairing* is active (working) to calculate and update the repair time. The flow-variable gives the information that

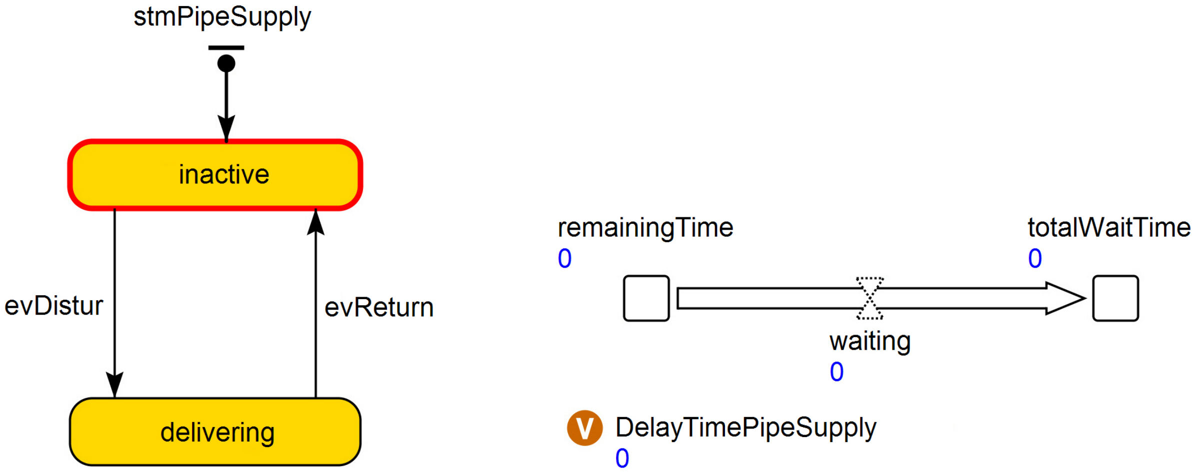


Figure 5.5: The *AOC PipesSupply* during *inactive* state

the total repair time is 53.5 min and that the disturbance will be completed in 112.50 min. When the repair time is over, the state re-enters to *active* state. In case another disturbance occurs, the *totalRepairTime* is updated.

5.1.2.1.2 Disturbances during preparation processes

Due to the tunnel construction with MTBM sometimes in a confined urban space, the limited space of pipes stock (storage of pipe) in the construction site or the transportation of the pipes through the road may be delayed because of traffic jam. These reasons are causes for disturbances that may occur due to pipes supply. Therefore, in this study the disturbance of the pipes supply is considered.

In case, the pipe is not available during the preparation process, the preparation process may be performed with works not related to the set-up of the pipe such as: disconnecting cables and hoses, mixing bentonite or cleaning the storage tank if necessary. When this is finished, the preparation process must be stopped to wait for the pipe to be available. In Figure 5.5 the internal composition of the *AOC PipesSupply* is highlighted. The *AOC PipesSupply* is developed also by state chart in AnyLogic. The transition from *inactive* state to *delivering* state is triggered by *evDistur* (the disturbance of the pipe occurred or no pipe is available on the construction site). When the waiting time for the pipe supply is completed (the pipe reaches the job site), the state *delivering* is re-entered to *inactive* state and the tasks related to the pipe may be performed.

The ”loading bar” is used to measure the waiting time for the pipes supply. In the ”loading bar” the *remainingTime* describes the remaining time to wait for the delivery of the pipe to the construction site. The flow-variable *waiting* reduces stock *remainingTime* by one every-time unit. Consequently the stock-variable *totalWaitTime* is increased by one every-time unit of waiting operation.

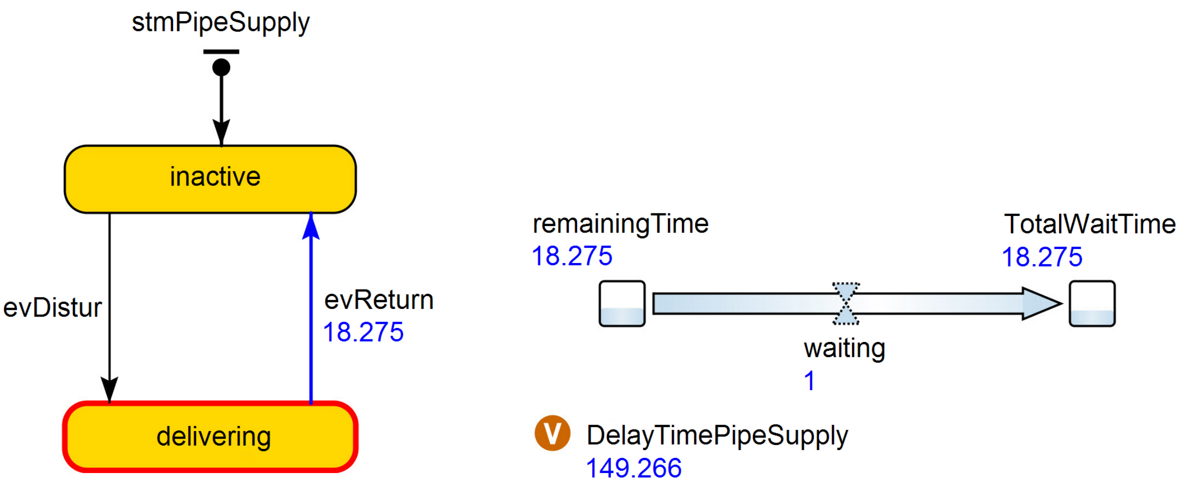


Figure 5.6: The *AOC PipesSupply* during *delivering* state

Figure 5.5 displays a screen shot during a simulation run without disturbances, the state of the *PipesSupply* is momentarily in the *inactive* - represented by the thick red border. When the *PipesSupply* is in *delivering* state, the flow-variable *waiting* is not active (not working). Figure 5.6 shows one capture during a simulation run with disturbances. When the disturbances of the pipe supply occur, the transition from *inactive* to *delivering* is carried out. The mean time (shown by variable *DelayTimePipeSupply*) to wait for the pipe to be available is computed by evaluating a triangular distribution. The flow-variable *waiting* active (working) serves to calculate and update the waiting time. The flow-variable gives the information that the total waited time is 130 minutes and in 18 minutes the pipe will reach the construction site. When the pipe is available, the state re-enters to *inactive* state and sends the message to the system that other tasks relating to the pipe may be performed.

5.1.2.2 Enhancement MiSAS module with different soil compositions

The MiSAS module is enhanced with soil compositions and used for experimentation of soil impacts study. Using a soil composition of equal portions of different soil conditions such as clay, fine sand, silt, sand, etc. the simulations are modified for testing the impact of different soil compositions on productivity. Then, the enhanced MiSAS module can be used to optimize microtunnelling operations in regard to soil and site conditions. The jacking processes are carried out in different types of soils, the difference in productivity arises from the jacking process. If the differences in the durations are significant, then building a MiSAS module with different soil compositions is a valid approach. In addition, the distributions of jacking pipe sections in different types of soils may be found.

The enhanced MiSAS module with different soil compositions is coded within the MiSAS module. The graphical user interface for the input of different soil conditions is depicted in sub-section 5.2.2.

5.2 Introduction MiSAS module

This section will introduce the MiSAS module. All the components of the developed module MiSAS and the entire of *Graphical User Interfaces* (*GUI*) have been designed and implemented utilizing AnyLogic simulation software. The author proposed in this study the development of a graphical interactive environment for the simulation of tunnels construction with MTBM. Here, the user will input the information through the *GUI*.

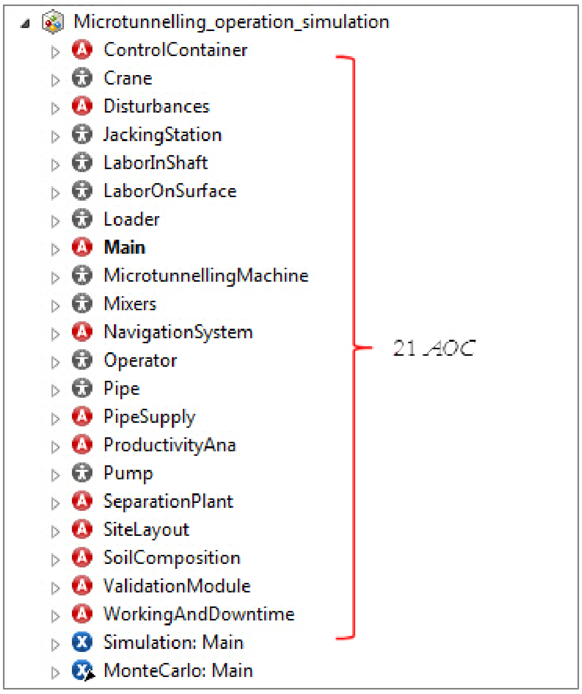
There have been twenty-one *AOCs* used to design and code in order to develop the module MiSAS. Thirteen of the *AOC* are designed in order to represent the behavior of the devices in microtunnelling (e.g. the behavior of MTBM, separation plant, crane, etc.). Three of them are designed to analyze the output results (e.g. rate of progress, prediction of the total time of a project with and without disturbances, 3D animation simulation, etc.). Six of the *AOC* have been coded and *GUI* developed to input the data and information. The role of six *GUI* is to input, define the various resources, activity durations, disturbances, site layout. Figure 5.7 and 5.8 depict twenty one *AOC* and an example of the interface of an input resource specification of the MiSAS module. The objective of this section is to introduce the design of *GUI* for input and output data.

5.2.1 The *GUI* - Input Resource specification

The *GUI* of input resource specification is depicted in Figure 5.8. The screen allows the user to: 1) Define the quantity of laborers working in the construction project; 2) Input of the activity durations (e.g. the time to connect and disconnect cables, the time for mixing lubricant and so on); 3) In addition, the definition of the project is also used (e.g. length of the project, attributes of type of pipe, and so forth). 4) Run simulation analysis and link to other interfaces such as: 3D animation, statistics analysis of the data during running MiSAS module.

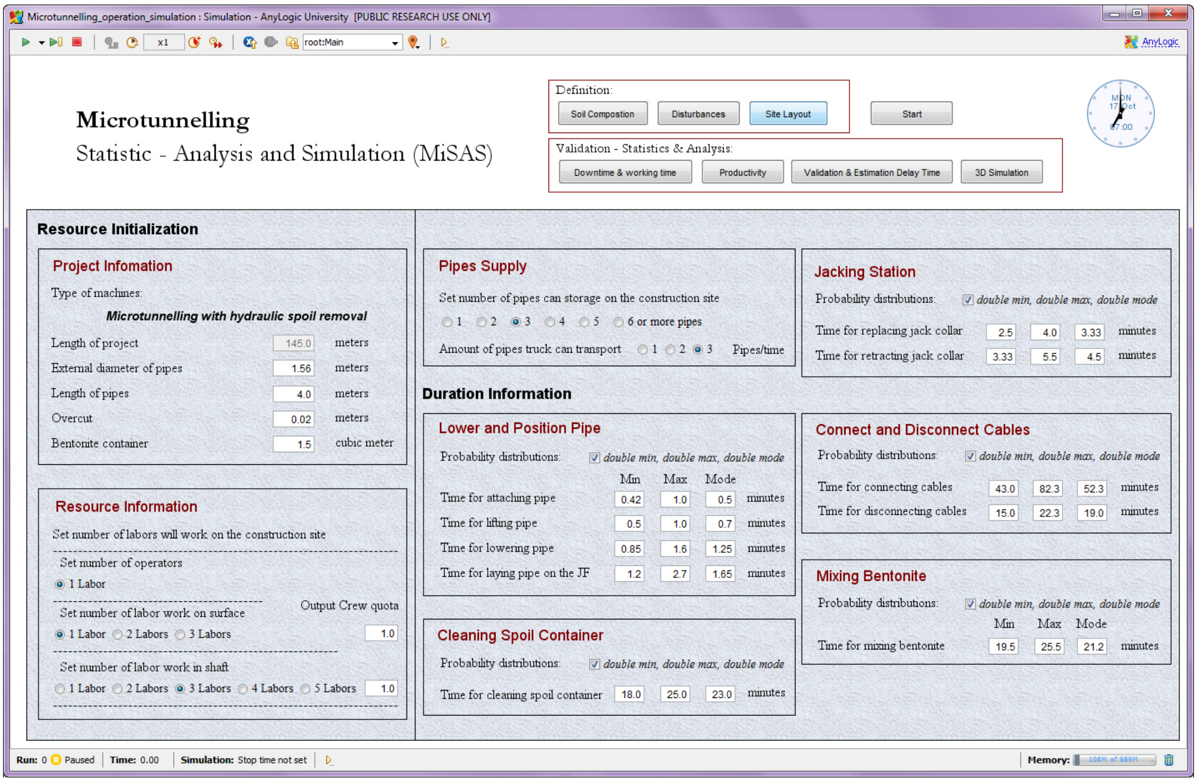
5.2.2 The *GUI* - Input different soil conditions

The tunnels construction with MTBM may be done through different types of soil conditions. Therefore, the *GUI* of input different soil conditions (shown in Figure 5.9) has been designed. It allows the user to: 1) Define the quantity of the different soil condition; 2) Input the length of each type of soil condition; 3) Input the penetration of MTBM (e.g. how many millimeter per minute of MTBM). In addition, because the layer of soil composition is more than 12 layers, user may use the Excel file to input the data (shown in Figure 5.9 (b)).



Microtunnelling_operation_simulation
ControlContainer
Crane
Disturbances
JackingStation
LaborInShaft
LaborOnSurface
Loader
Main
MicrotunnellingMachine
Mixers
NavigationSystem
Operator
Pipe
PipeSupply
ProductivityAna
Pump
SeparationPlant
SiteLayout
SoilComposition
ValidationModule
WorkingAndDowntime
Simulation: Main
MonteCarlo: Main

Figure 5.7: Twenty-one *AOC* of MiSAS



Microtunnelling_operation_simulation : Simulation - AnyLogic University [PUBLIC RESEARCH USE ONLY]

Microtunnelling
Statistic - Analysis and Simulation (MiSAS)

Definition:

Validation - Statistics & Analysis:

Resource Initialization

Project Infomation

Type of machines:

Microtunnelling with hydraulic spoil removal

Length of project	145.0	meters
External diameter of pipes	1.56	meters
Length of pipes	4.0	meters
Overcut	0.02	meters
Bentonite container	1.5	cubic meter

Resource Information

Set number of labors will work on the construction site

Set number of operators
● 1 Labor

Set number of labor work on surface
● 1 Labor ○ 2 Labors ○ 3 Labors
Output Crew quota 1.0

Set number of labor work in shaft
○ 1 Labor ○ 2 Labors ● 3 Labors ○ 4 Labors ○ 5 Labors 1.0

Pipes Supply

Set number of pipes can storage on the construction site
○ 1 ○ 2 ● 3 ○ 4 ○ 5 ○ 6 or more pipes

Amount of pipes truck can transport ○ 1 ○ 2 ● 3 Pipes/time

Duration Information

Lower and Position Pipe

Probability distributions: ☑ *double min, double max, double mode*

	Min	Max	Mode	
Time for attaching pipe	0.42	1.0	0.5	minutes
Time for lifting pipe	0.5	1.0	0.7	minutes
Time for lowering pipe	0.85	1.6	1.25	minutes
Time for laying pipe on the JF	1.2	2.7	1.65	minutes

Cleaning Spoil Container

Probability distributions: ☑ *double min, double max, double mode*

Time for cleaning spoil container	18.0	25.0	23.0	minutes

Jacking Station

Probability distributions: ☑ *double min, double max, double mode*

Time for replacing jack collar	2.5	4.0	3.33	minutes
Time for retracting jack collar	3.33	5.5	4.5	minutes

Connect and Disconnect Cables

Probability distributions: ☑ *double min, double max, double mode*

Time for connecting cables	43.0	82.3	52.3	minutes
Time for disconnecting cables	15.0	22.3	19.0	minutes

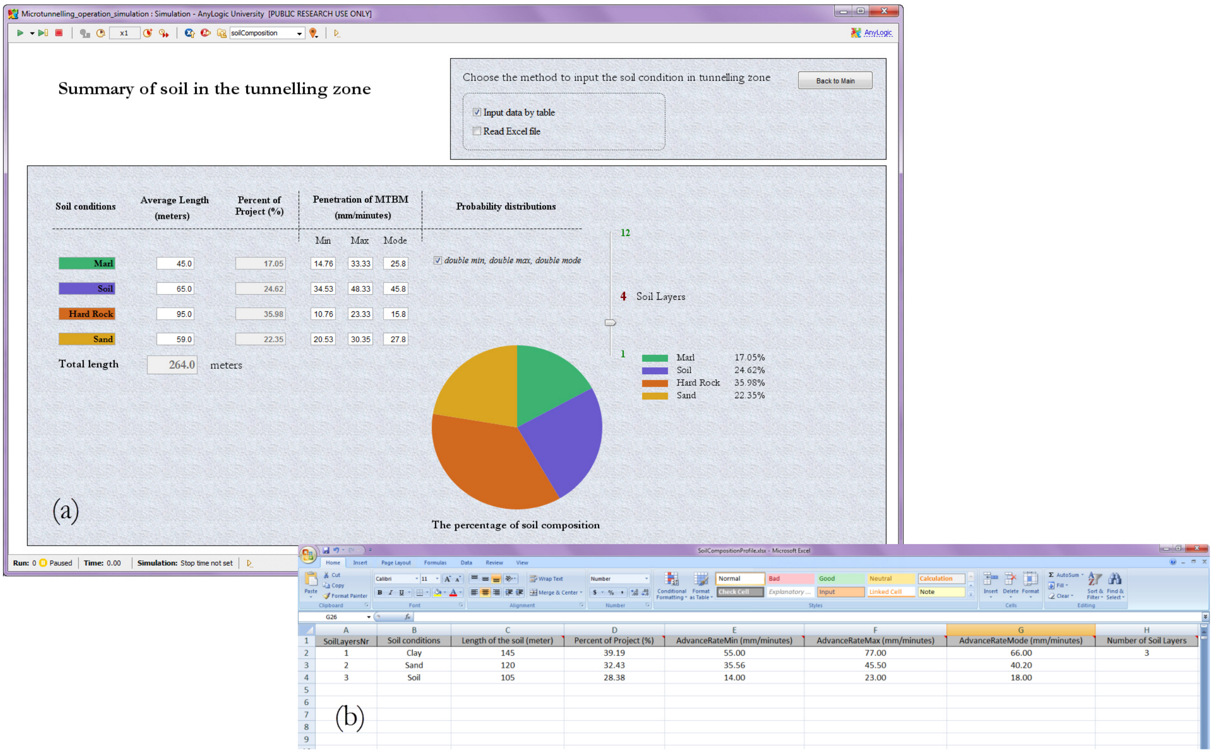
Mixing Bentonite

Probability distributions: ☑ *double min, double max, double mode*

	Min	Max	Mode	
Time for mixing bentonite	19.5	25.5	21.2	minutes

Run: 0 Paused | **Time:** 0.00 | **Simulation:** Stop time not set | **Memory:** 106M of 989M

Figure 5.8: An example of the *GUI* for resource specification



Summary of soil in the tunnelling zone

Choose the method to input the soil condition in tunnelling zone

☑ Input data by table
☐ Read Excel file

Soil conditions	Average Length (meters)	Percent of Project (%)	Penetration of MTBM (mm/minutes)			Probability distributions
			Min	Max	Mode	
Marl	45.0	17.05	14.76	33.33	25.8	☑ double min, double max, double mode
Soil	65.0	24.62	34.53	48.33	45.8	
Hard Rock	95.0	35.98	10.76	23.33	15.8	
Sand	59.0	22.35	20.53	30.35	27.8	

