DISCRETE EVENT SIMULATION OF A SHEARER PERFORMANCE FOR A LONGWALL OPERATION

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ABSTRACT

DISCRETE EVENT SIMULATION OF A SHEARER PERFORMANCE FOR A LONGWALL OPERATION

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Coal is an essential part of energy generation worldwide and has a major role in sustainable development. The amount of coal that can be extracted by surface mining is getting less which makes efficient underground mining operations crucial for both local and global economy. Underground coal mining is considered as a risky industry with a requirement of high amount of equipment investment. The majority of the investment in underground coal mines is generally related with the capital cost of initial equipment expenses. Therefore, equipment investment in underground coal mines can be considered as a decision making process that is not repeated frequently. This situation makes the selection of the mining equipment is an important decision and so, it is one of the most critical engineering judgement practices in underground coal mining activities. In addition to this, engineering judgement processes in mining are not restricted with the selection of the mining equipment. The majority of the operational decisions starts after the establishment of the mining system. One of the main engineering goals in an established system is increasing the efficiency by minor or major changes in the system. For this, effect of each factor on the system performance should be investigated.

The objective of this study is to examine the shearer performance for a longwall mine by discrete event simulation that includes modelling of the double-drum shearer, belt conveyors, stage loader, and armoured face conveyor (AFC) and as a result, to determine the most influential factor on production in the mining operations. In the study, the model is developed for the longwall top coal caving method (LTCC) having bi-directional cutting system. The underground mining system is modelled in Underground Coal Talpac® Software, and Arena® Simulation Software. The model is verified and validated by real operational data collected from an underground longwall coal mining operation in Turkey. 20 different scenarios were assessed in the model and duration of the shearer delay was the most influential factor in the system. Findings from the model revealed that daily coal production on the longwall face is 726.73 t/day and shearer utilization is 89.07 min/day in average. In addition, the model showed that when duration of the shearer delays is decreased to 80% of the actual situation, daily coal production on the longwall face, and shearer utilization could increase as much as 162.03 t/day and 19.58 min/day, respectively.

Keywords: Underground Longwall Mining, Discrete Event Simulation, Double-Drum Shearer, Underground Coal Talpac® Software, Arena® Simulation Software

ÖZ

UZUNAYAK ÜRETİM SİSTEMİNE SAHİP BİR YERALTI MADENİ İÇİN AYRIK OLAY SİMÜLASYONU İLE KESİCİ PERFORMANSININ İNCELENMESİ

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Kömür, dünya çapında enerji üretiminin önemli bir parçasıdır ve sürdürülebilir kalkınmada önemli bir role sahiptir. Açık ocak yöntemi ile elde edilebilecek kömür miktarı giderek azalmaktadır ve bu da hem yerel hem de küresel ekonomi için verimli yeraltı madencilik operasyonlarını önemli kılmaktadır. Yeraltı kömür madenciliği, yüksek miktarda ekipman yatırımı gerektiren riskli bir endüstri olarak değerlendirilmektedir. Yeraltı kömür madenlerine yapılan yatırımın büyük bir kısmı genel olarak ilk ekipman harcamalarının sermaye maliyeti ile ilgilidir. Bu nedenle yeraltı kömür madenlerine yapılan ekipman yatırımı, sık sık tekrarlanmayan bir karar verme süreci olarak düşünülebilir. Bu durum maden ekipmanının seçimini önemli bir karar haline getirmektedir ve bu yeraltı kömür madenciliği faaliyetlerinde en kritik mühendislik uygulamalarından biridir. Fakat, madencilikte mühendislik uygulamaları maden ekipmanının seçimi ile sınırlı değildir. Operasyonel kararların çoğunluğu madendeki sistemin kurulmasından sonra başlar. Kurulmuş bir sistemdeki ana mühendislik hedeflerinden biri, sistem içerisinde küçük veya büyük değişiklikler yaparak sistemin verimliliğini arttırmaktadır. Bunun için system içerisindeki her bir faktörün sistem performansı üzerindeki etkisi araştırılmalıdır.

Bu çalışmanın amacı, tam mekanize uzunayak kömür üretim yöntemine sahip olan bir madende, kesici performansını çift tamburlu kesici, bantlı konveyör, ara yükleyici ve zincirli konveyörün modellenmesini kapsayan ayrık olay simülasyonu ile inceleyerek operasyonel düzeyde üretim üzerindeki en etkili faktörü belirlemektir. Bu çalışmadaki model, çift yönlü kesim sistemine sahip tavan kömürü göçertmeli uzunayak kömür üretim yöntemi (LTCC) için geliştirilmiştir. Yeraltı madeninde uygulanan üretim yöntemi, Underground Talpac® ve Arena® Simülasyon programlarında modellenmiştir. Model, Türkiye'de uzunayak üretim yöntemine sahip bir yeraltı kömür madeni işletmesinden toplanan gerçek operasyonel verilerle doğrulanmış ve onaylanmıştır. Modelde 20 farklı senaryo değerlendirilmiş ve sistem performansı üzerine en etkili faktör, kesicinin gecikme süresi olmuştur. Modelden elde edilen bulgular, bir arındaki ortalama üretiminin 726.73 t/gün ve kesicinin kullanım süresinin ortalama 89.07 dk/gün olduğunu ortaya çıkarmıştır. Buna ek olarak model, kesicinin gecikme süresinin fiili durumun %80'ine düşmesi durumunda, bir arındaki ortalama üretimin 162.03 t/gün ve kesicinin kullanım süresinin 19.58 dk/gün artırılabileceğini ortaya koymuştur.

Anahtar Kelimeler: Yeraltı Uzunayak Kömür Madenciliği, Ayrık Olay Simülasyonu, Çift Tamburlu Kesici, Underground Coal Talpac® Programı, Arena® Simülasyon Programı

To My Beloved Family and Friends

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LIST OF SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS	DESCRIPTION
UCTEA	The Union of Chambers of Turkish Engineers and Architects
APCOM	Application of Computer and Operations Research in the Mineral Industry
IT	Information technology
SSE	Sum of square errors
H_0	Null hypothesis
CI	Confidence Interval
RN	Replication Number
T	Thickness of the seam
TNFES/C	Time needed for enough space on the conveyor
TNFC1ES/C	Time needed for creating one entity space on the conveyor
PTCE	Production time of the current entity
ETCE/C	Entry time of the current entity to conveyor
ETPE/C	Entry time of the previous entity to the conveyor
TBA	Time between arrivals
DT	Delay time
ST/C	Spent time on the conveyor
FC	Face coal
TC	Top coal
AFC	Armoured face conveyor
RC	Rear conveyor
BSL	Beam stage loader
LTCC	Longwall top coal caving

UNITS	DESCRIPTION
t	Tonne
m	Meter
m^2	Meter square
m^3	Meter cube
tph	Tonne per hour
t/m^3	Tonne per meter cube
sec	Second
min	Minute
mm:ss	Time format related to minute, and second
hrs	Hours
m/sec	Meter per second
m/min	Meter per minute
m^3/sec	Meter cube per second
kcal/kg	Kilocalorie per kilogram
SEK/t	Swedish krona per tonne
t/shift	Tonne per shift
kW	Kilowatt
TWH	Terawatt hour

CHAPTER 1

INTRODUCTION

Energy is a main requirement of human beings and a major part of their daily lives. In the World and Turkey, coal is used mainly for energy production. According to the World Energy Council (2016), coal consumption increased by 64% between the years 2000 and 2014. Currently, 7,700 Mt of coal are consumed in the world and 40% of the world's electricity is generated from coal. This situation is supported by using coal as a primary energy source in many countries. In Figure 1.1, it is shown that coal has been the second primary energy source worldwide since 2005.

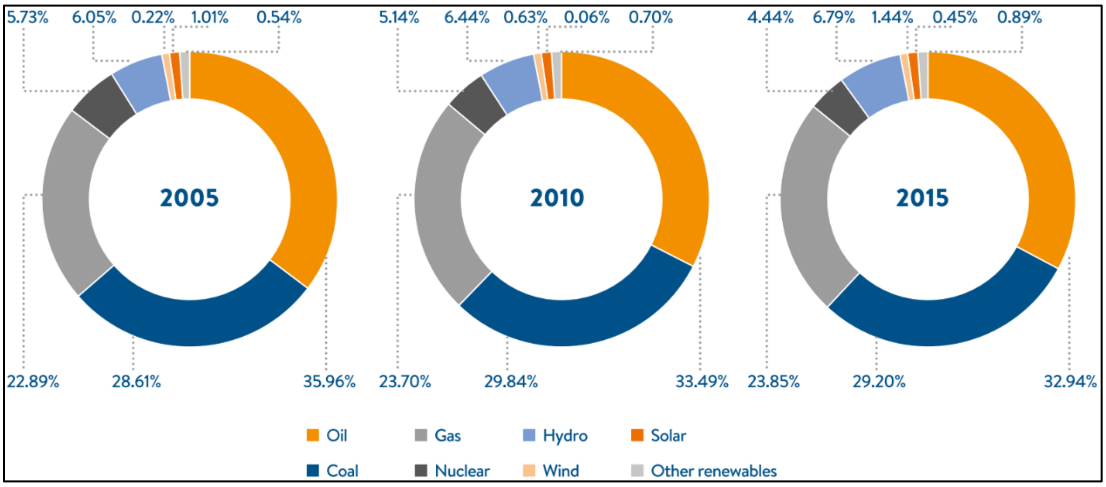

Figure 1.1 Comparison of primary energy consumption between 2005 and 2015 (World Energy Council, 2016)

In Turkey, coal was the primary energy source in 2016. Total energy production of Turkey was 274.4 TWH and energy production from coal was 89.3 TWH in 2016. Energy production in Turkey according to energy resources in 2016 is given in Figure 1.2.