Total length 264.0 meters

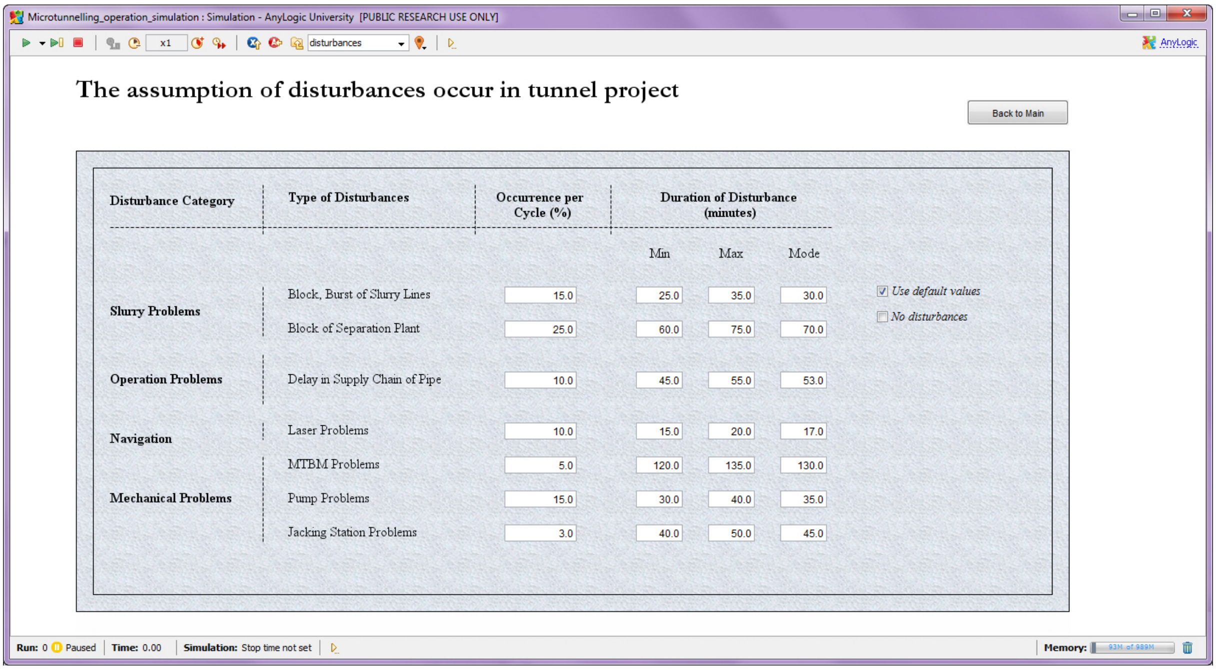
4 Soil Layers

🟩	Marl	17.05%
🟪	Soil	24.62%
🟧	Hard Rock	35.98%
🟨	Sand	22.35%

The percentage of soil composition

	A	B	C	D	E	F	G	H
1	SoilLayersNr	Soil conditions	Length of the soil (meter)	Percent of Project (%)	AdvanceRateMin (mm/minutes)	AdvanceRateMax (mm/minutes)	AdvanceRateMode (mm/minutes)	Number of Soil Layers
2	1	Clay	145	39.19	55.00	77.00	66.00	3
3	2	Sand	120	32.43	35.56	45.50	40.20	
4	3	Soil	105	28.38	14.00	23.00	18.00	

Figure 5.9: The *GUI* for different soil conditions



The assumption of disturbances occur in tunnel project

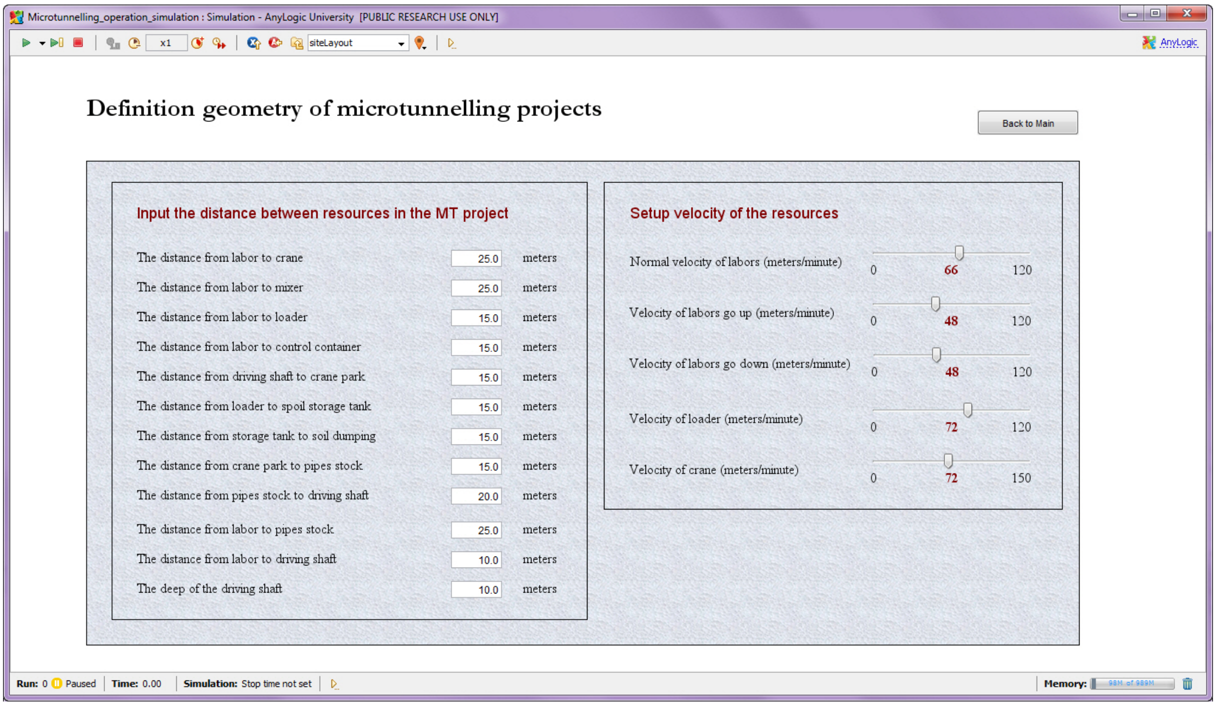
Disturbance Category	Type of Disturbances	Occurrence per Cycle (%)	Duration of Disturbance (minutes)		
			Min	Max	Mode
Slurry Problems	Block, Burst of Slurry Lines	15.0	25.0	35.0	30.0
	Block of Separation Plant	25.0	60.0	75.0	70.0
Operation Problems	Delay in Supply Chain of Pipe	10.0	45.0	55.0	53.0
Navigation	Laser Problems	10.0	15.0	20.0	17.0
	MTBM Problems	5.0	120.0	135.0	130.0
Mechanical Problems	Pump Problems	15.0	30.0	40.0	35.0
	Jacking Station Problems	3.0	40.0	50.0	45.0

☑ *Use default values*
☐ *No disturbances*

Figure 5.10: The *GUI* for defining disturbances

5.2.3 The *GUI* - Input disturbances

The *GUI* of input disturbances form as depicted in Figure 5.10. It describes and imputes the most common types of disturbances that normally occur on the job site. The screen allows the user to: 1) Define the type of disturbances that may occur. The type of disturbances used in this research are summarized and shown in Chapter 3, table 3.8; 2) Define the duration time to repair the disturbances. The examples of duration time (also called disturbances time) to repair are shown in column number 6 in Appendix A.1, A.2, A.3; 3) Define the occurrence per cycle. As the disturbances are stochastic. Therefore, the *GUI* of input disturbances may help the user to input their forecast about the percentage of disturbances that may be expected per cycle. The value of the occurrence per cycle depends on the experiences of the user.



Definition geometry of microtunnelling projects

Input the distance between resources in the MT project

The distance from labor to crane	25.0	meters
The distance from labor to mixer	25.0	meters
The distance from labor to loader	15.0	meters
The distance from labor to control container	15.0	meters
The distance from driving shaft to crane park	15.0	meters
The distance from loader to spoil storage tank	15.0	meters
The distance from storage tank to soil dumping	15.0	meters
The distance from crane park to pipes stock	15.0	meters
The distance from pipes stock to driving shaft	20.0	meters
The distance from labor to pipes stock	25.0	meters
The distance from labor to driving shaft	10.0	meters
The deep of the driving shaft	10.0	meters

Setup velocity of the resources

Normal velocity of labors (meters/minute)	0	66	120
Velocity of labors go up (meters/minute)	0	48	120
Velocity of labors go down (meters/minute)	0	48	120
Velocity of loader (meters/minute)	0	72	120
Velocity of crane (meters/minute)	0	72	150

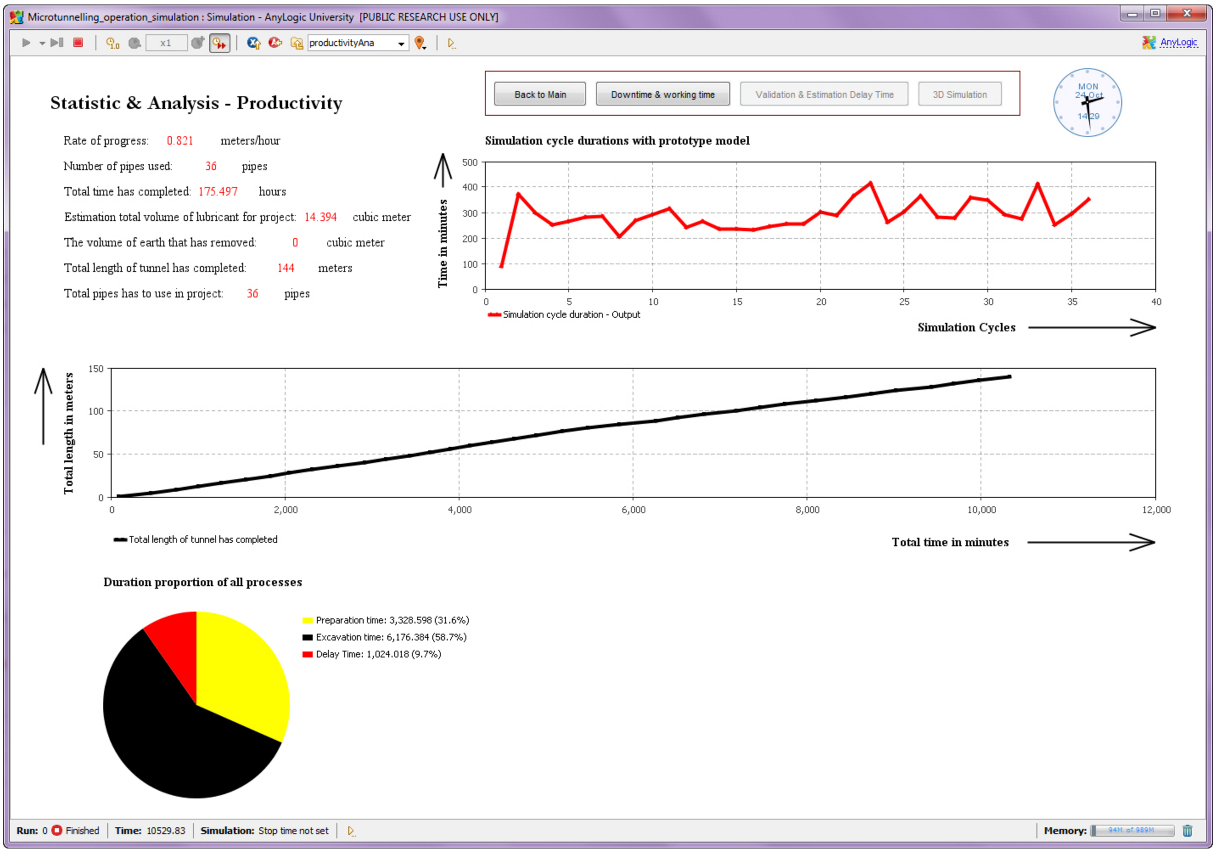
Figure 5.11: The *GUI* of site layout

5.2.4 The *GUI* - Definition geometry of the job site

The *GUI* of definition geometry of the job site is shown in Figure 5.10. The screen allows the user to: 1) Define the distances between devices on job site or the depth of the shaft. The common site lay-out of the construction site is shown in Appendix C in table C.1. 2) Define the velocity of the devices or laborers (e.g. velocity of crane, loader). This value may be consulted based on Appendix D in table D.1

5.2.5 The *GUI* - Static analysis and statistics

The static analysis and statistics extracts data from all of the system's component. Figure 5.12 depicts the main menus for the static analysis and statistics. Different types



Statistic & Analysis - Productivity

Rate of progress: 0.821 meters/hour

Number of pipes used: 36 pipes

Total time has completed: 175.497 hours

Estimation total volume of lubricant for project: 14.394 cubic meter

The volume of earth that has removed: 0 cubic meter

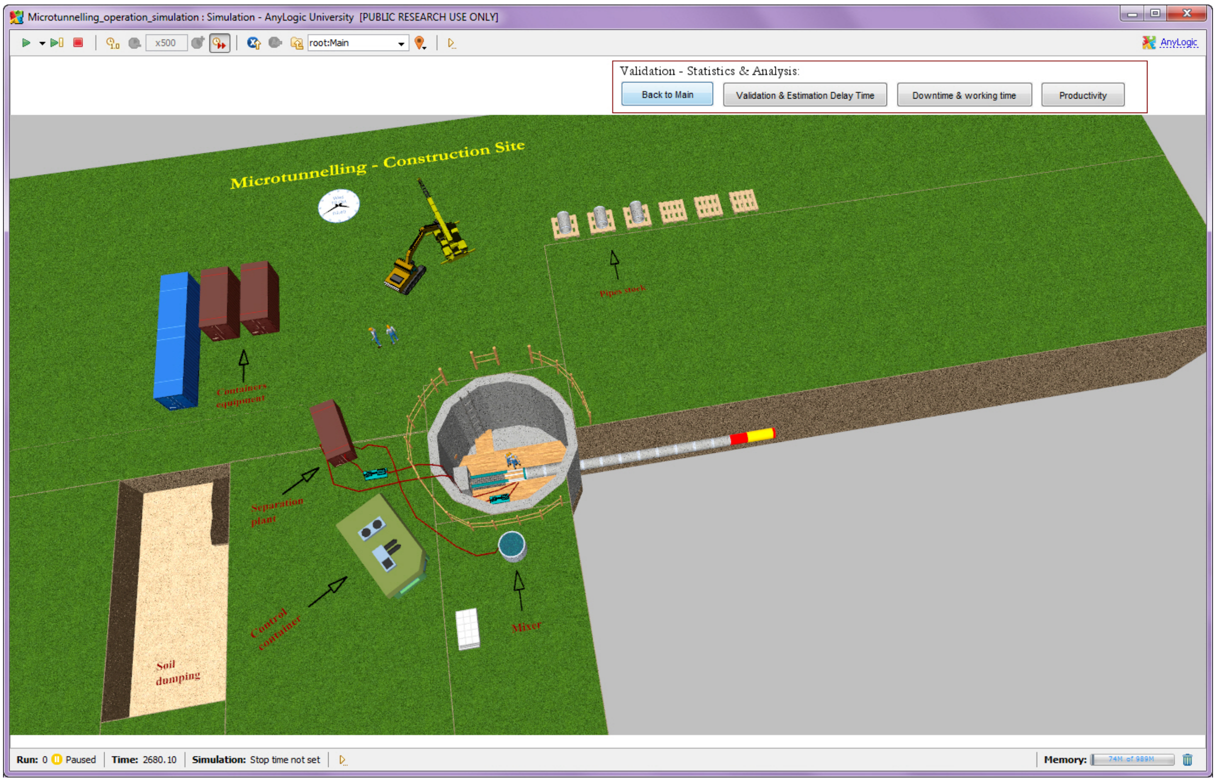
Total length of tunnel has completed: 144 meters

Total pipes has to use in project: 36 pipes

Preparation time: 3,328.598 (31.6%)
Excavation time: 6,176.384 (58.7%)
Delay Time: 1,024.018 (9.7%)

Run: 0 Finished | **Time:** 10529.83 | **Simulation:** Stop time not set | **Memory:**

Figure 5.12: The *GUI* - Static analysis and statistics



Run: 0 Paused | **Time:** 2680.10 | **Simulation:** Stop time not set | **Memory:**

Figure 5.13: The *GUI* - Dynamic analysis and statistics

of reports are obtained, there are: 1) rate of progress; 2) prediction of the productivity of microtunnelling with and without disturbances; 3) estimation of the productivity with different soil components; 4) evaluation of some information, which are helpful for microtunnelling (e.g. prediction of the total volume of lubricant support for project, estimation of the volume of spoils that need to be excavated, etc.).

5.2.6 The *GUI* - Dynamic analysis and statistics

The dynamic analysis and statistics supports animation to present the overall system dynamics, the interaction between laborers and resources, the delay associated to the individual resources. Figure 5.13 illustrates a screenshot of a layout of a tunnel construction with MTBM after 10 cycles of simulation. It also depicts animated screens of the overall activity of MTBM, resources, laborers.

Chapter 6

Microtunnelling reference projects

6.1 Introduction

The application of the MiSAS module has been executed on the three different microtunnelling projects in Germany. This chapter presents the data, which has been collected in the three construction sites located in Recklinghausen City, Germany. Details of the three different microtunnelling projects, including the general information, ground conditions, activities duration and disturbances will be discussed.

6.2 Project description

Since 2008 up to now (2013), 11km of water treatment has been built in Recklinghausen City, Germany. The name of the project is: ”Hellbach und Breuskes Mühlenbach Bau der Abwasserkanäle und Regelwasserbehandlungsanlagen in Recklinghausen”. The Client is Emschergenossenschaft/Lippeverband, which is the first water management association, founded on the 14th of December 1899 (Emschergenossenschaft and Lippeverband Company, 2013). The geographical location of the project is illustrated in Figure 6.1. The sources for the collection of the data to support this research have been three different microtunnelling projects: BV Recklinghausen V.5.1, BV Recklinghausen V.8 and BV Recklinghausen V.15 in Recklinghausen City. The microtunnelling boring machines used in all projects were hydraulic spoil removal microtunnelling machines. The basic information on the microtunnelling projects are described in Table 6.1 and will be discussed in detail in the next sections.