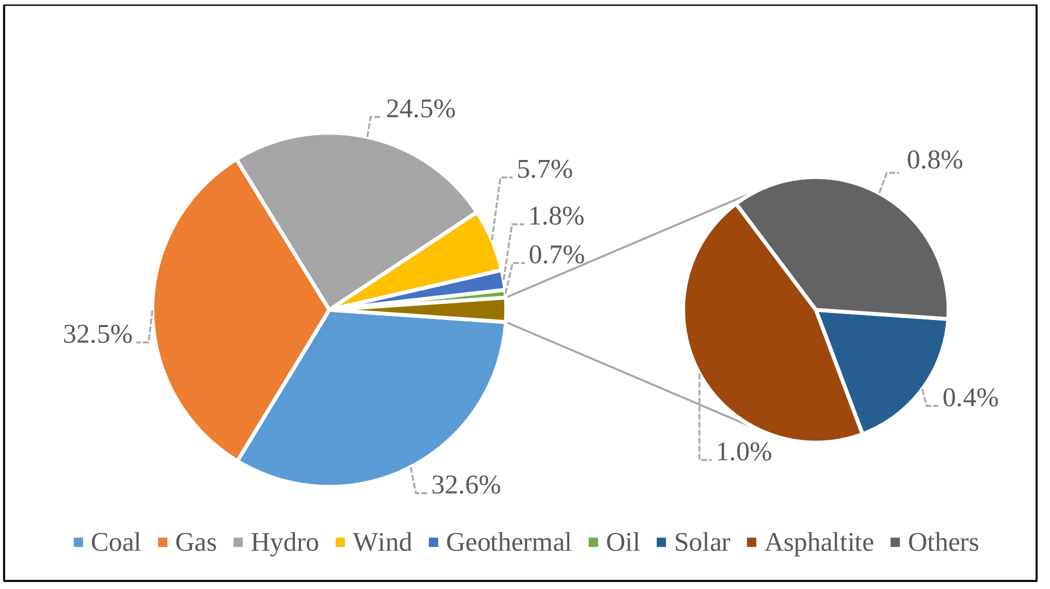

Figure 1.2 Energy production in 2016, Turkey (UCTEA, 2017)

According to the World Energy Council (2016), coal-based energy production in 2014 was 74 TWH in Turkey (Appendix A.1) and it was increased from 74 TWH to 89.3 TWH at the end of 2016. In fact, energy production from coal has increased continuously over the years in Turkey. Similarly, the World Energy Council (2016) predicts that coal will sustain its strategic importance in the next three decades. Therefore, coal mining activities will always be in the heart of the mining activities as coal maintains its significant share in primary energy production.

Coal has to be extracted from the Earth's crust in surface mining or underground mining operations for primary energy production from coal. Coal mining is performed by numerous private companies and governmental institutions worldwide. The selection of the mining method to extract coal depends on economic evaluations. Although surface mining can be considered as economically feasible for some coal deposits at present, the amount of overburden material to be removed, also related to the definition of stripping ratio, will continuously increase as the production continues. The inevitable increase in the energy requirement of humankind together with the exploitation of shallow coal deposits leads the mining industry towards underground mining activities.

As it is the case in other industrial activities, mining also concentrated on production that has the highest economical outcome with the lowest cost by extracting high-grade deposits. In fact, during this era, efficiency was of secondary importance in production planning. Most of the high-grade resources extracted, the global trend in mining, especially in developing countries, started to extract the remaining parts of their lower grade resources. Production costs related to the mining of low-grade resources is comparably higher which in turn emphasized the importance of production efficiency. This is due to the objective of decreasing the cost of production or increasing the production amount with same expenses to increase the profit. Thus, efficiency in the mining industry gained importance and in today's world, corporate mining companies consider as efficiency as a priority and they invest in research and development to continuously improve their systems. Concordantly, mining engineers started to focus on not only increasing the production rate but also considering efficiency of the system and one of the main objectives became to achieve a better system efficiency. In today's and future's world, increasing the system efficiency in mining activities will be one of the most important aspects of the industry.

1.1 Problem Statement

Mining activities are generally considered as complex processes that cover multiple aspects of different engineering aspects. Therefore, a single event in a mining operation can affect the entire system. As the efficiency increases in the mining operations, the effect of this event on the entire system might decrease. Therefore, system efficiency has always been an important issue in mining activities. In the past, when the utilization of computers was not common, analysis of the efficiency of mining activities was performed by using conventional methods. These analyses could not thoroughly examine the situation due to two reasons. The first reason is related to time spent in the analysis process. Duration of analysis varied depending on the scope of the analysis and it might take several days, weeks or even months. The second reason is related to the results of the conventional methods. The representation of production cases as close to reality as possible, may be biased by the limited information that can be gained. Conventional methods generally use deterministic methods. However, as in other systems, most mining systems consist of stochastic processes that incorporate uncertainties. These uncertainties cause different results of the system to occur despite the same operational conditions. Therefore, operational problems, and decision-making processes in mining activities should be handled by conducting simulation studies.