Table 6.1: Overview of job sites

Name of project	**BV Recklinghausen V.8**	**BV Recklinghausen V.5.1**	**BV Recklinghausen V.15**
Location	Recklinghausen City, Germany	Recklinghausen City, Germany	Recklinghausen City, Germany
Survey duration	22.05.2011 - 30.05.2011	06.12.2010 - 16.12.2010	28.06.2012 - 05.07.2012
Length of the project	ca. 145 meters	ca. 79.44 meters	ca. 86.23 meters
Contractor/Consultant	DIEZ GMBH & Co.KG	WUEWA Bau GmbH & Co.KG	Batteux Bauunternehmung GmbH & CO. KG
Site condition	Good	Good	Good
Working area	Open area	Open area	Open area
Diameter of tunnel	Inner diameter: 1600mm Outer diameter: 1200mm	Inner diameter: 2240mm Outer diameter: 1800mm	Inner diameter: 1500mm Outer diameter: 1000mm
Type of machine	AVN 1200T	VSM 1800	AVN 1200C
Type of pipe	DN 1200 Internal diameter: 1200mm External diameter: 1560mm Length of pipe: 4000mm	DN 1800 Internal diameter: 1800mm External diameter: 2200mm Length of pipe: 3500mm	DN1000 Internal diameter: 1000mm External diameter: 1460mm Length of pipe: 4020mm
Installation depth	8.7 meters	7.4 meters	Updating
Geotechnical condition	Clay & ground water	Fine sand, silt & ground water	Clayey/cohensive soil & sand

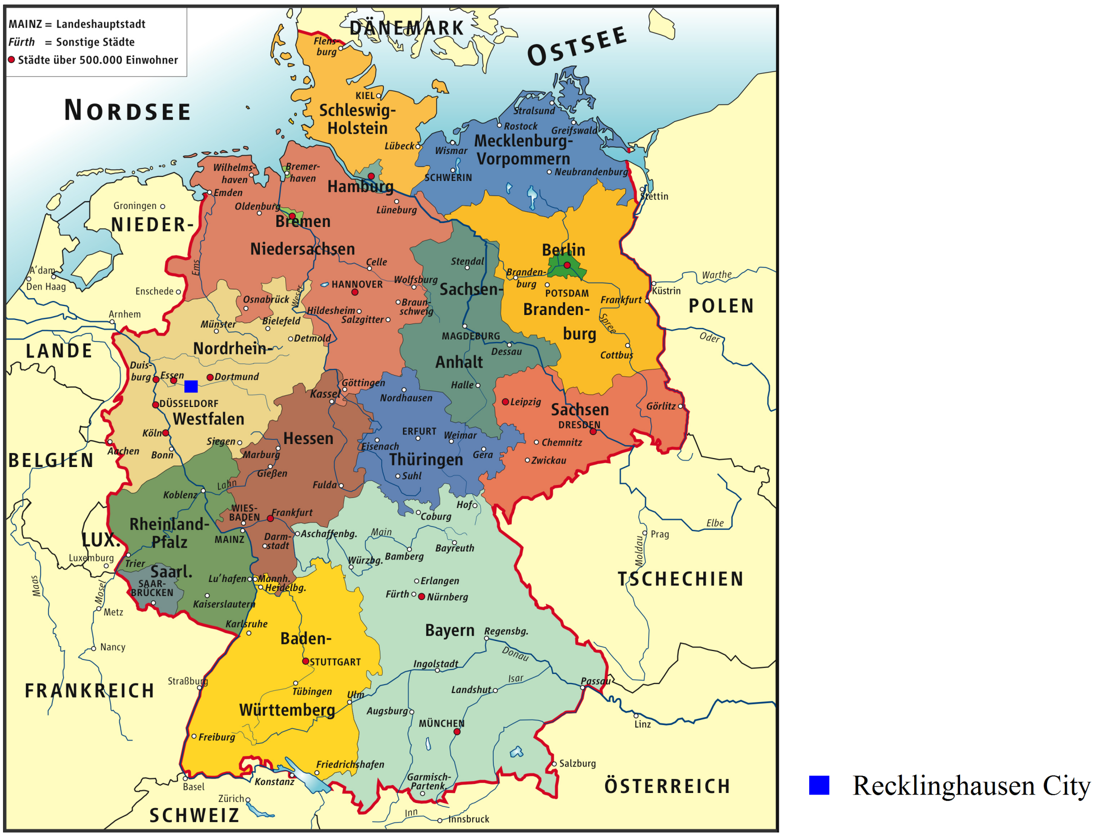


Figure 6.1: Location of Recklinghausen in Germany (Maps of World, 2013)

6.3 Scheme details

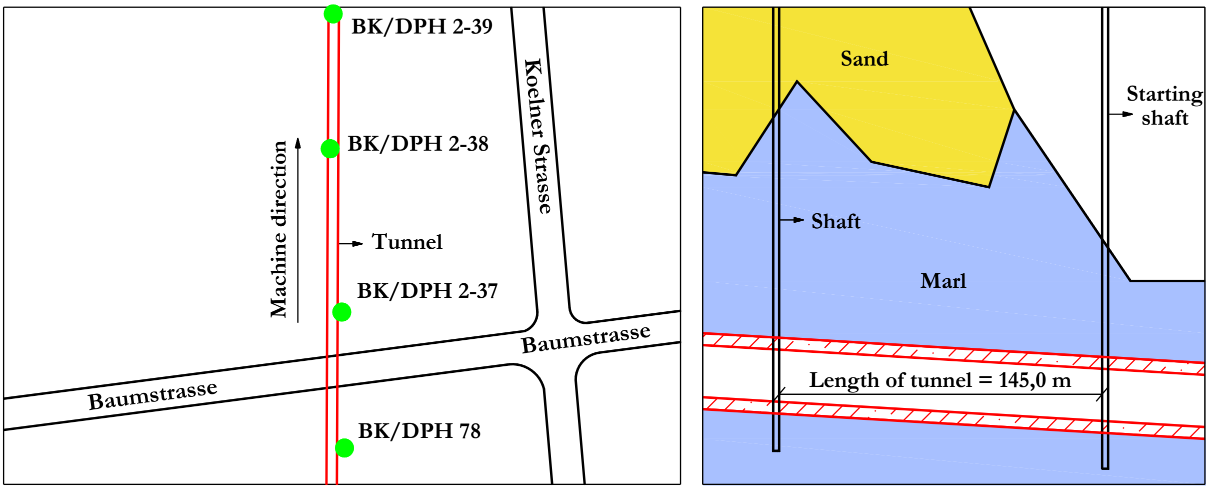
6.3.1 Site 1: BV Recklinghausen V.8

6.3.1.1 Project description

The tunnel crossed the ”Baumstraße” in Recklinghausen City as shown in Figure 6.2. A 145.0 meters long drive completely through marl. The depth to axis was approximately 8.7 meters, grade 2,6 ‰ and the used type of pipe was DN1200. The pipe size was 1.2 meters internal diameter, 1.56 meters external diameter, 4.0 meters length. The position of the construction site was easily accessible. Excavation was carried out by microtunnelling machine AVN 1200T using hydraulic spoil removal.

6.3.1.2 Microtunnelling machine description

In Figure 6.3 a MTBM type AVN-T (Automatic tunnelling machine with slurry material removal and an opening in the bulkhead partition door) is shown, which uses the same operation method and sequence as AVN 1200T. The AVN 1200T uses almost the same operating principles as MTBM, which is described in section 3.5.1. The difference is that AVN 1200T machines have the free centre drive that allows to be entered through a door to the working face. This allows obstacles, e.g. sheet piles, steel girders, boulders,

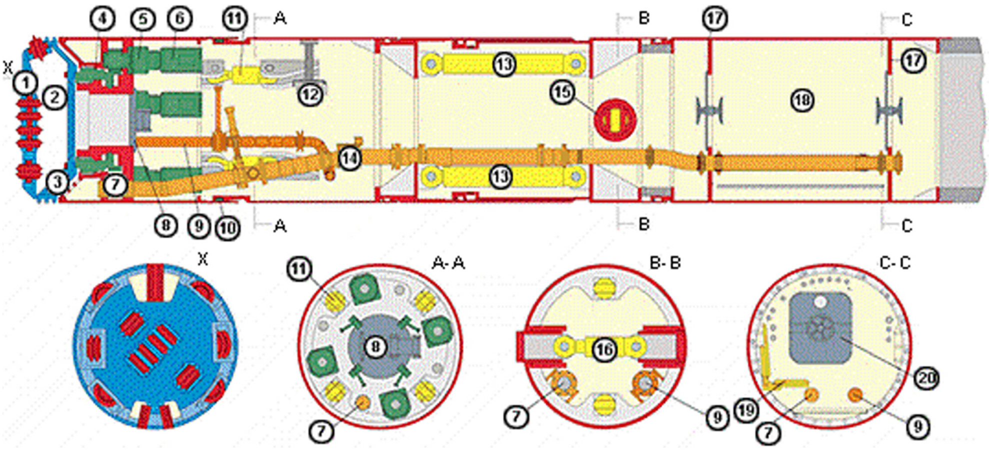


(a) Site plan and position of bore holes

(b) Simplified long section

Figure 6.2: Details of Recklinghausen V.8

etc. to be removed. The tunnels through rock can be extended to previously unimaginable retention lengths of over 500 meters due to the fact that it is possible to replace worn out roller bits. This makes it possible to reduce the number of intermediate shafts which results in a considerable reduction of the construction costs (Herrenknecht AG, 2013a).



1. cutting wheel
2. extraction chamber
3. crusher space
4. main bearing
5. gear unit
6. drive motor
7. conveyor conduit
8. pressure wall door
9. supply conduit
10. articulated shield seal
11. steering cylinder
12. target
13. telescope cylinder
14. bypass
15. gripper
16. gripper cylinder
17. pressure wall lock
18. lock
19. lock seat
20. lock door

Figure 6.3: Longitudinal section of a microtunnelling machine AVN-T (Herrenknecht AG, 2013a)

6.3.1.3 Ground conditions

A site investigation was carried out around the area for the project in May 2010. Four boreholes were put down along the centre line of the tunnels. The position of the boreholes is shown in Figure 6.2(a). The boreholes BK/DPH 78 and BK/DPH 2-39 were put down at the start and the end of the tunnel to depths of 13.65 meters and 11.0 meters, respectively. The boreholes BK/DPH 2-37 and BK/DPH 2-38 were put down along the tunnel to depths of 11 meters.

The borehole BK/DPH 78 at the start of the tunnel indicated that the stratum below ground level to a depth of about 4.7 meters was backfilling, silt, fine sand and medium sand. The stratum below 2 meters up a depth of about 6.3 meters consisted of silt and fine sand. The tunnel passes through the stratum underlying the soil. Groundwater was encountered approximately 4.7 meters below ground level. The borehole BK/DPH 78 details are shown in Figure 6.4.

The borehole BK/DPH 2-37 that indicated the stratum below ground level at a depth of about 0.5 meters was backfilling, silt, sand and humus. The stratum under 0.5 meters up to a depth of 3.0 meters consisted of fine sand, medium sand and silt. The soil condition below 3.0 meters up a depth of about 4.6 meters included medium sand, silt and clay. The tunnel passes through the stratum underlying the rock has RQD (the Rock Quality Designation) index of 40% to 50%. The borehole BK/DPH 2-37 details are shown in Figure 6.5.

The borehole BK/DPH 2-38 indicated that the stratigraphy below ground level to a depth of about 1.0 meter was backfilling, including silt, sand and humus. The stratum under 1.0 meter up to a depth of 2.8 meters was medium sand and silt. The tunnel passes through the stratum underlying the soil comprising clay and fine sand. The borehole BK/DPH 2-38 details are shown in Figure 6.6.

The borehole BK/DPH 2-39 indicated that the stratum below ground level to a depth of about 0.35 meter was backfilling, silt, sand and humus. The stratum under 0.35 meter up to a depth of 4.0 meters consisted of silt, fine sand, medium sand and humus. Almost the same borehole, BK/DPH 2-39, the tunnel passes through the stratum underlying the soil comprising clay and fine sand. The borehole BK/DPH 2-39 details are shown in Figure 6.7.

According to the analysis above, it may be concluded that: the whole tunnel of project BV Recklinghausen V.8 will encounter types of soil conditions, which are marl, clay and fine sand. The soil condition of the project is not convenient for the jacking processes. The average time for jacking processes based on the data collected from the job site ranges from 120.00 to 271.00 minutes.

6.3.1.4 Duration data collection

The input data duration used for running the simulation model must be collected. In order to collect duration information, the eleven important durations affecting the productivity of the microtunnelling construction are collected. There are: 1) velocity of the labor in the construction site; 2) attaching pipe; 3) lowering pipe; 4) laying pipe; 5) replacing jack collar; 6) connecting cables and hoses; 7) jacking processes; 8) retracting jack collar; 9) disconnecting cables and hoses; 10) time for cleaning spoil container; 11) time for mixing bentonite. The activities duration is archived within 10 days by using

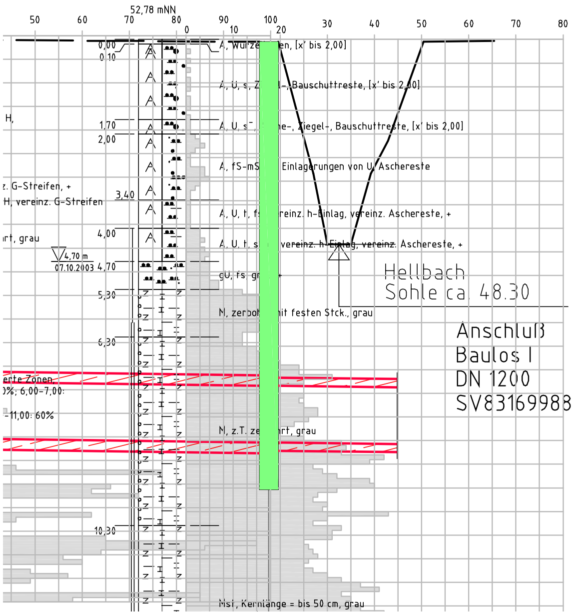


Figure 6.4: Borehole BK/DPH 78 details (Erdbaulaboratorium Essen, 2010)

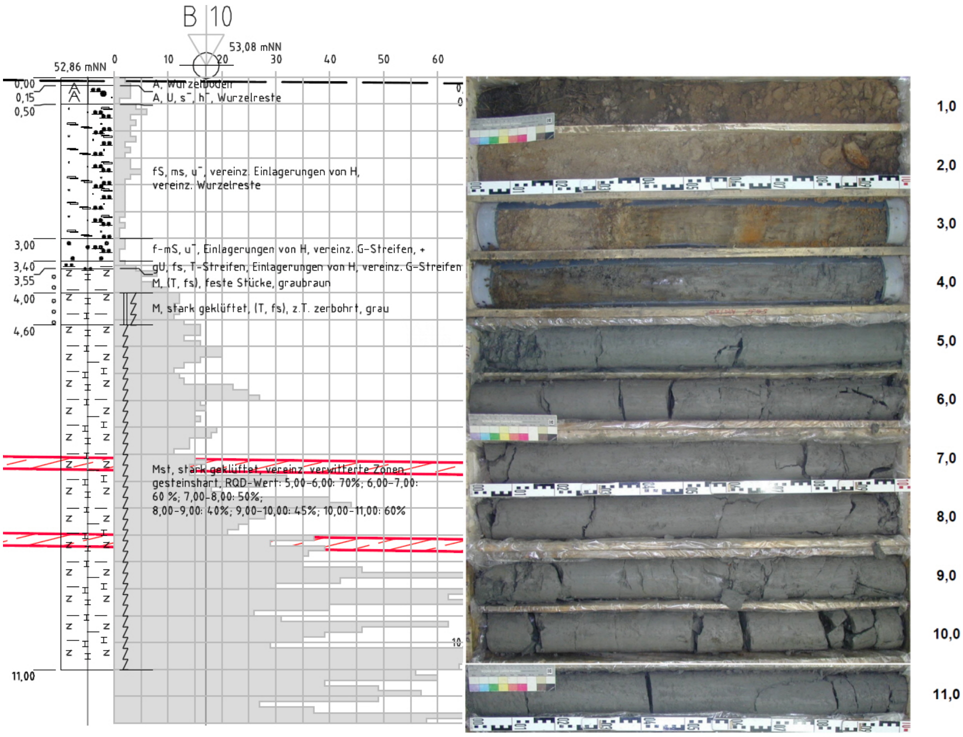


Figure 6.5: Borehole BK/DPH 2-37 details (Erdbaulaboratorium Essen, 2010)

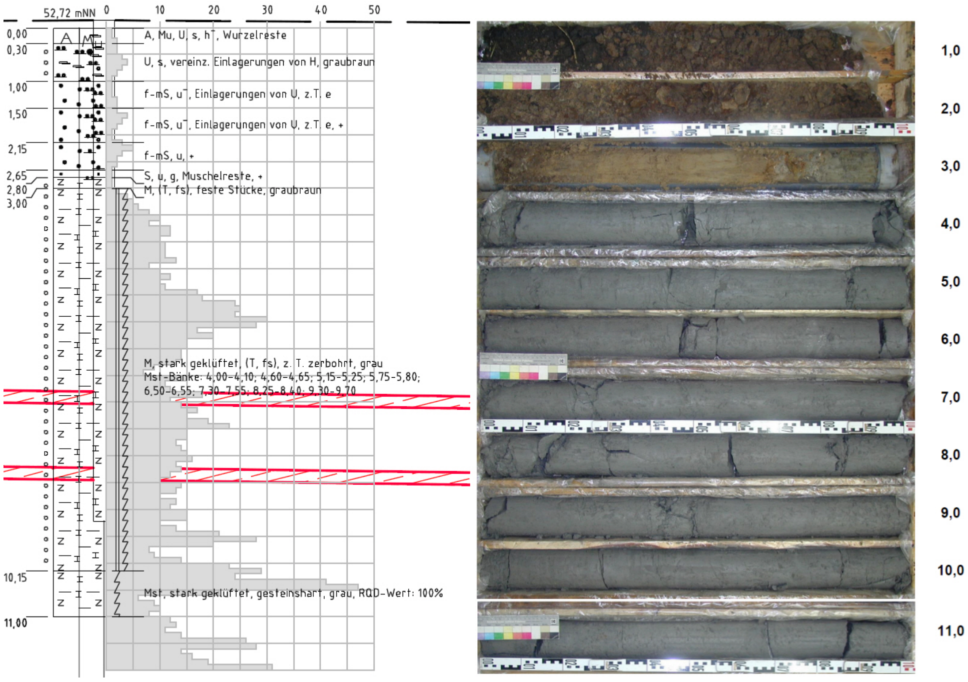


Figure 6.6: Borehole BK/DPH 2-38 details (Erdbaulaboratorium Essen, 2010)

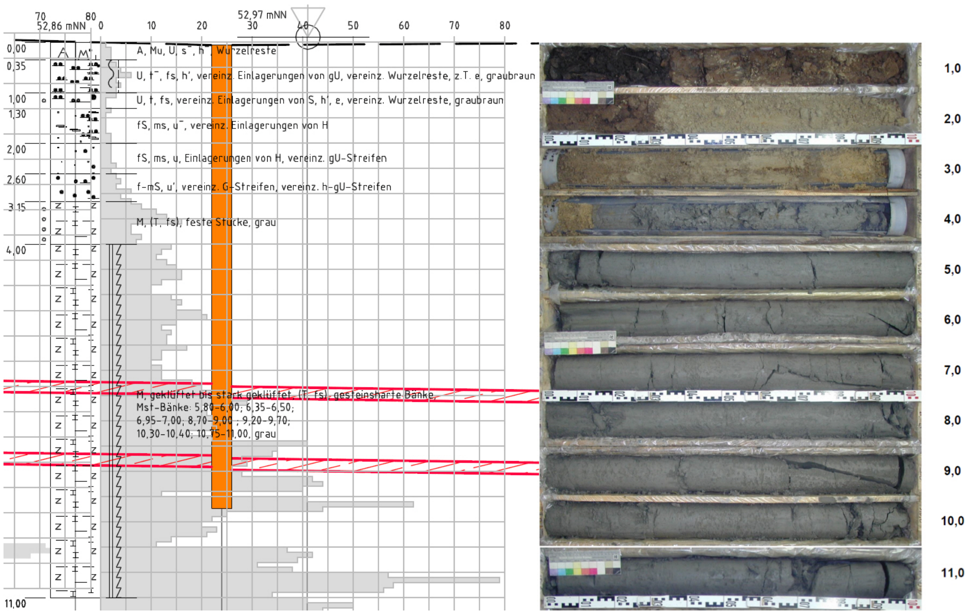


Figure 6.7: Borehole BK/DPH 2-39 details (Erdbaulaboratorium Essen, 2010)

Table 6.2: Duration information of job site: BV Recklinghausen V.8

Activity number	**Activity**	**Lowest value (min)**	**Mode value (min)**	**Highest value (min)**
1	Attaching Pipe	0.42	0.50	1.00
2	Lifting pipe	0.50	0.80	1.00
3	Lowering pipe	0.85	1.25	1.60
4	Laying pipe	1.20	1.65	2.70
5	Replace jack collar	2.50	3.33	4.00
6	Connect cables	43.00	52.30	82.30
7	Jacking processes	120.00	155.00	271.00
8	Retract jack collar	3.33	4.50	5.50
9	Disconnect cables	15.00	19.00	22.30
10	Time for cleaning spoil container	18.00	23.00	25.00
11	Time for mixing bentonite	19.50	21.20	25.50

Note:

- Lowest value: The minimum value
- Highest value: The maximum value
- Mode value: The most likely value

a stop watch at the job site as shown in Table 6.2.