The underground mine simulated in this study is a longwall top coal caving system with retreat type mining direction. The effect of different operational factors on daily shearer production that occur in longwall coal mining has not been examined in detail by utilizing simulation in a flexible environment. For a better understanding of the operational efficiency in the underground mine, the shearer operations should be examined in detail.

1.2 Objectives and Scope of the Study

Main objective of this study is to investigate the effect of different operational factors, which are time between arrivals of the shearer delays, duration of the shearer delays, turnaround time of the shearer, cutting speed of the shearer, and flit speed of the shearer, on daily shearer production of the mine and determine the most influential factor on coal production for improving the decision making process in mine management. The expanded aim of this study is to contribute to the LTCC literature.

For achieving these objectives,

- real operational data were collected and analysed,
- simulation model in Underground Coal Talpac® were constructed,
- simulation model in Arena® were constructed, and
- alternatives mentioned above were compared via simulation model.

According to the literature reviewed, simulation studies implemented in the mining industry focused on underground coal mining activities, especially material handling processes. These processes are generally investigated for cases using different equipment types. For a better understanding of the system behaviour, production, and transportation system have to be examined together. In this thesis study, a model is developed for underground coal mines that covers not only the transportation system of an underground coal mine but also the cutting system of the shearer at the coal face.

This thesis study investigates the daily shearer production of an underground longwall top coal caving mine under different operational conditions. Following conditions are not covered in this thesis study.

- Cavability properties of lignite in LTCC method are not covered in this thesis study. Top coal production were modelled according to the data collected from the mine during site visits.
- Cost analyses (e.g. production cost analysis) are not covered in this thesis study.
- Causes of downtime related to the shearer are not covered in this thesis study. All downtime events were evaluated as shearer maintenance irrespective of their causes.

1.3 Research Methodology

Research methodology in this thesis study is composed of two parts, which are data collection and simulation study. In data collection part, an underground longwall mining operation in Soma region was visited between July 07, 2018 and July 13, 2018. During the mine site visit,

- 231 data points for time between arrivals of the shearer delays,
- 231 data points for duration of the shearer delays,
- 119 data points for turnaround time of the shearer delays,
- 484 data points for cutting speed of the shearer, and
- 1,082 data points for flit speed of the shearer

were recorded manually. All the data were analysed and used in the second part, which is the simulation study. Steps followed in the simulation study part are listed below.

- Specifying the mining problem.
- Building the concept of the algorithms.
- Construction of the algorithms in Underground Coal Talpac® Software.
- Construction of the algorithms in Arena® Software.
- Testing the algorithms whether the model works properly or not.
- Combining analysed data and the simulation model.
- Verification and validation processes for calibration of the developed model.
- Testing alternatives.
- Reporting.

1.4 Thesis Structure

This thesis is composed of five main chapters.

- In Chapter 1, general explanation of the thesis study, a brief introduction to simulation concept, and importance of the simulation studies are described.
- In Chapter 2, a literature review associated with simulation background, historical development of the simulation studies in the mining industry, statistical data analysis, and underground longwall top coal caving method is presented.
- In Chapter 3, general overview on the case study including geological structure of the mining area, data collection, modelling algorithms, and construction of the simulation models are explained.
- In Chapter 4, results of statistical data analysis and simulation models, assumptions and limitations of the model, verification and validation processes, and discussion about results of the simulation models are described.
- In Chapter 5, conclusions, and recommendations about future simulation researches are presented.

CHAPTER 2

LITERATURE REVIEW

Simulation has been a powerful tool for the test and evaluation of different alternatives in different branches of industry. This literature review is an overview on general information about simulation, previous studies on simulation applications in mining industry, statistical data analysis, and longwall mining methods used for extraction of coal.

2.1 Simulation Background

Simulation is the imitation of a real system in a virtual world without making any changes in the real-world system (Banks et al., 2004). It enables the analysts to see the results of possible changes in the system. For a better understanding of the simulation concept, general structure of the system should be comprehended as a first step. Systems are composed of system components, system boundaries, and environments. In this structure, an input enters the system. After that, it is processed in a logic and output is formed. The conceptualization of the system is given in Figure 2.1.

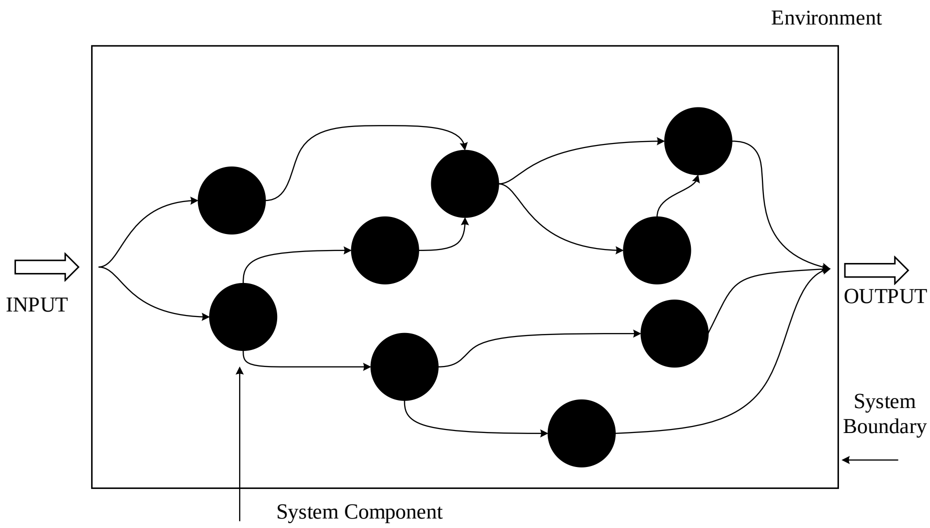

Figure 2.1 System conceptualization (Rossetti, 2016)

Success of the simulation outputs depends on how accurate the simulation model represents the real-life system. Therefore, as much as developing a simulation model, collection of data, validation, and verification of the system play an important role in a simulation study. On the other hand, there are many simulation model types, which can be developed according to system properties. These types are as follows:

- deterministic or stochastic,
- dynamic or static, and
- continuous or discrete.

In deterministic models, initial conditions are identified and the result is obtained by solving equations (Runciman, 1997). In other words, unlike stochastic simulations, deterministic simulations do not contain random variables. This means that the number of runs the analyst completes in a deterministic model is not important. In every run, the outputs are the same and exact in deterministic simulations. In stochastic models, at least one input contains random variables. Random variables lead to changing the result of the simulation model in every run. Therefore, the number of runs plays an important role in stochastic models.

In static models, time is commonly not considered with a real world meaning. Static models are commonly used in forming statistical outcome by generating random samples. One of the well known examples to static simulation is the Monte Carlo simulation, commonly used in problems defined for financial analysis. On the contrary to static models, time is an important parameter for dynamic models. Models evolve in time in dynamic models. Therefore, dynamic models are best suited for analysing production and service systems.

In continuous models, as it is understood from its name, variables of the modelled system change continuously by time. In continuous systems, rate of change is important and differential equations are used to define rate of change. For example, flowing systems like pipes and tanks are suitable for continuous simulations (Banks et al., 2004). In discrete models, change in a system occurs in discrete points of time.

Typical example to the discrete system is defined as a restaurant while investigating variables of customer numbers. Total number of customers in a restaurant changes at certain time intervals. Therefore, when the number of customers in a restaurant is analysed, restaurant systems are investigated as discrete systems. On the other hand, discrete simulations can be used to estimate continuous systems in some cases (Arsham, 1995).

Common types of systems and their relationships are given in Figure 2.2.

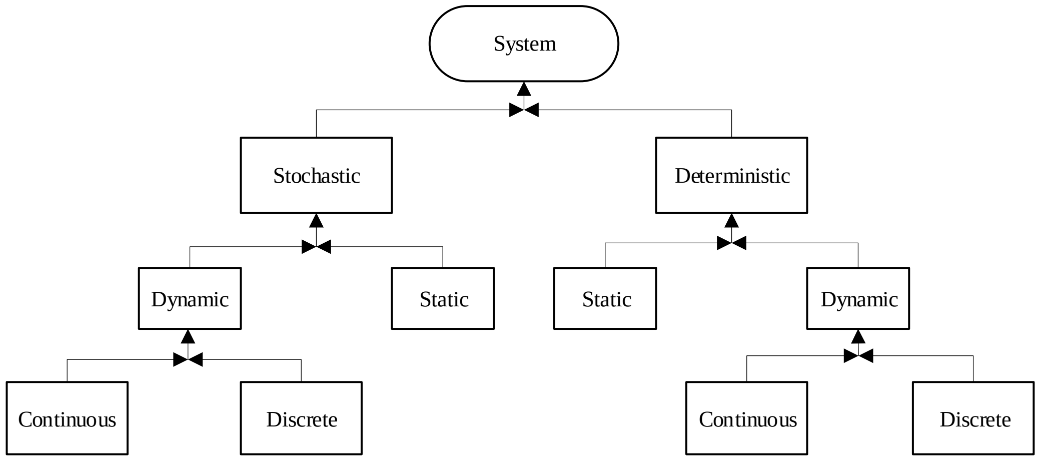

Figure 2.2 Common system types and their relationships (Rossetti, 2016)

In this study, the system has stochastic, dynamic, and discrete processes. Therefore, discrete event simulation technique is used in the study.