6.3.1.5 Jacking processes analysis

The microtunnelling works started on 19.05.2011 and stopped on 22.06.2011 after 24 working days. Table A.1 in Appendix A.1 shows the productivities that are recorded from the control panel in the construction site. They indicate that the total length of the tunnel is approximately 145 meters and the average advance rate is approximately 6.04 meters per day. Figure 6.8 shows the change of the productivities in 24 days (without holidays and weekend). A pattern can be easily observed by plotting productivities data from Table A.1 in Appendix A.1. The productivity for this project ranged from 0 meter to 12 meters per day. Moreover, Table A.1 in Appendix A.1 and Figure 6.8 can be explaining due to the fact that disturbances are one of the crucial causes to reduce the productivity. The analysis of the recorded data from the microtunnelling machine shows that on the working days 6, 8, 16, 22 the productivity could be reached with a maximum of 12 meters per day without disturbances. Meanwhile, on the working days

7, 11, 12, 19 no pipe could be jacked because of the effect of the disturbances.

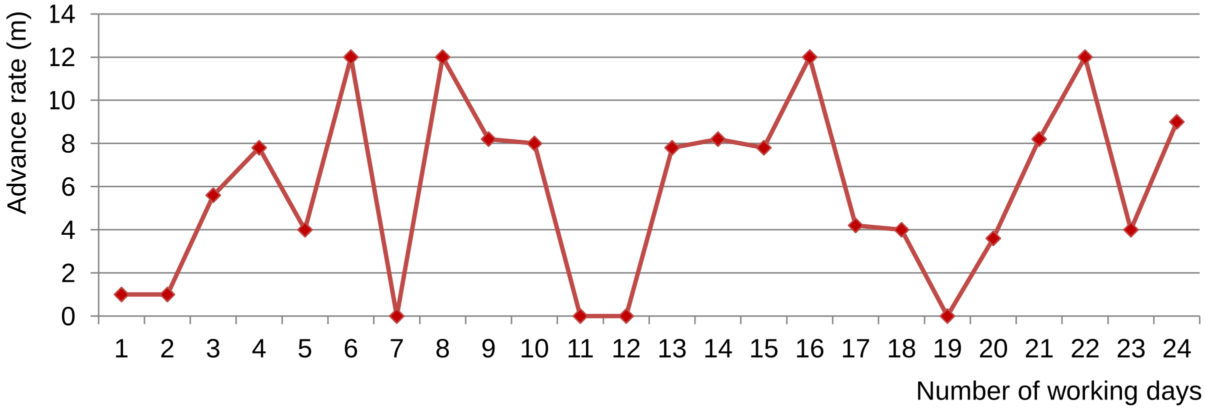


Figure 6.8: The actual productivity of the project BV Recklinghausen V.8

6.3.1.6 The analysis of disturbances

Operation records representing 24 days of machine time show that 32 pipes were used and 13 disturbance events were recorded as illustrated in Table A.1 in Appendix A.1. The recorded disturbance time for this project ranged from 32 minutes to 1188 minutes with an average of 337 minutes per delay event. The disturbance causes were not recorded for each event but an interview with the operator during operations was made. The main delay causes of this project was the blocking of slurry lines and the blocking of the separation plant. Figure 6.9 shows the overall disturbance and jacking processes time of the project BV Recklinghausen V.8. Figure 6.9 can be easily observed by plotting disturbances data from Table A.1. It is also shown that the disturbance time consumed about 27.66% of the total recorded driving time and the jacking and preparation processes took about 72.34% of the time.

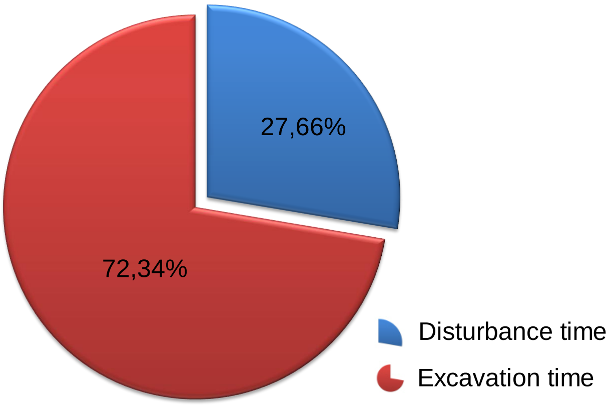
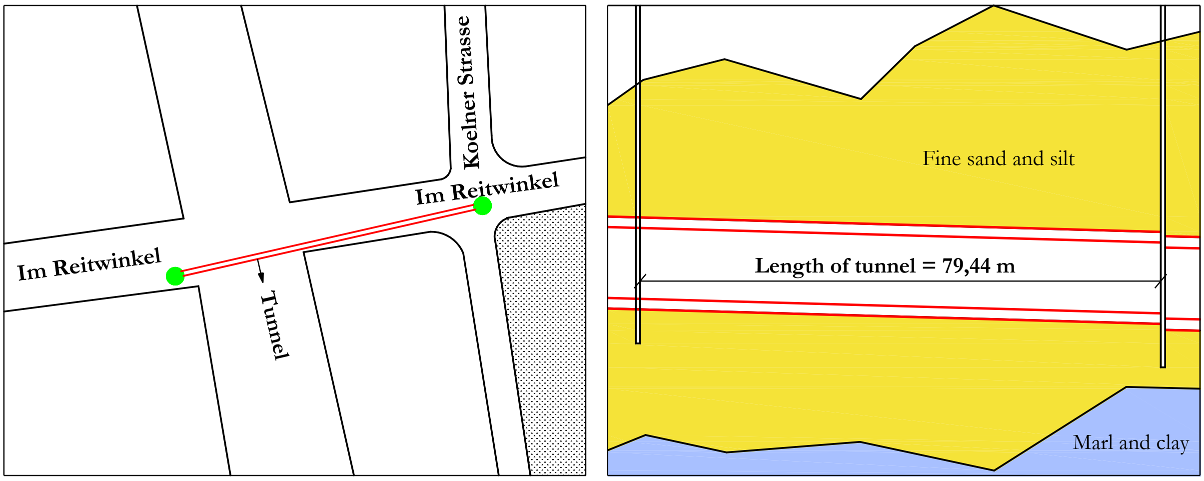


Figure 6.9: Disturbance and jacking processes time of the project BV Recklinghausen V.8

6.3.2 Site 2: BV Recklinghausen V.5.1

6.3.2.1 Project description

The tunnel went along the road ”Im Reitwinkel” as shown in Figure 6.10(a). A 79.44 meters long drive completely through fine sand and silt. The depth to the axis was approximately 7.4 meters, grade 1.4‰ and the pipe size was 1.8 meters internal diameter, 2.2 meters external diameter, 3.5 meters length. Excavation was carried out by the microtunnelling machine VSM 1800 with an outside diameter of 2.20 meters using hydraulic spoil removal. The position of the construction site was easily accessible.



(a) Site plan and position of bore holes

(b) Simplified long section

Figure 6.10: Details of BV Recklinghausen V.5.1

6.3.2.2 Ground conditions

A site investigation was carried out around the area of the project in March 2005. Two boreholes were put down along the centre line of the tunnels. The first borehole BK 2-28 and the second borehole BK 2-28.1 were put down at the beginning and the middle of the tunnel to depths of 9.0 and 11.0 meters, respectively.

The borehole BK 2-28 at the beginning of the tunnel indicated that the stratum below ground level to a depth of about 2 meters was backfilling, comprising humus and sand. The stratum below 2 meters up a depth of about 5.7 meters also consisted of humus, sand, medium sand, coarse sand and silt. The tunnel passed through the stratum underlying the fine sand and silt. Clay and fine sand, typically lies about 7.6 meters below the tunnel. Groundwater was encountered approximately at 3.0 meters to depths of 3.6 meters below ground level. The borehole BK 2-28 details are shown in Figure 6.11.

The borehole in the middle of the tunnel BK 2-28.1 indicated that the stratum below ground level to a depth of about 1 meter was backfilling, comprising sand, medium sand, silt and gravel. The stratum below 1 meter up a depth of about 3 meters was

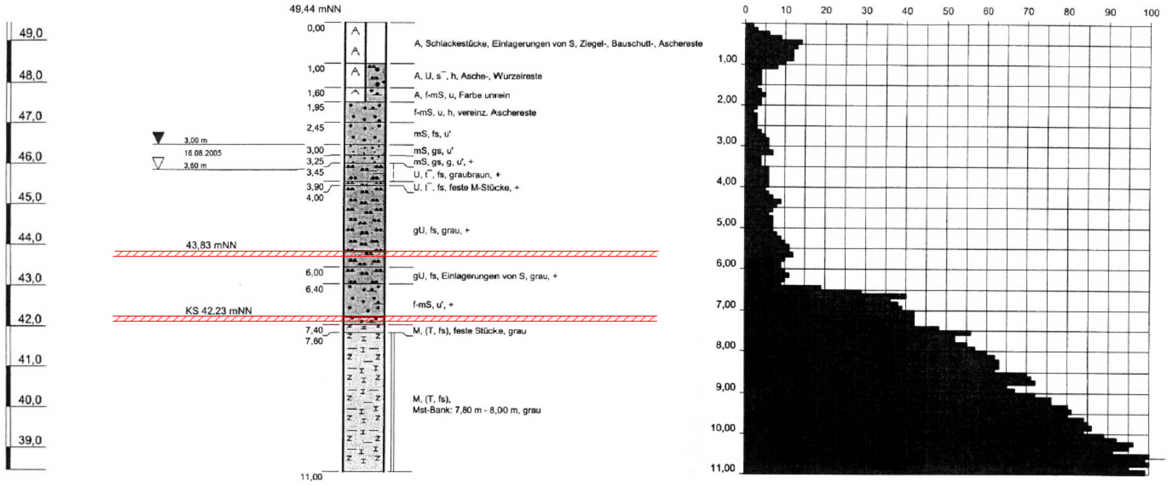


Figure 6.11: Borehole BK 2-28 details (Erdbaulaboratorium Essen, 2005)

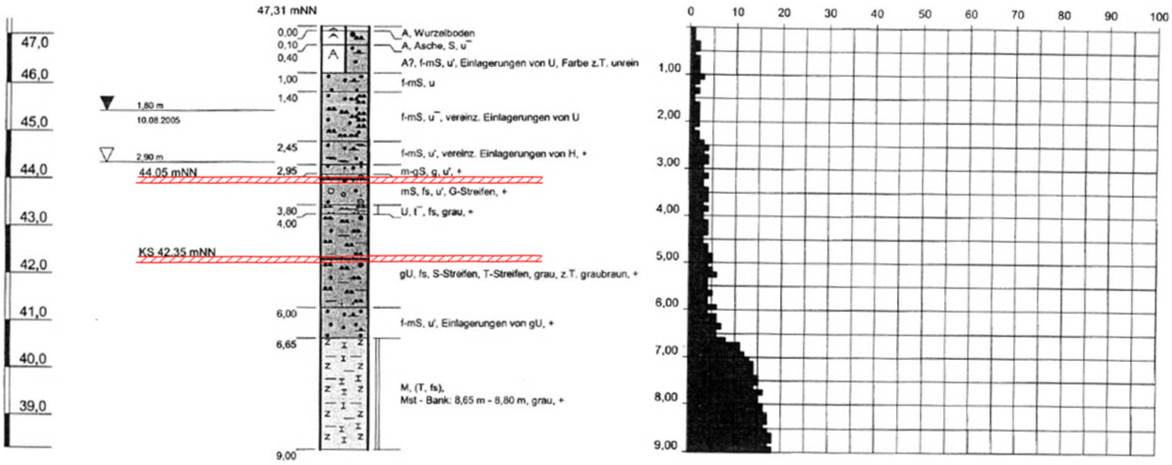


Figure 6.12: Borehole BK 2-28.1 details (Erdbaulaboratorium Essen, 2005)

medium sand, silt, gravel and coarse sand. The tunnel passed through the stratum underlying the silt, fine sand, medium sand and clay. Silt, clay and fine sand typically lie at about 5.5 meters below the tunnel. Groundwater was encountered approximately at 1.8 meters to depths of 2.9 meters below ground level. The borehole BK 2-28.1 details are shown in Figure 6.12.

According to the analysis above, it may be concluded that: the whole tunnel of project Recklinghausen V.5.1 will encounter the types of soil conditions which are fine sand and silt. That is a good soil condition in order to execute jacking processes. The average time for jacking processes based on the data collected from the job site ranged from 85.00 minutes to 99.00 minutes.

6.3.2.3 Duration data collection

As mentioned in detail in section 6.3.1.4, the most important duration affecting the productivity of the project BV Recklinghausen V.5.1 was recorded by using a stop watch

Table 6.3: Duration information of job site: BV Recklinghausen V.5.1

Activity number	**Activity**	**Minimum value (min)**	**Mode value (min)**	**Maximum value (min)**
1	Attaching Pipe	0.30	0.50	0.70
2	Lifting pipe	0.50	0.80	1.00
3	Lowering pipe	0.90	1.20	1.50
4	Laying pipe	1.00	1.70	2.00
5	Replacing jack collar	10.00	12.50	15.00
6	Connecting cables	12.00	15.00	16.00
7	Jacking processes	53.00	95.00	165.00
8	Retracting jack collar	11.00	13.30	15.00
9	Disconnecting cables	23.00	25.00	27.50
10	Time for cleaning spoil container	15.00	23.00	27.00
11	Time for mixing bentonite	13.00	15.00	16.00

Note:

- Lowest value: The minimum value
- Highest value: The maximum value
- Mode value: The most likely value

as well. The duration information is shown in Table 6.3.

6.3.2.4 Jacking processes analysis

The microtunnelling works started on 29.11.2010 and stopped on 16.12.2010 after 13 working days. Appendix A.1 Table A.2 shows the productivities which were recorded from the control panel in the construction site. The total length of the tunnel was approximately 79.44 meters and the average advance rate was approximately 6.10 meters per day. Figure 6.13 shows the change of the productivities during the 13 days (without holidays and weekend). A pattern can be easily observed by plotting productivities data from Table A.2 in Appendix A.1. The productivity for this project ranged from 0 meter to 14 meters per day. Moreover, Table A.2 and Figure 6.13 can be explained by the fact that disturbances are one of the crucial causes to reduce the productivity. The analysis of the recorded data from the microtunnelling machine shows that on working days 11 the productivity could be reached with a maximum of 14 meters per day without disturbances. Meanwhile, on the working days 2, 3, 4, 5 no pipe could be jacked or on working days 8 only one pipe with a length of 3.5 meters could be jacked due to the effect of the disturbances.

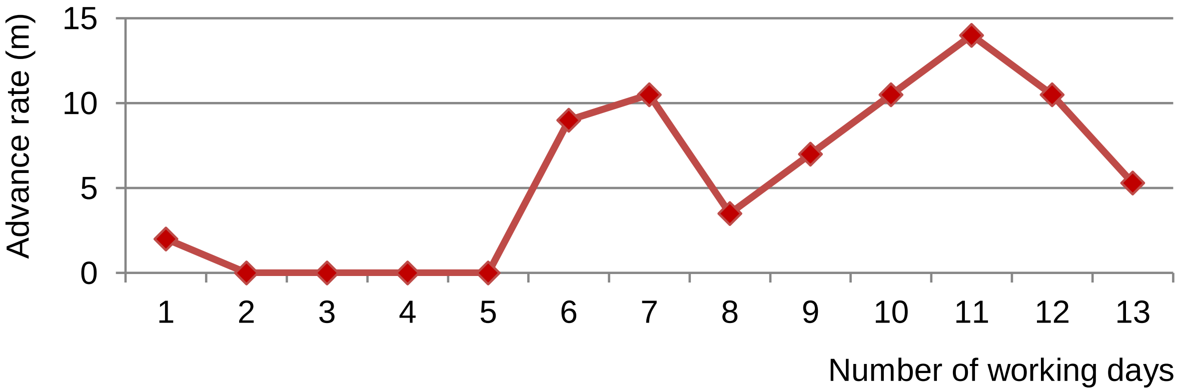


Figure 6.13: The actual productivity of project BV Recklinghausen V.5.1

6.3.2.5 The analysis of disturbances

Operation records that represent 13 days of machine time shows that 22 pipes were used and 6 disturbance events were recorded as illustrated in Appendix A.1 Table A.2. The recorded disturbances time for this project ranged from 56 minutes to 624 minutes with an average of 208 minutes per delay event. The disturbance causes were not recorded for each event but an interview with the operator was carried out during the operations. The main delay causes of this project were the blocking of slurry lines and the blocking of the separation plant. Figure 6.14 shows the overall disturbance and jacking processes time of the project BV Recklinghausen V.5.1. Figure 6.14 can be easily explained by plotting disturbances data from Table A.2 in Appendix A.1. It is also shown that the disturbance time consumed about 42.91% of the total recorded driving time and the jacking and preparation processes used about 57.09% of time.

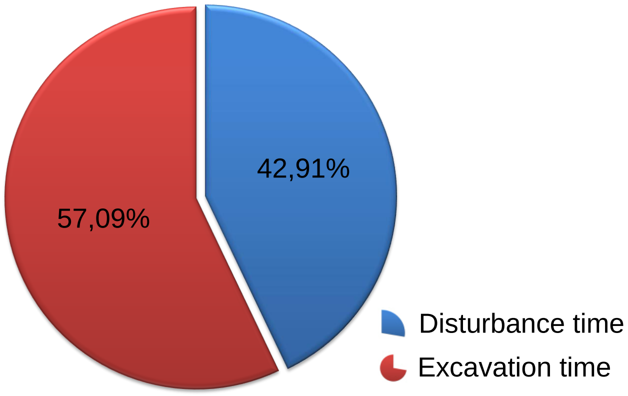
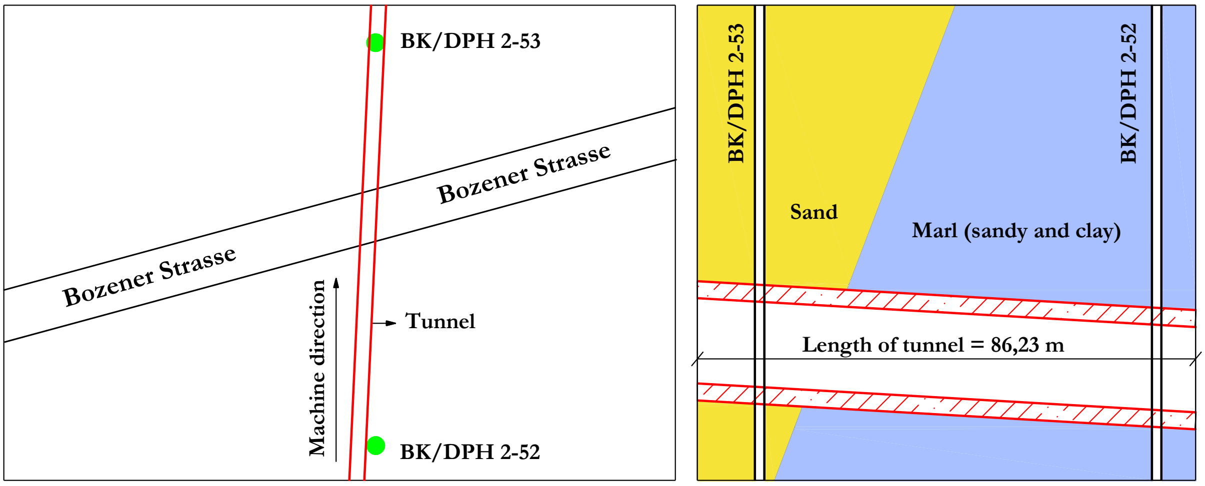


Figure 6.14: Disturbance and jacking processes time of the project BV Recklinghausen V.5.1

6.3.3 Site 3: BV Recklinghausen V.15

6.3.3.1 Project description

The tunnel went across the ”Bozener Strasse” road such as shown in Figure 6.15(a). The total length of the tunnel in project BV Recklinghausen V.15 was ca. 86.23 meters. The first approx. 50 meters long drive went completely through marl with sand and clay. The last approx. 35 meters of the tunnel went through sand. The depth to the axis was about 7.3 meters, grade 1.3‰ and the pipe size was 1.0 meters internal diameter, 1.46 meters external diameter, 4.02 meters length. The position of the construction site was easily accessible.