2.1.1 Basic Concepts in Discrete Event Simulation

Before beginning the simulation study, basic terminologies and their concepts should be comprehended. The most important definitions are systems, system states, entities, resources, attributes, variables events, event lists, activities, delays, and simulation clock (Banks et al., 2004).

- ❖ System is the collection of entities, machines that interact with each other in a logic.

- System state is the condition of the system and it is described by information from collection of variables.
- Entity is an observed component of the system. Entity can be a permanent component that remains in the system like cycling systems or it can be a temporary component that flows through the system, and then leaves the system.
- Resource is a part of the system that entities utilize. One of the examples to the entity-resource relation is the material handling process. If the material on the belt conveyor can be called "entity", the belt conveyor can be called a type of "resource".
- Attribute is a type of data that the entity stores. Attributes are not global. They are only entity-related properties.
- Variable is a type of data that describes the system. Variables can also be defined as "global variables". Any entity in the system can change property of the variables and as a result property of the system.
- Event is the incident that changes the system state such as, entering of an entity to the system.
- Event list, also known as future event list (FEL), controls the events sequence order in the simulation.
- Activity is the time duration of events with a specified length such as, service time of a resource. Activity can be defined by either statistical distributions or a constant value.
- Delay time is also defined as time duration. Delays can depend on a condition. In this type of delay, entity waits until the condition occurs. Therefore, delays can have an indefinite time duration.
- Simulation clock is a variable in the software that controls the simulation time. It can be arranged according to real time.

2.1.2 Simulation History and Applications in Mining Activities

Simulation studies in the mining industry began with the introduction of computers in the industry. Various researchers studied different fields of mining activities by using simulation. In this chapter, significant developments in the simulation history in different branches of mining activities will be summarized.

In 1950s, simulation was introduced in mining activities due to the development of cyclic queues, which was one of the significant improvements in simulation history. Cyclic queue models deal with queuing problems for cyclical systems whose elements always remain in the system instead of leaving the system, as it is common in the mining industry. The first example of the cyclic queue was introduced by Koenigsberg in 1958 who validated his outputs in many underground coal mines located in Illinois, USA (Sturgul, 2015).

In 1960s, the simulation studies advanced and became more common in the evaluation of mining activities. The first and the most significant example of simulation studies in the mining industry was realized by Rist (1961). The aim of the study was to obtain the optimal truck number of a haulage system in an underground molybdenum mine owned by Climax Molybdenum Company. After the study of Rist (1961), Falkie and Mitchell (1963) conducted research on a colliery in Pennsylvania. The researchers concentrated on the underground rail haulage of the mine. This study was the first example of an approach based on the stochastic process of the Monte Carlo method (Sturgul, 2015). At the year 1964, GPSS (General Purpose Simulation System) language was used to simulate the Climax Molybdenum Company's mine by Harvey (1964), which was studied by Rist (1961) before. In the study, 44,000 hours of the production was simulated and simulation results were within 1.5% of actual production. In the same year, Madge (1964) conducted research on the movement of trucks in an open pit mine. This study was an important improvement in the mining history as it was the first simulation example of "dispatching" systems. In 1965, Sanford (1965) modelled conveyor belt systems. Verification of the model was achieved at the significance level of 5% (Raj et al., 2009). In 1967, O'Neil and Manula (1967) approached movement of trucks in an open pit with "Monte Carlo Simulation Technique" and "Clock Advance Technique". This study was the first research on computer simulation for an open pit mine. In 1968, Morgan and Peterson (1968) concentrated on establishing the stochastic sense in surface mining activities. The aim of these researchers was to predict production under known entries including loading, hauling, and dumping time of the trucks. Then, the simulation model developed by Morgan and Peterson was used to estimate the number of trucks at the optimal value of production amount per unit cost. In 1969, Cross and Williamson (1969) compared dispatch systems with non-dispatch systems for an open pit mine located in the USA. The developed model was one of the best examples in the early stage of mining simulation history. In the study, all the time variables were deterministic and thousands of lines of code was developed. Results of the study showed that production could be increased by 1250 t/shift when a dispatch system was used. Suboleski and Lucas (1969) simulated the room-and-pillar mining method by using a software called SIMULATOR1 developed in FORTRAN language. This software model was used by different mining companies during the 1970s.