(a) Site plan (b) Simplified long section

Figure 6.15: Details of BV Recklinghausen V.15

6.3.3.2 Microtunnelling machine description

The project BV Recklinghausen V.15 was carried out by MTBM AVN 1200C using hydraulic spoil removal. The characteristic of the machine AVN 1200C is that it uses almost the same operating principle as MTBM, which is described in section 3.5.1.

6.3.3.3 Ground conditions

A site investigation was carried out around the area of the project in March 2005. Two boreholes were put down along the centre line of the tunnels. The first borehole BK 2-52 and the second borehole BK 2-53 were put down at the beginning and the end of the tunnel to depths of 12.0 meters and 11.5 meters, respectively.

The borehole BK/DPH 2-52 at the beginning of the tunnel indicated that the stratum below ground level to a depth of about 1.4 meters was made of sand backfilling, including humus. The stratum below 1.4 meters up a depth of about 4.0 meters also consisted of sand, medium sand and coarse sand. The tunnel passed through the

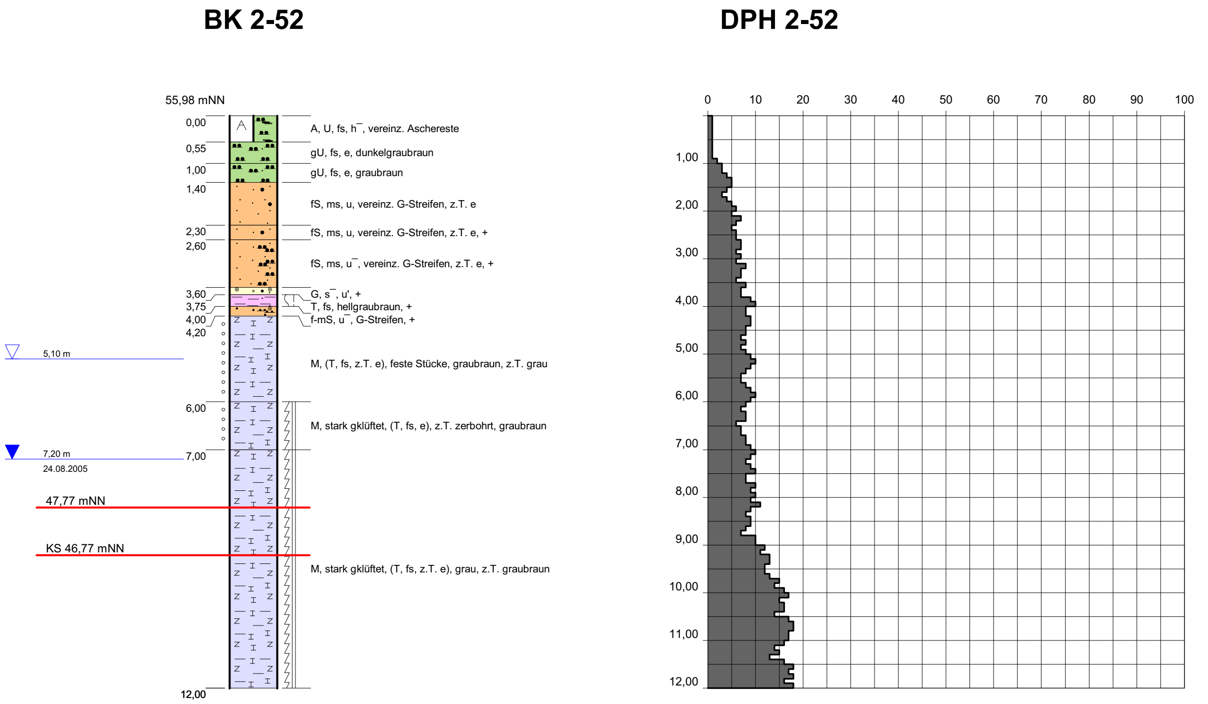


Figure 6.16: Borehole BK2-52 details (Erdbaulaboratorium Essen, 2008)

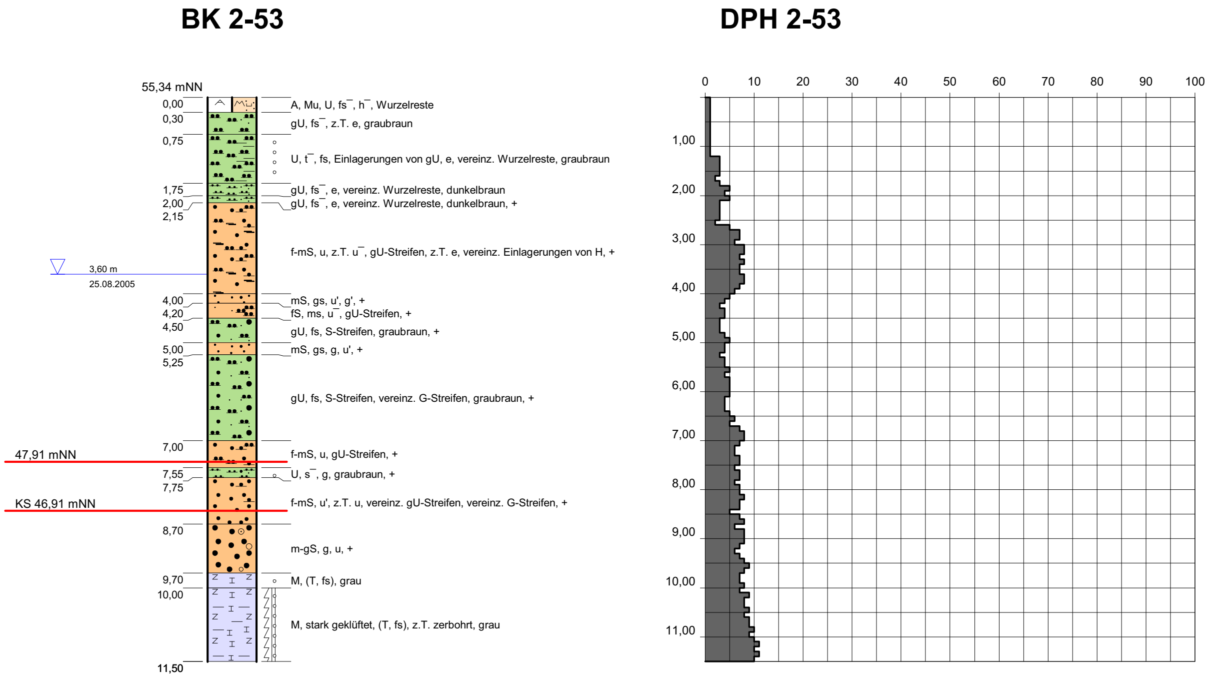


Figure 6.17: Borehole BK2-53 details (Erdbaulaboratorium Essen, 2008)

stratum underlying the marl with clay and cohesive soil. Groundwater was encountered under the ground face at approximately 3.0 meters. The borehole BK/DPH 2-52 details are shown in Figure 6.16.

The borehole in the middle of the tunnel BK/DPH 2-53 indicated that the stratum below ground level to a depth of about 2.0 meters was backfilling, including clay. The stratum below 2.0 meters up a depth of about 7.0 meters was medium sand, silt, gravel and coarse sand. The tunnel passed through the stratum underlying the sand, medium sand. Clay lies at about 9.7 meters below the tunnel. Groundwater was encountered under the ground face at approximately 3.6 meters. The borehole BK/DPH 2-53 details are shown in Figure 6.17.

Table 6.4: Duration information of job site: BV Recklinghausen V.15

Activity number	**Activity**	**Minimum value (min)**	**Mode value (min)**	**Maximum value (min)**
1	Attaching Pipe	1.00	1.50	2.00
2	Lifting pipe	0.75	1.00	1.25
3	Lowering pipe	1.10	1.30	1.70
4	Laying pipe	1.30	1.60	2.10
5	Replacing jack collar	0.57	1.10	1.20
6	Connecting cables	15.51	17.40	19.20
7	Jacking processes:			
	Clay, marl & cohesive soil	234.23	280.00	336.32
	Sand and Gravel	83.45	124.00	138.34
8	Retracting jack collar	1.20	1.35	1.50
9	Disconnecting cables	11.23	11.59	13.12
10	Time for cleaning spoil container	13.48	15.38	25.00
11	Time for mixing bentonite	16.32	18.21	21.45

Note:

- Lowest value: The minimum value
- Highest value: The maximum value
- Mode value: The most likely value

According to the analysis above, it may be concluded that: the tunnel of project BV Recklinghausen V.15 will encounter two types of soil conditions, which are sand and marl. The discussion was carried out with the manager of the project. Based on the information achieved, the first ca. 50 meters of the tunnel encountered the soil conditions which were clayey, marl and cohesive soil. With this type of soil condition, the duration time for jacking processes is time-consuming. Normally the average time for jacking processes for a pipe (4.02 meters) is more than 4 hours. 30 meters before the end of the tunnel, the soil condition is sand and gravel, the average time for jacking processes for a pipe (4,02 meters) is ca. 1.5 hours to 2 hours. This matches the data analyzed in sub-section 6.3.3.5.

6.3.3.4 Duration data collection

As mentioned in detail in section 6.3.1.4, the most important duration affecting the productivity of the project BV Recklinghausen V.15 was recorded by using a stop watch as well. The activity duration information is shown in Table 6.4.

6.3.3.5 Jacking processes analysis

The microtunnelling works started on 18.06.2012 and stopped on 04.07.2012, after 13 working days (not considering holidays and weekends). Appendix A.1 Table A.3 shows the productivities which were recorded from the control panel in the construction site. The total length of the tunnel was approximately 86.23 meters and the average advance rate was approximately 6.63 meters per day. Figure 6.18 shows the change of the productivities during the 13 days. A pattern can be easily observed by plotting productivities data from Table A.3 in Appendix A.1. The productivity for this project ranged from 2.2 meters to 16.08 meters per day. Moreover, Table A.3 in Appendix A.1 and Figure 6.18 can be explaining by the fact that disturbances are one of the main causes to reduce productivity. The analysis of the recorded data from microtunnelling machine shows that on working days 11 and 12 the productivity of 16.08 and 12.06 meters per day, respectively, could be reached. Meanwhile, on working days 4, 5, 8, 10 only one pipe with the length of 4.02 meters could be jacked due to the effect of the disturbances.

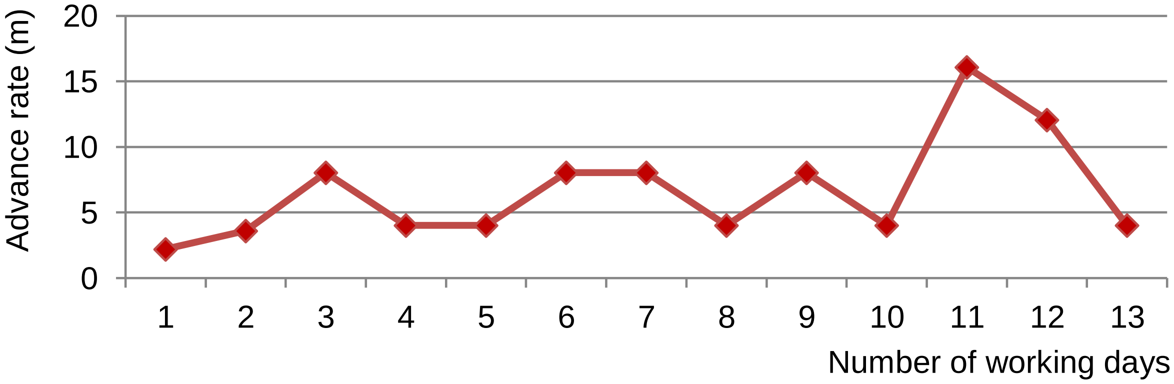


Figure 6.18: The actual productivity of project BV Recklinghausen V.15

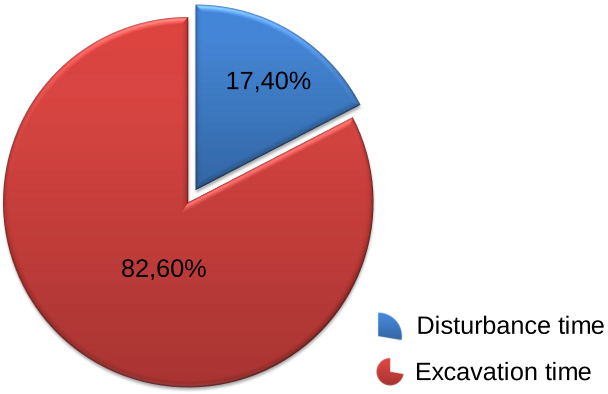


Figure 6.19: Disturbance and jacking processes time of the project BV Recklinghausen V.15

6.3.3.6 The analysis of disturbances

Operation records that represent 13 days of the machine time show that 19 pipes were used and 11 disturbance events were recorded as shown in Appendix A.1 Table A.3. The recorded disturbances time for this project ranged from 28 minutes to 243 minutes with an average of 275.5 minutes per delay event. The disturbance causes were also not recorded for each event but an interview with the operator was carried out during the operations. The main delay causes of this project were the blocking of slurry lines and the blocking of the separation plant. Figure 6.19 shows the overall disturbance and jacking processes time of the project BV Recklinghausen V.5.1. Figure 6.19 can be easily observed by plotting disturbances data from Table A.3 in Appendix A.1. It is also shown that the disturbance time consumed about 17.40% of the total recorded driving time and the jacking and preparation processes used about 82.60% of the time.

Chapter 7

Simulation results

This Chapter starts with proof the MiSAS module is credibility by utilizing validation and verification. Subsequently, the application of the module to the three different projects are described. The simulation module is performed to evaluate and analyze the impact of the different ground conditions, disturbances and predict the resulting tunnel advance rate. Further, the impact of varying resources on the MTBM advance rate is studied in a sensitivity analysis.

7.1 Validation and verification of the MiSAS module

Before using the MiSAS simulation module, the MiSAS module must be demonstrated to achieve simulation module credibility. The use of the validation and verification process is to gain the credibility. Therefore, in order to demonstrate the MiSAS module credibility, the validation and verification process are applied in this study.

7.1.1 Validation of the MiSAS module

The data from the three actual microtunnelling fields study in the city of Recklinghausen, Germany are selected and compared with the output data of the MiSAS module in order to obtain a *valid* module. The output data is not considered of soil impacts and disturbances. If the data compared *"closely"*, then the module of the system is considered *"valid"*. In the opposite case, if the data compared *"not closely"*, then the module must be modified or corrected.

Table 7.1: Overall simulated microtunnelling process productivity in project BV Recklinghausen V.8

Total sim. time unit (min)	Cycle number	Productivity for one pipe (4m)	Productivity per time unit
8996.647	36	249.91	0.004001491

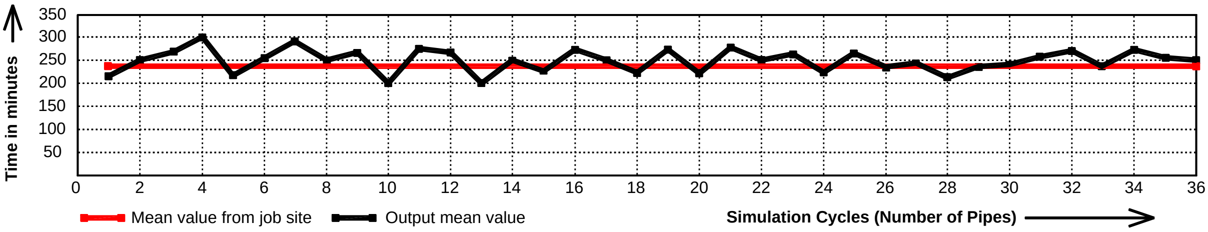


Figure 7.1: Simulation cycle durations without disturbances in project BV Recklinghausen V.8

7.1.1.1 BV Recklinghausen V.8

For the first project BV Recklinghausen V.8, a total of 36 simulations were executed with the MiSAS simulation module. Table 7.1 shows the productivities obtained from these simulations. Figure 7.1 shows the change of productivities in 36 cycles. A pattern can be easily obtained from these simulations. Figure 7.1 shows that the productivities between data from job site and the output data are quite similar. The average productivity from job site for installing one 4.0 m pipe section is 236.77 min, as shown by the red line in Figure 7.1. The average simulated duration of 36 cycles, shown as a black line in Figure 7.1, is 249.91 min, that means that 5.4% are higher than the average productivity obtained in the job site, which is clearly within a reasonable range of a typical microtunnelling project.

7.1.1.2 BV Recklinghausen V.5.1

For the first project BV Recklinghausen V.5.1, a total of 22 simulations were executed with the MiSAS simulation module. Table 7.2 shows the productivities obtained from these simulations. Figure 7.2 shows the change of productivities in 22 cycles. A pattern can be easily obtained from these simulations. Such as the diagram of project BV Recklinghausen V.8, Figure 7.2 shows that the productivities between mean value from job site data and the output data are quite similar as well. The average productivity from job site for installing one 3.5m pipe section is 165 min, as shown by the red line in Figure 7.2. The average simulated duration of 22 cycles, shown as a black line in Figure 7.2, is 159.925 min, that means that 3.123% are lower than the average productivity obtained in job site, which is clearly within a reasonable range of a typical microtunnelling project.

Table 7.2: Overall simulated microtunnelling process productivity in project BV Recklinghausen V.5.1

Total sim. time unit (min)	Cycle number	Productivity for one pipe (3,5m)	Productivity per time unit
3518.35	22	159.925	0.006252931

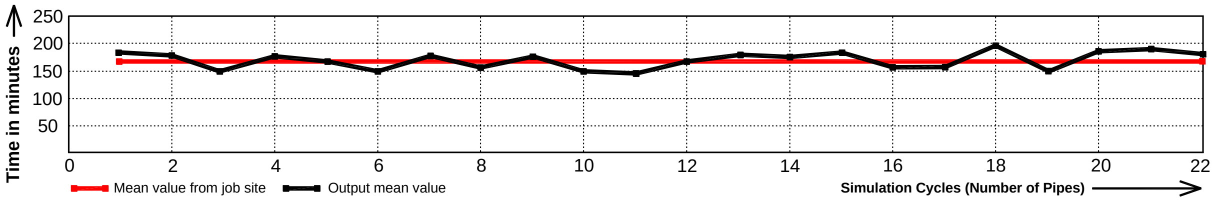


Figure 7.2: Simulation cycle durations without disturbances in project BV Recklinghausen V.5.1

7.1.1.3 BV Recklinghausen V.15

For the project BV Recklinghausen V.15, a total of 21 simulations were executed with the MiSAS simulation module. Table 7.3 shows the productivities obtained from these simulations. Figure 7.3 shows the change of productivities in 21 cycles. A pattern can be easily obtained from these simulations. Such as the diagrams of the two projects mentioned above, Figure 7.3 shows that the productivities between data from job site and the output data are quite similar as well. The other part of the plot in Figure 7.3 shows that after pipe number 14 was jacked, productivities increased from pipe section 15 to pipe section 21, following exactly the real conditions. Due to the fact that the soil condition changed from clayey, marl and cohesive soil to the sand and gravel. When the soil condition was sand and gravel, the penetration speed of the MTBM was faster than when the soil condition was clayey, marl and cohesive soil. The average productivity from job site for installing one 4.020m pipe section was 249.931 min, as shown by the red line in Figure 7.3. The average simulated duration from 21 cycles, shown as a black line in Figure 7.3, is 251.339 min, that means that 0.561% are higher than the average productivity obtained in the job site, which is clearly in a reasonable range of a typical microtunnelling project.

7.1.2 Verification of the MiSAS module

In order to verify the computer program of a dynamic system, the analysts may use *animation*. The users then see dynamic displays (moving resources, cartoons) of the simulated system. Since the users are familiar with the corresponding real system, they can detect the conceptual errors (Kleijnen, 1995). Therefore, the MiSAS module is verified for the 3D animation.

Table 7.3: Overall simulated microtunnelling process productivity in project BV Recklinghausen V.15

Total sim. time unit (min)	Cycle number	Productivity for one pipe (4.02m)	Productivity per time unit
5278.13	21	251.339	0.00397868184

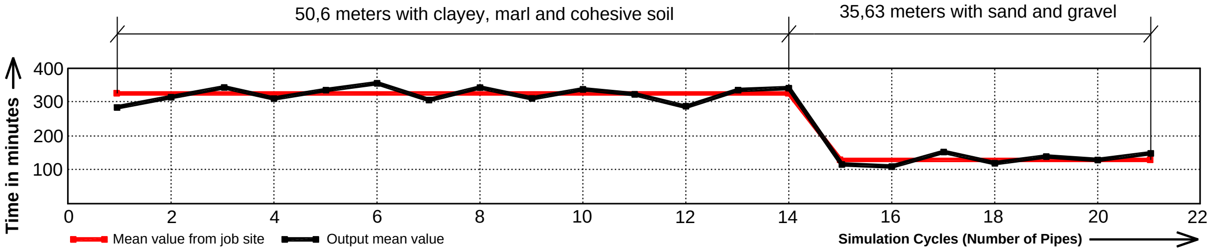


Figure 7.3: Simulation cycle durations without disturbances in project BV Recklinghausen V.15

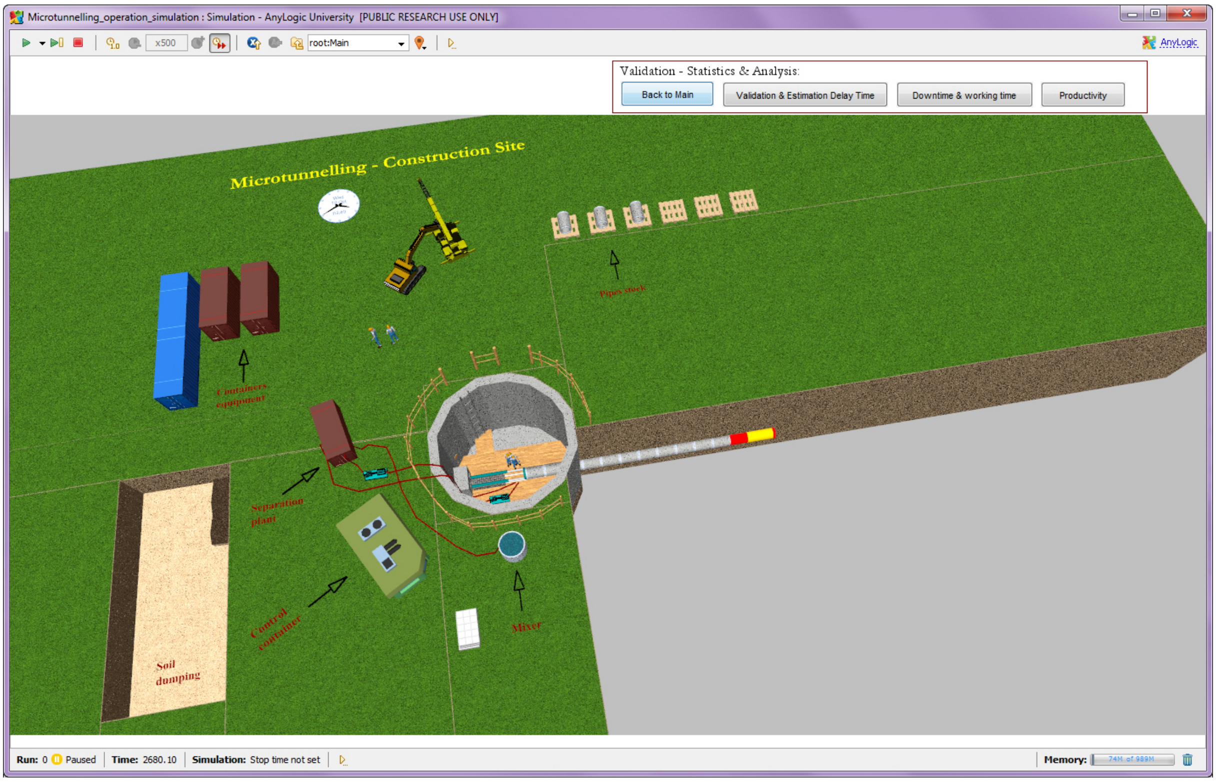


Figure 7.4: 3D animation of MTBM operations

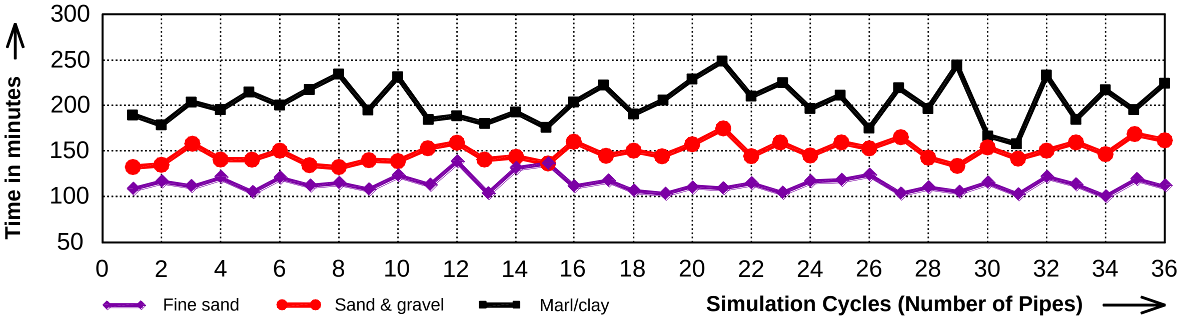
7.1.2.1 Animation

Figure 7.4 shows a 3D graphic screenshotted from the MiSAS simulation module during the run. The 3D animation describes the information about the internal behavior of the resources during the excavation of MTBM in a graphical way. All actions and behavior of the resources during running the MiSAS module are observed. The results indicate that the structure and logics of each stage in the MiSAS module are similar to the practical results.

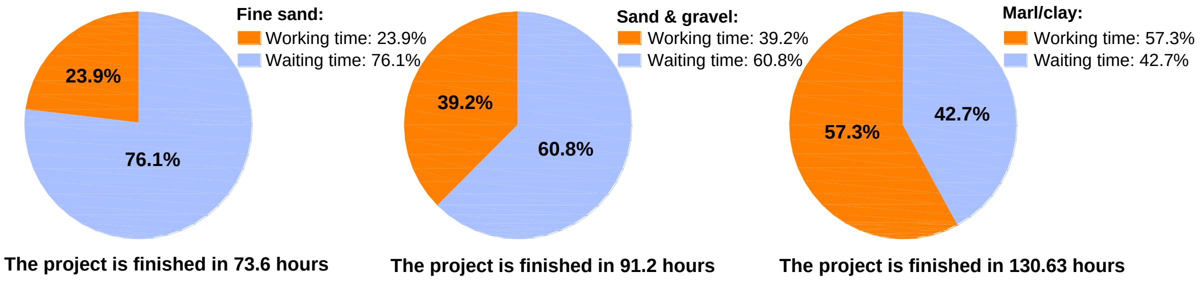
Based on the analysis above, it can be concluded that: the MiSAS module can represent the logic and structure of the MTBM. In addition, it also represents an indirect evidence that the MiSAS simulation model may be used to evaluate and analyze the factors that affect the productivity in MTBM operations if the model is enhanced with soil composition and disturbances.

7.2 Simulation with different soil compositions

After verifying and validating the simulation module, the model can be enhanced with different soil conditions. The encounter of such a soil variety would be probably rare in the actual practice for a single microtunnelling operation. Therefore, it can be assumed that the results of the module test could be used for the simulation of impacts of similar types of soils and the tunnel encountering different types of soils. In order to select a specific type of soil mostly encountered in real situations, three types of soil (marl/clay, fine sand, sand and gravel) are chosen. The minimum, maximum and mode values of the durations of pipe jacking are as mentioned in Chapter 3 section 3.7.



a. Simulation production results

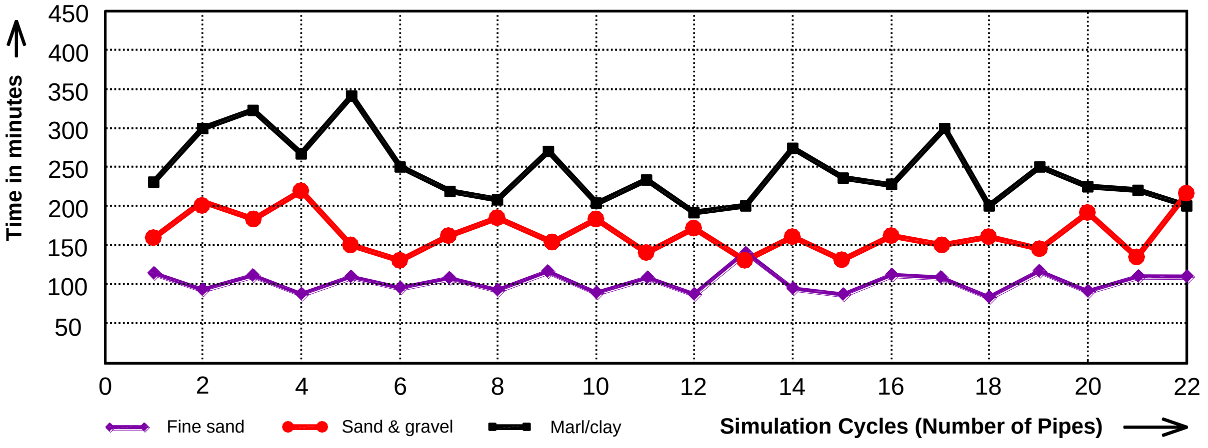


b. Utilization of MTBM (as % of total time)

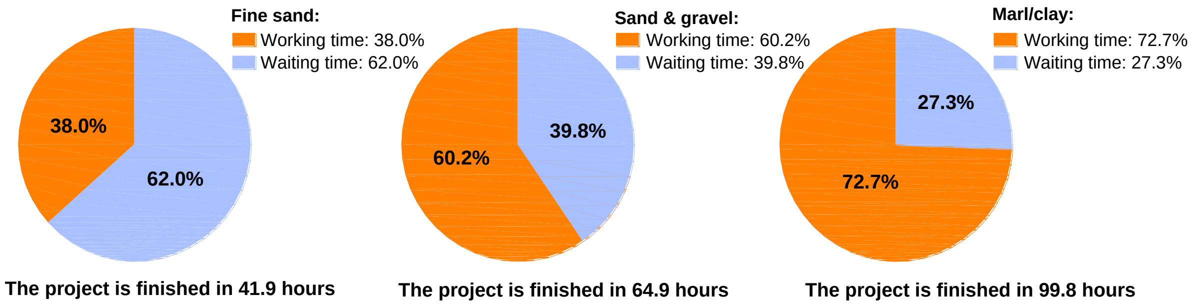
Figure 7.5: Simulation results for different soil compositions in project BV Recklinghausen V.8

7.2.1 Different soil compositions in BV Recklinghausen V.8

Figure 7.5 shows the productivity and the operation time of the MTBM in three cases. In the first case, the soil encountered at the construction site is fine sand. The rate of progress is 1.97 m/h, the project will be finished in 73.6 hours. The percentage of



a. Simulation production results



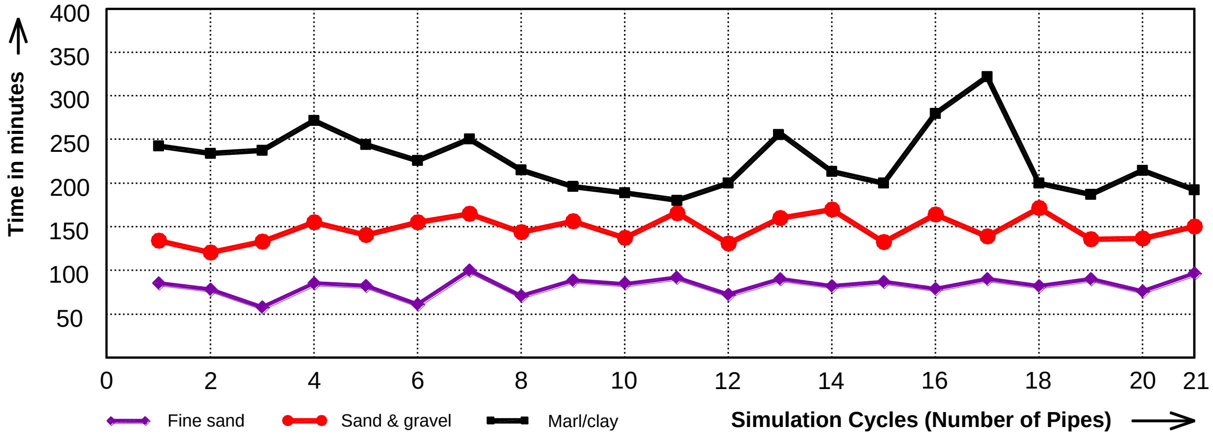
b. Utilization of MTBM (as % of total time)

Figure 7.6: Simulation results for different soil compositions in project BV Recklinghausen V.5.1

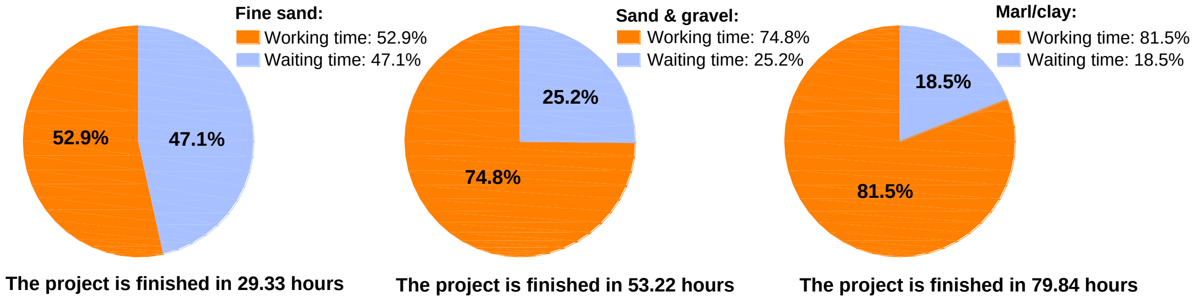
working time and waiting time of the MTBM are 23.9% and 76.1%, respectively. For the second case, the length of the tunnel going completely through sand and gravel, the rate of progress is 1.59 m/h, the project will be finished in 91.2 hours. The percentage of working time of the MTBM is 39.2% and waiting time is 60.8%. For the third case, the soil encountered along the tunnel being clay and marl, the rate of progress is 1.11 m/h, the project will be finished in 130.63 hours. The percentage of working time and waiting time of the MTBM are 57.3% and 42.7%, respectively. For all cases, the disturbances are not considered, the resources are always available, the equipment is not maintained during the construction.

7.2.2 Different soil compositions in BV Recklinghausen V.5.1

Figure 7.6 also shows the productivity and the operation time of the MTBM in three cases. In the first case, the soil encountered at the construction site is fine sand. The rate of progress is 1.894 m/h, the project will be finished in 41.9 hours. The percentage of working time and waiting time of the MTBM are 38.0% and 62.0%, respectively. For the second case, the length of the tunnel going completely through sand and gravel, the rate of progress is 1.223 m/h, the project will be finished in 64.9 hours. The percentage of working time of the MTBM is 60.2% and waiting time is 39.8%. For the third case,



a. Simulation production results



b. Utilization of MTBM (as % of total time)

Figure 7.7: Simulation results for different soil compositions in project BV Recklinghausen V.15

the soil encountered a long the tunnel being clay and marl, the rate of progress is 0.802 m/h, the project will be finished in 99.8 hours. The percentage of working time and waiting time of MTBM are 72.7% and 27.3%, respectively. The disturbances are not considered, the resources are always available, the equipment is not maintained during the construction.

7.2.3 Different soil compositions in BV Recklinghausen V.15

Figure 7.7 also shows the productivity and the operation time of the MTBM in three cases. For the first case, the soil encountered at the construction site being fine sand, the rate of progress is 2.94 m/h, the project will be finished in 29.33 hours. The percentage of working time and waiting time of the MTBM are 52.9% and 47.1%, respectively. For the second case, the length of the tunnel going completely through sand and gravel, the rate of progress is 1.62 m/h, the project will be finished in 53.22 hours. The percentage of working time of the MTBM is 74.8% and waiting time is 25.2%. In the last case, the soil encountered along the tunnel being clay and marl, the rate of progress is 1.08 m/h, the project will be finished in 79.84 hours. The percentage of working time and waiting time of the MTBM are 81.5% and 18.5%, respectively. The disturbances are also not considered, the resources are always available, the equipment is not maintained during the construction.

7.3 Simulation results with enhanced model considering disturbances

The MiSAS module can be also used to analysis the effect of the disturbances on the productivity of MTBM. The simulation experiment consider the disturbances occur during jacking processes. The mean time between failure (MTBF) are generated by the triangular distribution. The assumptions input values made for the applications in this study shown in Table 7.4.

Table 7.4: Configuration of disturbance simulation

Type of disturbances	Mean cycles between failure (%)	Time to repair (min) Min	Max	Mode
Blocking, Burst of Slurry Lines	15	65	85	70
Blocking of Separation Plant	35	60	75	70
Laser Problems	10	15	20	17
MTBM Problems	5	220	235	250
Pump Problems	15	50	60	55
Jacking Station Problems	3	40	50	45

7.3.1 Simulation of disturbances in BV Recklinghausen V.8

Figure 7.8 shows the change of productivity of the tunnel in the sub-project BV Recklinghausen V.8 considering disturbances. Table 7.5 displays the productivities obtained from the simulation using MiSAS. In comparison with the case without disturbances, the project duration is expected to be longer. After 36 cycles, the average simulated duration with disturbances is 288.40 min for one pipe of 4 m length (compared with 249.91 min for one pipe without disturbances), that means that it is ca. 14.30% higher than the average productivity obtained without disturbances. The total time to finish the project with disturbances is 10382.4 min. The total time is 1385.8 min (ca. 23 hours) higher if compared with the total time to finish the project without disturbances which is 8996.65 min.

Table 7.5: Overall simulated microtunnelling process productivity in project BV Recklinghausen V.8 with disturbances

Total sim. time unit (min)	Cycle number	Productivity for one pipe (4m)	Productivity per time unit
10382.4	36	288.40	0.00346737298

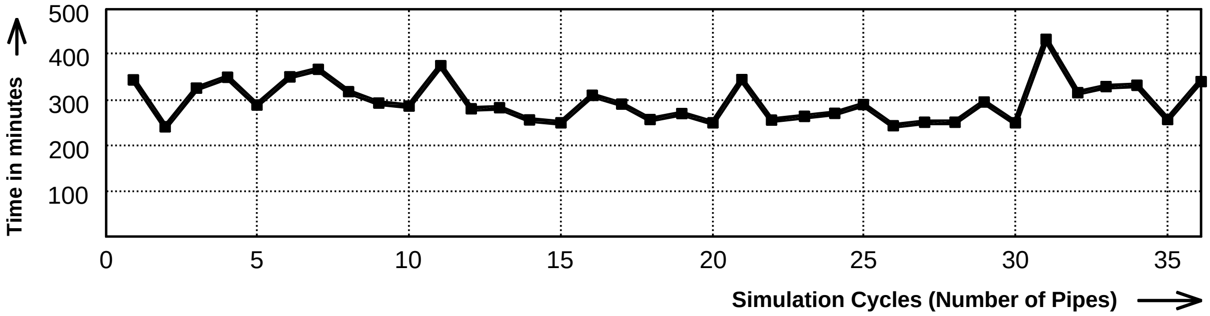


Figure 7.8: Simulation cycle durations considering disturbances in project BV Recklinghausen V.8

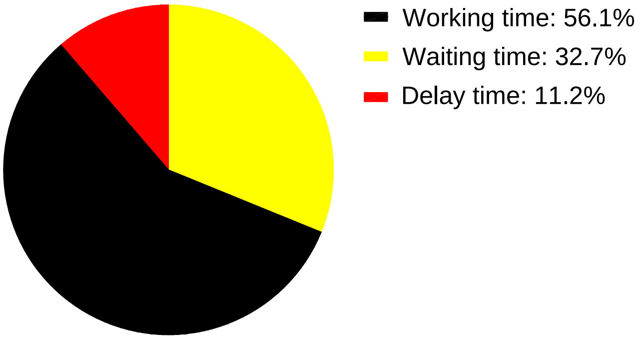


Figure 7.9: Utilization of MTBM (as % of total time) considering disturbances in project BV Recklinghausen V.8

The simulation results in Figure 7.9 indicate the working time, waiting time and delay time of the MTBM. The results show that the working time of the MTBM is 56.1%, as shown in Figure 7.9 represented as the black area. The waiting time for jacking processes is 32.7%, as shown in Figure 7.9 in the yellow area and the delay time (because of the disturbances that occur and the time that therefore must be taken to repair the malfunction) is 11.2%, as represented as the red area in Figure 7.9.