In 1970s, simulation studies were pervaded in academic researches. In 1970, Venkataramani and Manula (1970) conducted a research on developing a software including stochastic processes. Results of the model were promising for bucket wheel excavator (BWE) activity. In 1972, Touwen and Joughin (1972) studied the production operations such as, supporting and rock breaking in a stope of gold mining activity by using more than 150 parameters. The researchers also modelled the movements of all rail vehicles in their study. In 1974, Chatterjee et al. (1974) modelled sublevel caving methods applied in metal mines. Manula and Richard (1974) developed a software for surface mining transportation systems, which involves the combination of bucket wheel excavators, trucks, trains, and conveyor belts. At the same year, Lee (1974) studied the optimum stockpile size by using Monte Carlo Simulation technique. This study was the first example on application of inventory theory to a mining operation. Hatherly and Ruffles (1974) simulated mining operations including extraction of ores, haulage, crushing, and hoisting stages for an underground copper mine. In the years 1974 and 1975, Hanson and Selim (1974, 1975) conducted a research comparing room-and-pillar mining method and longwall mining method by an event-based model. In 1976, Ryder (1976) developed a model via TRANSIM II for the transportation activities of underground mines by trains. The model had stochastic variables such as, delay time, fluctuations in loading and unloading time. In 1977, Barnes et al. (1977) studied probability techniques for analysing open pit production systems as an implementation of a queue system in the mining industry. Naplatanov et al. (1977) conducted research on a truck dispatching system for Medet copper mine, which is located at Pazardzhik Province, Bulgaria, by increasing productivity under the circumstances of the required ore quality condition. Talbot (1977) simulated belt systems of underground mining activities by using a FORTRAN software, BELTSIM, which was developed at Virginia Polytechnic Institute in 1968. In 1979, Beckett et al. (1979) developed a software, LHDSIM, for analysing and simulating transportation systems of underground coal mining operated by room-and-pillar mining method. Meyer (1979) integrated optimization of short-term scheduling of an open pit mine with a linear programming dispatching algorithm.

In 1980s, simulation studies continued to be commonly utilized in research conducted on mining operations. In 1982, Marshall and Kim (1982) conducted a research on developing a model for material handling operations in an open pit mine. The developed model was composed of two software packages, which were CYCLE and PITSIM. CYCLE was used for the haulage cycle and PITSIM was used for analysing the truck and shovel interaction. In 1984, Hancock and Lyons (1984) developed models for the simulation of underground transportation systems. SIMBELT 2, which was one of the most important models developed by Hancock and Lyons (1984), was used to model and simulate sections and operations in underground mining systems including production at the face, belt conveyor activities, drifts, shafts, and bunkers. Haycocks et al. (1984) developed a programme (FRAPS) for continuous mining and also for conventional mining operations such as, drilling, blasting, supporting, and loading according to ground control conditions and data obtained from geostatistical analysis. Macaulay and Notley (1984) developed a programme (UHSP) for underground transportation systems. Importance of this study was that the system was considered as a composition of the nodes which were connected to each other by segments. Materials in the system could flow via these segments. Validation of the study was achieved with a level of 90% confidence interval. In 1985, Tu and Hucka (1985) focused on increasing production rates of an open pit mine by investigating alternative truck dispatch systems and alternative routes of trucks. In the study, the model was developed by using SLAM language. However, the achieved increase in production rate at the end of the study was only 2.5%. In 1986, Doe and Griffin (1986) had a research on developing a model for oil sands mines by using SLAM II language. The aim of the study was to investigate the effect of bin size change on the system. In 1988, Thompson and Adler (1988) developed a simulator, Coal Mine Belt Capacity Simulator aiming to reach the optimum belt conveyor area by Monte Carlo Simulation approach in clock advance process. In 1989, Lavrencic (1989) developed MINSIM model by network theory and artificial intelligence techniques to forecast production rates of a mine under the conditions of using different sizes of equipment on a daily basis and personnel training in decision-making.

In 1990s, researches on simulation continued in every aspect of mining activities as in 1980s. In 1990, Almgren (1990) studied time planning of mines by probabilistic approach instead of deterministic approach. Completion time of the mining activity was estimated by using probabilistic techniques based on Monte Carlo Simulation. Gray (1990) developed a model for a clearence system of underground coal mining activity to analyze the effect of bin size storage on production rate of the mine. In 1992, Hoare and Willis (1992) studied the modelling and animation of material handling operations for Elura underground lead zinc mine located in NSW, Australia by using SIMAN language for modelling works and CINEMA for animating works. In 1993, Litke et al. (1993) conducted research on the comparative effectiveness of system components on system production. The developed model handled drilling, blasting, mucking, hauling, and back filling activities. In 1997, Runciman (1997) completed a thesis research on cyclic and semicontinuous development systems for an underground mine. The study analysed drilling and blasting operations in detail. The models used in the study were developed in WITNESS simulation environment. At the end of the study, results showed that production rate could be increased up to 45%.