7.3.2 Simulation of disturbances in BV Recklinghausen V.5.1

Figure 7.10 shows the change of productivity of the tunnel in the sub-project BV Recklinghausen V.5.1 considering disturbances. Table 7.6 displays the productivities obtained from the simulation. The comparison with the case without disturbances was carried out. After 22 cycles, the average simulated duration with disturbances is 210,07 min for one pipe of 3.5m length (compared with 159.925 min for one pipe without disturbances), that means that it is ca. 27.1% higher than the average productivity obtained without disturbances. The total time to finish the project with disturbances is 4621.50 min. The total time is 1103.15 min (ca. 18.4 hours) higher if compared with the total time to finish the project without disturbances which is 3518.35 min.

The simulation results in Figure 7.11 also represent the working time, waiting time and delay time of the MTBM. The results show that the working time of the MTBM is

Table 7.6: Overall simulated microtunnelling process productivity in project BV Recklinghausen V.5.1 with disturbances

Total sim. time unit (min)	Cycle number	Productivity for one pipe (3.5m)	Productivity per time unit
4621.5	22	210.07	0.00476035919

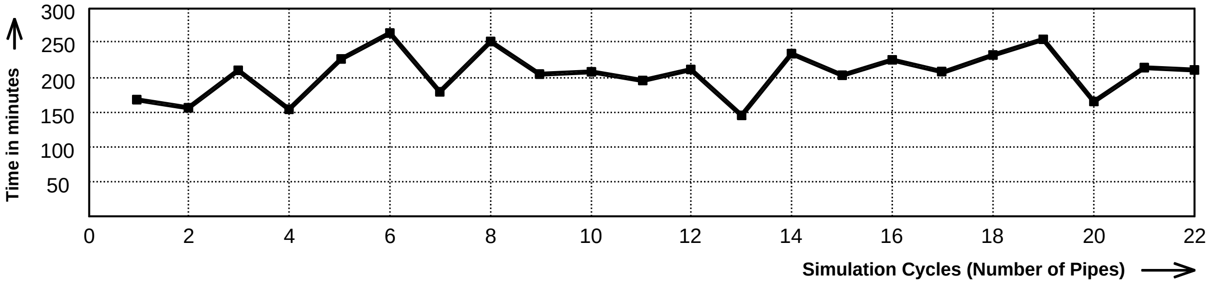


Figure 7.10: Simulation cycle durations considering disturbances in project BV Recklinghausen V.5.1

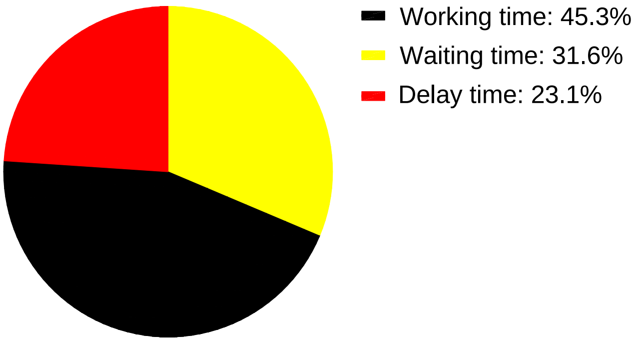


Figure 7.11: Utilization of MTBM (as % of total time) considering disturbances in project BV Recklinghausen V.5.1

45.3%, as shown in Figure 7.11, black area. The waiting time for jacking processes is 31.6%, represented in Figure 7.11, yellow area, and the delay time (because of the occurring disturbances) is 23.1%, represented as red area in Figure 7.11.

7.3.3 Simulation of disturbances in BV Recklinghausen V.15

Figure 7.12 shows the change of productivity of the tunnel in sub-project BV Recklinghausen V.15 considering disturbances. Table 7.7 displays the productivities obtained from the simulation using MiSAS. The comparison with the case without disturbances is carried out according to the last two microtunnelling projects. After 21 cycles, the average simulated duration with disturbances is 310.42 min for one pipe of 4.02m length (compared with 251.339 min for one pipe without disturbances), that means that it is ca. 21,03% higher than the average productivity obtained without disturbances. The total time to finish the project with disturbances is 6518.9 min. The total time is 1240.77 min (ca. 20.7 hours) higher if compared with the total time to finish the project without disturbances which is 5278.13 min.

Table 7.7: Overall simulated microtunnelling process productivity in project BV Recklinghausen V.15 with disturbances

Total sim. time unit (min)	Cycle number	Productivity for one pipe (4.02m)	Productivity per time unit
6518.9	21	310.42	0.0032214023838

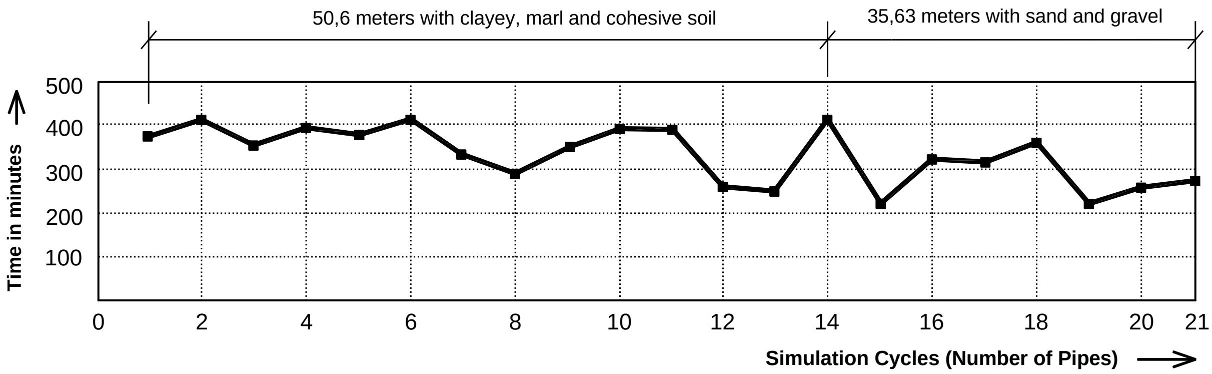


Figure 7.12: Simulation cycle durations considering disturbances in project BV Recklinghausen V.15

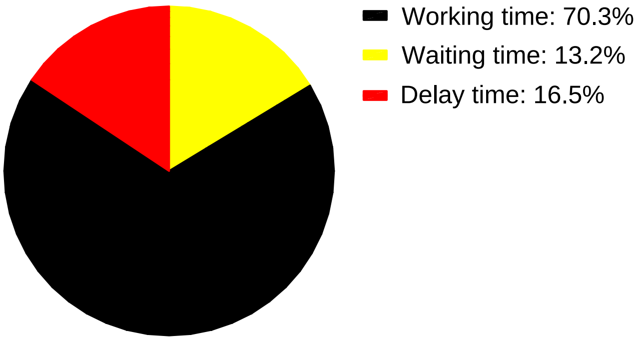


Figure 7.13: Utilization of MTBM (as % of total time) considering disturbances in project BV Recklinghausen V.15

The simulation results in Figure 7.13 represent the working time, waiting time and delay time of the MTBM as well. The results show that the working time of the MTBM is 70.3%, as shown in Figure 7.13, black area. The waiting time for jacking processes is 13.2%, represented in Figure 7.13, yellow area and the delay time (because of the disturbances occur and time must therefore be taken to repair the malfunction) is 16.5%, represented as red area in Figure 7.13.

7.4 Prediction of productivity in microtunnelling

In order to predict the productivity in microtunnelling, the combination of MiSAS with the calculation of disturbances time in microtunnelling is implemented. The productivity of microtunnelling without disturbances is computed by using the MiSAS module. The disturbances time can be calculated by using the equations of Mohamed and Gary (2007). The total value of these two results represents the productivity of microtunnelling.

According to Mohamed and Gary (2007), the disturbances time can be represented by three models representing the assumed performance as high performance in the first quartile, average performance in the median, and low performance in the lower quartile. These models are described by three equations:

For high performance (Q_1):

$$Delaytime(min) = e^{0.011166(drivenlength,m)+5.337} \tag{7.4.1}$$

For average performance (median):

$$Delaytime(min) = e^{0.011166(drivenlength,m)+5.628} \tag{7.4.2}$$

For low performance (Q_3):

$$Delaytime(min) = e^{0.011166(drivenlength,m)+5.919} \tag{7.4.3}$$

These equations are limited as they only include those projects that include applications of slurry MTBM for drives of a length less than 400m, diameters between 400 and 1760 mm, jacking force of 700t, and shearing force less than 300t. Two different microtunnelling projects, the surveyed BV Recklinghausen V.8 and BV Recklinghausen V.15 in Recklinghausen satisfy the equations' limitation. Therefore the comparison between the actual data to finish the project with the simulation experiments are performed.

Table 7.8: Prediction of productivity in microtunnelling

Name of Project	Actual total time to finish (min)	Total time to finish (min)		
		Q_1	median	Q_3
BV Recklinghausen V.8	11400	10430.6	10792.4	11266.7
BV Recklinghausen V.15	7200	5989.6	6177.2	6423.3

Table 7.8 displays the prediction of productivity in microtunnelling applied on the two microtunnelling projects BV Recklinghausen V.8 and BV Recklinghausen V.15. The actual total time to finish the microtunnelling project BV Recklinghausen V.8 is 11400 minutes. The simulated total times to finish the microtunnelling project BV Recklinghausen V.8 for the case of high performance, average performance and low performance are 10430.6, 10792.4 and 11266.7 minutes, respectively. The time to finish by using simulation is ca. 4% lower for the case of high performance, ca. 2% lower for the case of

average performance and ca. 1% lower for the case of high performance. It is clearly within a reasonable range of a typical microtunnelling project.

Based on the results mentioned above, it can be concluded that: the MiSAS simulation model may be used to predict the productivity of microtunnelling.

7.5 Simulation with variation of resources

The sensitivity analysis focuses on manpower and *Output Crew Quota (OCQ)*. The combination of adding 1 laborer to Crew 1, adding and reducing 1 or 2 laborers to Crew 2 with different *OCQ* is simulated. The *OCQ* may be defined as the productivity of the crew and calculated by the formula:

$$\mathit{OCQ} = T_{at}/T_{tp} \tag{7.5.1}$$

Where T_{at} is the actual time spent by the number of laborers executing the task; T_{tp} is the time planned for executing the task. For instance, normally the Crew 2 consists of 3 laborers and the T_{tp} is 19 min in order to complete the ”disconnect cables” task, with 2 laborers the Crew 2 needs the T_{at} of 24 min to finish. The ratio of the times based on formula 7.5.1 is *OCQ*. In other words, the *OCQ* is defined by the ratio of the actual time and time planned in order to complete the task. The change of *OCQ* value is based on actual data, which were collected in the job site. The *OCQ* is used within the paper based on the data and experience from the construction site (shown in appendix B.1).

7.5.1 Simulation with variation of resources in BV Recklinghausen V.8

Table 7.9: Sensitivity analysis results for BV Recklinghausen V.8 (Dang et al., 2013)

Resource information			**Parameters**	**Productivity and cost information**			
No. of Operator	No. of Crew 1	No. of Crew 2	*OCQ* for Crew 2	Productivity per unit time (min)	Duration (min) for one pipe (4.0 m)	Percentage of productivity (%)	Percentage of labor cost (%)
1	1	1	0.3	0.0032	316.614	75.7	37.5
1	1	2	0.8	0.0038	265.177	90.5	50.0
1	1	3	1.0	0.0040	246.185	97.5	62.5
1	1	4	1.1	0.0041	241.656	99.3	75.0
1	1	5	1.15	0.0042	240.904	99.6	87.5
1	2	1	0.3	0.0032	314.768	76.3	50.0
1	2	2	0.8	0.0038	264.245	90.8	62.5
1	2	3	1.0	0.0041	245.347	97.8	75.0
1	2	4	1.1	0.0041	241.159	99.5	87.5
1	2	5	1.15	0.0042	240.024	100.0	100.0

A sensitivity analysis is carried out by using the simulation module to analyze the resource optimization as shows in Table 7.9. In general, Table 7.9 shows that the productivity is increased overall by adding one laborer to Crew 1 and adding 1 or 2 laborers to Crew 2. In addition, the real phenomenon *"density"* is shown in the job site: If too many laborers are working, they will occupy more space and equipment. Therefore, they will interfere with each other and the productivity will only slightly improve. In other words, the productivity and quantity of laborers has a linear relationship. When more laborers are added, the productivity improvement rate is decreased and eventually becomes zero or even negative. The case *"highest productivity"* is achieved by adding one laborer to Crew 1 and two laborers to Crew 2. But the cost in this case is maximum making this alternative undesirable. By adding 1 laborer to Crew 2, the productivity equal 99.3% and the laborer cost equal 75%, if compared to *"highest productivity"* case. By using simple analysis, it may be concluded that in case adding 1 laborer to Crew 2 the productivity and the cost is more beneficial compared with other cases shown in Table 7.9. Not considering costs this study, the sensitivity analysis only considered the relationship between productivity improvements and number of laborers. Therefore, if simulation is used for decision making, the cost factor such as the cost for labor, equipment, job site installation or cost for contract milestone date must also be included.

Chapter 8

Summary, Conclusion and Outlook

8.1 Summary

This thesis presented an approach to analyze microtunnelling construction processes using computer simulation. The research aims at the development of an appropriate and adaptable simulation module for microtunnelling construction operations. It helps to analyze the processes and to identify the factors which influence the operation productivity of the construction process. In addition, the relationship between different soil conditions, disturbances and the microtunnelling productivity had to be determined.

In the first part of the thesis, the role of the use of process simulation in the analysis and improvement of construction operations was discussed. The fundamental principle of tunnel construction with microtunnelling and the main hitches that exist in typical microtunnelling projects were described as well. In addition, the information gathered about activities and resources (e.g. laboratory, special machinery and materials) used in the microtunnelling project was analyzed. Moreover, the disturbance causes and the influence of disturbances on the construction sequences were also discussed in this part. As a first step, the entire of these information have been used to help building simulation models in the next steps.

In the second part describes the development of appropriate simulation models for MTBM. Based on the Systems Modeling Language (SysML), simulation models, representing the tunnel construction process with microtunnelling, were developed. The simulation models were built by using three types of diagrams, the so-called block definition diagram, state machine diagram and sequence diagram, which are supported in SysML. The diagrams represent the composition, sequence and the interaction within the MTBM. These simulation models are used to help to better understand the process involved in microtunnelling construction, and identify the model variables for which information needs to be collected.

Based on the developed simulation model, in the third part a simulation module called MiSAS (Microtunnelling: Statistics, Analysis and Simulation) has been developed using AnyLogic simulation software. It has been designed utilizing discrete event simulation, system dynamic and agent based methodologies, which are supported in AnyLogic software. The simulation module has been coded utilizing Java platform. Due to the MiSAS module has to be built accurately, therefore it has to be validated. Numerical examples of three actual cases have been worked out to validate the developed MiSAS and demonstrate its capabilities. In order to validate the module, the output data of the simulation module is compared with the data from actual microtunnelling projects. The three actual projects, namely, ”BV Recklinghausen V.5.1”, ”BV Recklinghausen V.8” and ”BV Recklinghausen V.15” in Recklinghausen, Germany have been chosen to get the real data. The real data about probability distributions of time durations of activities, resources and the relationships between model parameters in the construction site are collected. These real measured data were used to be compared with the output data of the simulation module. According to the comparison of output data and real data, the MiSAS module may be adjusted if necessary and simulation needs to be redone to validate the model.

In the fourth part, after the validation and verification of the simulation module, the same structure and logic were used with enhancement of soil composition and disturbances. The enhanced MiSAS module can be modified to include possibilities of soil compositions, disturbances and simulation corresponding to productivity. Therefore, the statistical relationship between soil composition, disturbances and microtunnelling projects productivity can be analyzed, anticipated and studied. Further, the graphical user interface has also been designed and implemented utilizing AnyLogic simulation software to help the user’s interaction being as simple and efficient as possible.

The last part involves the performance of experiments and analysis of the results. As an application module, the operational and statistical analysis are performed using simulation. A sensitivity analysis is carried out, using the simulation module with real microtunnelling case data, to identify and analyze the most critical microtunnelling variables affecting productivity of microtunnelling construction process. Critical variables are the variables that have major impact on productivity of microtunnelling construction. On the basis of the obtained results, working time, downtime of the resources, microtunnelling, labors, and the effective resource allocation regarding a real microtunnelling project is determined.

8.2 Conclusion

In this thesis, a methodology for simulating utility tunnels construction with MTBM using computer simulation was described. Within the research, an appropriate and adaptable simulation module for microtunnelling construction operations based on a formal model description of MTBM with hydraulic spoil removal was developed. The simulation modules were conducted on the cyclic of the microtunnelling process, including pipe segments preparation to pipe section jacked in place. In mobilization and demobilization stages, activities including digging shafts, hauling MTBM, setting up control console, the cost of the project etc. were not considered into simulation modules due to the non-cyclic nature. The formal model is a simulation model that has been established based on SysML. The simulation module focuses on the evaluation of the effect of alternating soil conditions and disturbances on the productivity of the microtunnelling process.

The conclusions of the study can be summarized as follows:

1. The development of a simulation model capturing the tunnel construction process with MTBM based on SysML methodology has been carried out. Based on established SysML simulation, the simulation module has been developed. The module accounts for the uncertainty involved in these operations and captures the interaction amongst devices and resources. Moreover, it consists of a powerful set of tools that can help the manager to identify the factors which influence the operation productivity of the construction process.

2. The simulation module delivers the manager or engineer the effect of the following variables on the advance rate such as: different soil conditions, disturbances. Furthermore, several sensitivity analysis studies to investigate the effect of the resources on the productivity of tunnel construction with MTBM have been performed. In addition, the simulation module can be used to predict the actual advance rate of the microtunnelling with and without disturbances.

3. In specific applications, the MiSAS module helps the manager or engineer to analyze the possibility of multiple approaches to execute the tunnel construction with MTBM. Using MiSAS, it is also shown that the best allocation of resources can be determined based on productivity.

4. The special characteristics of the simulation module makes it more attractive for use than other planning systems. The terms and mode of operation closely resemble the usual practices in tunnels construction with MTBM and its orientation provides the job site manager with more usable information than other systems.

5. In terms of scheduling alternatives for the overall project, the user can easily restructure the approach taken and evaluate the effects of the decision. Through

repetitive analysis of the same tunnel, the best or better alternative can be found. It also helps the user to view the possibilities of the overall of the tunnel construction project with MTBM.

6. Overall, the developed simulation module accomplishes the initial objectives as defined. It provides a set of flexible and powerful analytic techniques that can be customized by any user according to the specific applications that are desired.

8.3 Outlook

This research has presented a approach for analyzing the tunnel construction with MTBM by utilizing computer simulation. The research could be expanded to account for the following:

1. As already mentioned in this study, the MiSAS module covers the analysis of the factors which effect the productivity of microtunnelling. The module has not mentioned the effect of the factor e.g. disturbance or soil composition on the total cost of the tunnel construction with MTBM. For future research purposes, the MiSAS simulation can be expanded to include sub-modules to estimate the time and cost of tunnels construction with MTBM. Hereby, the relationship between resources, equipment and productivity can be analysed as well as economical optimum may be achieved.

2. The MiSAS module was only applied for the MTBM with hydraulic spoil removal. For future research work, the simulation module can be upgraded with different types of MTBM, such as: tunnel construction with auger spoil removal and with pneumatic spoil removal.

3. The simulation can be enhanced to predict the jacking force for microtunnelling operations. For future work, the module may be extended to calculate the jacking force for MTBM. This can be helpful for planning, design, and construction phases of microtunnelling projects.

4. This study focuses primarily on the tunnel construction with MTBM without intermediate jacking stations processes. Therefore, the simulation module and algorithm can be extended to include the intermediate jacking stations.

5. The development of a decision support system, which can be used by contractors to estimate projects' markup and by owners to evaluate bid proposals, in a flexible manner.

6. In this the research, the minimum, maximum and the mode likely value of the triangular distribution was decided based on the data from only three construction sites. For future purposes, the time durations of the activities may be modelled by probability distributions, based on the amount of data collected from the construction site. This will help to make the results output more accurate.

7. Within this study, assumptions were made, regarding the pipes handling processes to the construction site. The MiSAS module only assumed two cases during transportation time: with and without disturbance. The module did not mention the pipes handling processes in detail. For future study purposes, the pipe handling material processes may be modelled in detail according to the transporting sequence. This will help to module real world tunnel projects with MTBM more accurately.

8. The effectiveness of the use of process simulation is proven through a lot of studies and research. It is especially useful to describe and analyze construction projects that consist of repetitive construction cycles. For future research works, the use of process simulation can be expanded to encompass different construction operations e.g. the tunnel construction with NATM (New Austrian Tunnelling Method), with TBM (tunnel boring machine) or the construction of highways, bridges, mining, earthmoving, etc.

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Appendix A

Excavation time analysis

This appendix describes the analysis of time disturbances during jacking processes in three different projects, which are mentioned in Chapter 6. The time for jacking processes are recorded by control container in the construction site.

A.1 Site 1: BV Recklinghausen V.8

Table A.1: Recorded data from project BV Recklinghausen V.8

Date	Week-day	Number of pipe	Number of day	Jacking time		Disturbance time [h]	TFJP with disturbance [h]	TFJP without disturbance [h]	Jacking length [m]
				Start	End				
19.05.2011	Thursday	0	1	18:58	19:21	00:00	00:23	00:23	1
20.05.2011	Friday	0	2	06:58	13:40	00:00	06:42	06:42	1
23.05.2011	Monday	0	3	07:03	19:40	00:00	12:37	12:37	5,6
24.05.2011	Tuesday	0	4	08:02	18:46	00:00	10:44	10:44	7,8
25.05.2011	Wednesday	1	5	09:11	11:32	00:00	02:21	02:21	4,0
26.05.2011	Thursday	2	6	09:45	11:36	00:00	01:51	01:51	4,0
26.05.2011		3		14:38	17:33	00:00	02:55	02:55	4,0
26.05.2011		4		18:44	20:44	00:00	02:00	02:00	4,0
27.05.2011	Friday		7	00:00	00:00	00:00	00:00	00:00	0,0
30.05.2011	Monday	5	8	07:42	10:31	00:00	02:49	02:49	4,2
30.05.2011		6		12:10	14:01	00:00	01:51	01:51	3,8
30.05.2011		7		15:54	19:10	00:32[1]	03:16	02:44	4,0
31.05.2011	Tuesday	8	9	09:45	12:09	00:00	02:24	02:24	4,0
31.05.2011		9		15:07	18:01	01:23[2]	02:54	01:31	4,2
01.06.2011	Wednesday	10	10	07:31	12:02	02:46[3]	04:31	01:45	3,8
01.06.2011		11		13:40	15:37	00:00	01:57	01:57	4,2
02.06.2011	Thursday		11	00:00	00:00	00:00	00:00	00:00	0,0

Table A.1: Recorded data from project BV Recklinghausen V.8

Date	Week-day	Number of pipe	Number of day	Jacking time		Disturbance time [h]	TFJP with disturbance [h]	TFJP without disturbance [h]	Jacking length [m]
				Start	End				
03.06.2011	Friday		12	00:00	00:00	00:00	00:00	00:00	0,0
06.06.2011	Monday	12	13	08:23	15:26	04:24[4]	07:03	02:39	3,8
06.06.2011		13		16:48	18:33	00:00	01:45	01:45	4,0
07.06.2011	Tuesday	14	14	08:27	10:37	00:00	02:10	02:10	4,0
07.06.2011		15		12:19	13:56	00:00	01:37	01:37	4,0
07.06.2011		16		17:10		08:27[5]	10:32	02:05	4,2
08.06.2011	Wednesday		15		15:42				3,8
08.06.2011		17		16:45	18:20	00:00	01:35	01:35	4,0
09.06.2011	Thursday	18	16	07:30	09:10	00:00	01:40	01:40	4,0
09.06.2011		19		10:14	11:50	00:00	01:36	01:36	4,0
09.06.2011		20		13:24	17:24	01:46[6]	04:00	02:14	4,0
10.06.2011	Friday	21	17	07:24	08:07	00:00	00:43	00:43	4,2
10.06.2011		22		09:23		19:48[7]	21:48	02:00	4,0
11.06.2011	Saturday		18		19:11				
16.06.2011	Thursday		19	07:00	17:13	10:13[8]	00:00	00:00	0,0
16.06.2011		23		17:13		09:21[9]	12:13	02:52	3,6
17.06.2011	Friday		20		16:26				

Table A.1: Recorded data from project BV Recklinghausen V.8

Date	Week-day	Number of pipe	Number of day	Jacking time		Disturbance time [h]	TFJP with disturbance [h]	TFJP without disturbance [h]	Jacking length [m]
				Start	End				
17.06.2011		24		17:19		05:42[10]	06:59	01:17	4,2
18.06.2011	Saturday		21		12:18				
18.06.2011		25		14:59	17:07	00:00	02:08	02:08	4,0
20.06.2011	Monday		22	07:00	12:09	05:09[11]	00:00	00:00	0,0
20.06.2011		26		12:09	14:41	00:00	02:32	02:32	4,0
20.06.2011		27		16:52	18:53	00:00	02:01	02:01	4,0
20.06.2011		28		20:03	21:57	00:00	01:54	01:54	4,0
21.06.2011	Tuesday	29	23	09:22	14:57	03:31[12]	05:35	02:04	4,0
21.06.2011		30		16:43		07:51[13]	09:42	01:33	4,2
22.06.2011	Wednesday		24		13:53				
22.06.2011		31		15:04	17:08	00:00	02:04	02:04	4,0
22.06.2011		32		19:04	19:37	00:00	00:33	00:33	0,8

Legend:

- TFJP: Time For Jacking Processes
- Time^{n} : Number of disturbances

A.2 Site 2: BV Recklinghausen V.5.1

Table A.2: Recorded data from project BV Recklinghausen V.5.1

Date	Week-day	Number of pipe	Number of day	Jacking time		Disturbance time [h]	TFJP with disturbance [h]	TFJP without disturbance [h]	Jacking length [m]
				Start	End				
29.11.2010	Monday	0	1	11:47	18:21	00:00	06:34	06:34	2,0
30.11.2010	Tuesday	0	2	00:00	00:00	11:00[1]	00:00	00:00	0,0
01.12.2010	Wednesday	0	3	00:00	00:00	11:00[1]	00:00	00:00	0,0
02.12.2010	Thursday	0	4	00:00	00:00	11:00[1]	00:00	00:00	0,0
03.12.2010	Friday	0	5	00:00	00:00	11:00[1]	00:00	00:00	0,0
06.12.2010		0		10:29	11:35	00:00	01:06	01:06	2,0
06.12.2010	Monday	1	6	14:42	16:27	00:00	01:45	01:45	3,5
06.12.2010		2		17:12	18:20	00:00	01:08	01:08	3,5
07.12.2010		3		09:10	10:13	00:00	01:03	01:03	3,5
07.12.2010	Tuesday	4	7	12:02	14:11	01:12[2]	02:09	00:57	3,5
07.12.2010		5		15:22	17:50	01:19[3]	02:28	01:09	3,5
08.12.2010	Wednesday	6	8	07:50	09:52	00:56[4]	02:02	01:06	3,5
08.12.2010		7		11:03					
09.12.2010		8			12:01	10:24[5]	12:58	02:34	3,5
09.12.2010	Thursday	9	9	13:57	16:10	00:00	02:13	02:13	3,5
09.12.2010		10		16:45					
13.12.2010		11			10:22	03:31[6]	05:37	02:06	3,5

Table A.2: Recorded data from project BV Recklinghausen V.5.1

Date	Week-day	Number of pipe	Number of day	Jacking time		Disturbance time [h]	TFJP with disturbance [h]	TFJP without disturbance [h]	Jacking length [m]
				Start	End				
13.12.2010	Monday	12	10	11:50	14:35	00:00	02:45	02:45	3,5
13.12.2010		13		15:15	17:42	00:00	02:27	02:27	3,5
14.12.2010	Tuesday	14	11	08:09	10:03	00:00	01:54	01:54	3,5
14.12.2010		15		11:37	13:36	00:00	01:59	01:59	3,5
14.12.2010		16		14:28	16:17	00:00	01:49	01:49	3,5
14.12.2010		17		17:07	18:30	00:00	01:23	01:23	3,5
15.12.2010	Wednesday	18	12	08:27	09:55	00:00	01:28	01:28	3,5
15.12.2010		19		13:50	15:05	00:00	01:15	01:15	3,5
15.12.2010		20		16:23	17:28	00:00	01:05	01:05	3,5
16.12.2010	Thursday	21	13	09:36	10:29	00:00	00:53	00:53	3,5
16.12.2010		22		11:10	11:32	00:00	00:22	00:22	1,8

Legend:

- TFJP: Time For Jacking Processes
- Time^n : Number of disturbances

A.3 Site 3: BV Recklinghausen V.15

Table A.3: Recorded data from project BV Recklinghausen V.15

Date	Week-day	Number of pipe	Number of day	Jacking time		Disturbance time [h]	TFJP with disturbance [h]	TFJP without disturbance [h]	Jacking length [m]
				Start	End				
18.06.2012	Monday	0	1	14:30	17:42	00:00	03:12	03:12	2,20
19.06.2012	Tuesday	0	2	08:25	14:01	00:00	05:36	05:36	3,60
19.06.2012		1		16:01		00:00	00:00	00:00	
20.06.2012	Wednesday		3		11:53	02:16[1]	07:52	05:36	4,02
20.06.2012		2		12:50	17:18	00:00	04:28	04:28	4,02
21.06.2012	Thursday	3	4	08:36	13:06	00:00	04:30	04:30	4,02
21.06.2012		4		14:00		00:00	00:00	00:00	
22.06.2012	Friday		5		08:28	01:45[2]	06:28	04:43	4,02
22.06.2012		5		10:03		00:00	00:00	00:00	
25.06.2012	Monday		6		09:21	07:24[3]	11:18	03:54	4,02
25.06.2012		6		10:06	15:03	00:00	04:57	04:57	4,02
25.06.2012		7		15:43		00:00	00:00	00:00	
26.06.2012	Tuesday		7		09:55	01:41[4]	06:12	04:31	4,02
26.06.2012		8		11:08	17:05	01:21[5]	05:57	04:36	4,02
27.06.2012	Wednesday	9	8	07:29	12:14	00:28[6]	04:45	04:17	4,02
27.06.2012		10		13:12		00:00	00:00	00:00	
28.06.2012	Thursday	10	9		09:43	04:01[7]	08:31	04:30	4,02

Table A.3: Recorded data from project BV Recklinghausen V.15

Date	Week-day	Number of pipe	Number of day	Jacking time		Disturbance time [h]	TFJP with disturbance [h]	TFJP without disturbance [h]	Jacking length [m]
				Start	End				
28.06.2012		11		11:09	16:37	01:12[8]	05:28	04:16	4,02
29.06.2012	Friday	12	10	07:38	09:35	00:00	01:57	01:57	4,02
29.06.2012		13		10:20		04:07[9]	00:00	00:00	
02.07.2012	Monday		11		08:41	03:56[10]	10:21	02:18	4,02
02.07.2012		14		09:49	11:59	00:00	02:10	02:10	4,02
02.07.2012		15		13:28	15:21	00:00	01:53	01:53	4,02
02.07.2012		16		16:15	17:57	00:00	01:42	01:42	4,02
03.07.2012	Tuesday	17	12	08:02	10:06	00:00	02:04	02:04	4,02
03.07.2012		18		11:00	12:23	00:00	01:23	01:23	4,02
03.07.2012		18		12:58	16:12	01:04[11]	03:14	02:10	4,02
04.07.2012	Wednesday	19	13	10:10	14:06	02:30[12]	03:56	01:26	4,02

Legend:

- TFJP: Time For Jacking Processes
- Time^n : Number of disturbances

Appendix B

Output Crew Quota (OCQ)

Table B.1: Summary of OCQ value in the job-site BV Recklinghausen V.8

Activity	Number of laborers	Duration (min)	OCQ value
Disconnect cables	1	174	0.3
	2	65	0.8
	3	52	1
	4	47	1.1
	5	45	1.15
Diconnect cables	1	63	0.3
	2	24	0.8
	3	19	1
	4	17	1.1
	5	16	1.15

Appendix C

Site layout

The device site layout is considered a critical factor defining simulation module, due to the fact that it reflects the resource cycle patterns of the project. Project site layout should provide adequate space for the microtunnelling operation, ease of material delivery, and the equipment arranged reasonably to minimize any waste of time of the resources cycle. In order to generalize the site layout for the simulation module, the common site layout of microtunnelling project is slightly modified based on the site layout observed in the job-site. Figure C.1 shows the common site layout of the project.

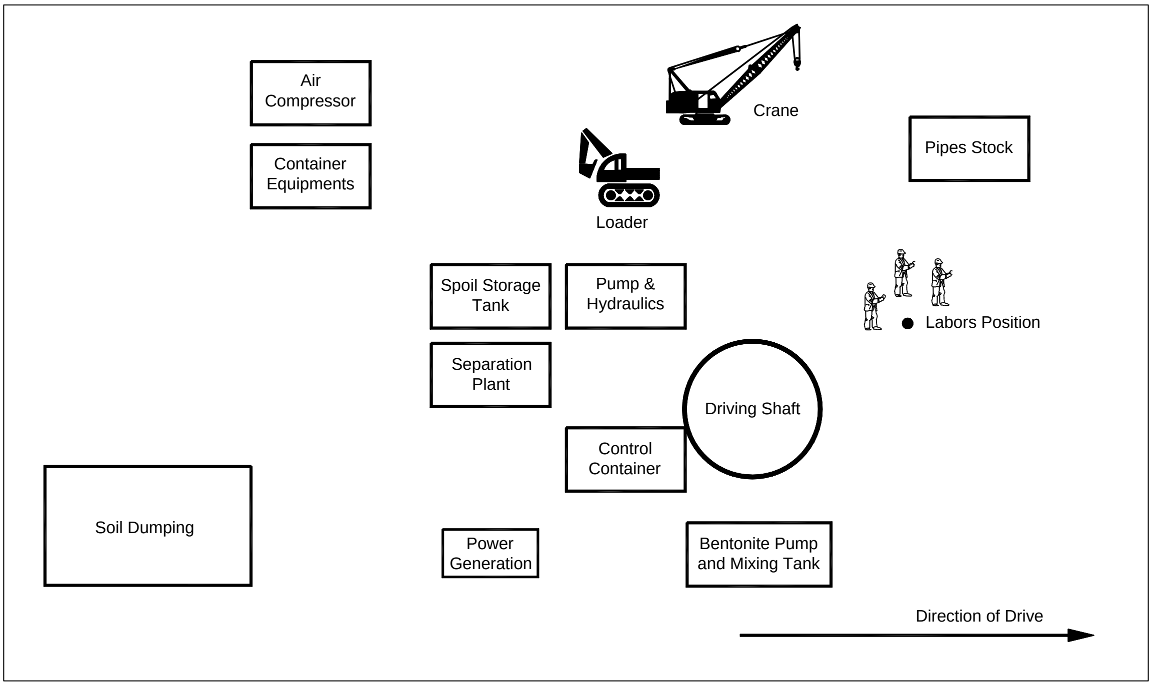

Figure C.1: Common site layout of microtunnelling project

Appendix D

Velocity of the devices and resources

The devices used in the different construction site are not the same. Therefore, the velocity of the devices in the job-site is different as well. Table D.1 shows the common velocity of the devices and resources used in the tunnel construction with MTBM.

Table D.1: Summary of common velocity of the devices and resources used in the construction site (French Society for Trenchless Technology, 2004)

Type of equipment	Velocity (km/h)	Sources
Laborer	4.3	Waldock (2011)
Truck mounted crane	9.5	Shanghai Yingji Crane Co., Ltd (2013b)
Crawler crane	0.8 to 2.4	Shanghai Yingji Crane Co., Ltd (2013a)
Wheel loaders	7 to 20	Komatsu Ltd. (2013)
Backhoe loaders	7 to 40	Volvo (2013)

Appendix E

Glossary

Mean time to repair (MTTR): is a basic measure of the maintainability of repairable items. It represents the average time required to repair a failed component or device

Mean time between failures (MTBF): is the predicted elapsed time between inherent failures of a system during operation

Mean time to repair (MTTR): is a basic measure of the maintainability of repairable items

Mean cycles between failure (MCBF): is the average number of equipment cycles between failures; total equipment cycles divided by the number of failures during those cycles.

Breakdown: A breaking down, wearing out, or sudden loss of ability to function efficiently, as of a machine.

Cutter head: A rotating tool or system of tools that excavates at the face of the microtunnelling bore (International Society of Trenchless Technology (ISTT), 1999).

Cutter shape: The actual teeth and supporting structure that is attached to the front face of the microtunnelling machine. It is used to reduce the material that is being drilled or bored to sand or loose dirt so that it can be conveyed out of the hole (International Society of Trenchless Technology (ISTT), 1999).

Disturbance: unexpected occurrences causing an interruption or at least a delay in the execution of tasks; they cause a significant discrepancy between the target and actual data (REFA, 1991).

Jacking force: Force applied to pipes in a pipe jacking operation (International Society of Trenchless Technology (ISTT), 1999).

Idle time: The period for which an operator or worker are available for production but is prevented from working by shortage of material or tooling, or by machine breakdown. Also called down time, delay time or standstill.

Jetting (water jet): A process using high pressure water to wash out the face of a utility crossing without any mechanical or hand excavation of the soils in the face. This process can be used to loosen hard soils in front face of the microtunnelling machine (International Society of Trenchless Technology (ISTT), 1999).

Obstruction: Any object or feature that lies completely or partially within the cross section of the microtunnel and prevents continued forward progress (International Society of Trenchless Technology (ISTT), 1999).

Slurry: A fluid, normally water, used in a closed loop system for the removal of spoil and for the balance of groundwater pressure during microtunnelling (International Society of Trenchless Technology (ISTT), 1999).

Separation plant: A plant that has a set of equipment, where excavated material is separated from the circulation slurry (International Society of Trenchless Technology (ISTT), 1999).

Torque: The rotary force available at the drive chuck (International Society of Trenchless Technology (ISTT), 1999).

Lubrication: injection of lubricants around the pipeline during tunneling (International Society of Trenchless Technology (ISTT), 1999)

Waiting time: The time that a worker or equipment are idle when no work is available. This time is acceptance in the tunnel construction with MTBM. Also called allowed time.

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