In this chapter, a brief history about how the simulation concept was introduced to the mining industry and in which application areas simulation studies focused on during the introduction and development stages of simulation in mining activities is given. In the simulation history, various researchers contributed to the development of simulation in the mining industry. In this context, APCOM (Application of Computer and Operations Research in the Mineral Industry) has an important position in the mining simulation history, founded by four universities (Colorado Schools of Mines, Pennsylvania State University, University of Arizona, and University of Stanford) of USA in 1961. The first APCOM was organized by the University of Arizona, USA in the year 1961 and the 38th APCOM symposium was realized by Colorado School of Mines, USA between August 9-11, 2017.

Currently, simulation models implanted on mining activities still maintain their importance worldwide due to the potential benefits. In the mining history, several researchers showed an approach to mining problems in different branches of mining activities with mathematical techniques involving nonlinear programming, linear programming, genetic algorithm, machine repair model, and mixed integer programming. However, mining systems cannot be perfectly modelled with mathematical deterministic approach as every stage of the mining activities is generally composed of stochastic processes. On the other hand, discrete event simulation can be applied to the queuing systems with stochastic processes. Thus, discrete event simulation technique is commonly used in mining activities (Dindarloo and Siami-Irdemoosa, 2016).

2.1.3 Recent Studies on Discrete Event Simulation in Mining Activities

This chapter focuses on recent discrete event simulation studies in different branches of the mining industry in detail.

Que et al. (2016) investigated ground articulate pipeline systems and shovel interaction. They developed a model for increasing efficiency of the oil sand continuous transport system. The simulation model was developed in Arena® Simulation Software. At the end of the study, the researchers recommended using 70-ton shovels and surge hoppers on the mobile slurry system to maximize the efficiency of the ground articulate pipeline system. The importance of this study is that a ground articulate pipeline system and a shovel operation was combined and as a result, the efficiency of the system under different scenarios was investigated.

Tarshizi (2014) studied on developing and animating a series of discrete event simulation models for two open pit gold mines, an open cast coal mine, an aggregate mine, and an underground mine. Except for the underground mine, aims of the studies were to increase efficiency of the haulage operations, production rates, and decrease the impact of the operations on the environment. On the other hand, the aim of the study for the underground mine was to simulate evacuation scenarios, places of rescue chambers, and equipment used in rescue operations according to the characteristics of the mining operations. The models used in the study was developed in GPSS/H language with PROOF Professional®. According to the study, in case data taken from the mines was properly collected, the difference between actual production and simulated results reached an error under 1%. Importance of this study is that many models for different types of mining activities were generated and evacuation in an underground mine was simulated.

Salama et al. (2014) conducted a research on underground material handling operations of a pyrite and chalcopyrite mine with a yearly production of 2.62 Mt. The mine was operated with 4 different mining methods, which were sublevel stoping mining, Alimak mining, drift and fill mining, and narrow vein mining according to zone characteristics of the ore mineralization. The haulage operation was performed by LHDs (Load-Haul-Damp machines), and mining trucks in the mine. In the study, simulation-modelling environment for the developed model was SimMine Software. In the developed model, different sizes of mining trucks with different number of trucks were considered as alternatives. Validation and verification were performed with the comparison of actual system data and output of the model. Differences between the actual system and output of the model were about 1%. In the model, truck traffic was also considered and demonstrated that traffic jam decreased utilization rates of the equipment. The study also showed that it was impossible to reach the production target under the available circumstances.

Ahmed et al. (2016) had a research on a case study examining mining extraction layouts of Offset Harringbone and El Teniente mines by comparison. Underground caving mining methods with different layout types were used in these mines. In this study, advantages and disadvantages of both layouts were investigated and the development stage of the mines were modelled. The software where the model was built was ExtendSim©. The study concluded that developments of El Teniente and Offset Harringbone layouts were completed in 18.4 months and 20.1 months, respectively; but 3% additional drive development was needed for El Tiente layout on average. The importance of the study is that discrete event simulation technique was applied to a different concept, optimizing the mining extraction layout design in underground caving mines.

Vasquez-Coronado (2014) studied haulage unit optimization of an open pit mine. An alert system was designed for haulage unit of the mine to receive an alert massage when status of trucks were switched from busy to idle. According to these alerts, arrangements were made on the model and simulation model were rerun. The modelling environment for this study was Arena® Simulation Software. Cycle time of the trucks were taken from Caterpillar's FPC system. The importance of this study is that simulation together with a context-based alert system was implemented in a simulation study.

Faraji (2013) focused on the haulage operation in an open pit coal mine by following both deterministic and stochastic approach. In the study, LP (Linear Programming) model and a simulation model were developed. Simulation-modelling environment was Arena® Simulation Software and the developed model was a real time model including identical trucks and shovels. In the model, LP constraints such as, stripping ratio were taken into account. Bottleneck analysis at the crusher area and at the shovel loading area were investigated with the aid of the developed model. In LP model, waiting time and queues at servers such as, shovels, and crushers are not included. Therefore, LP model and simulation model gave different outputs during the study. Thus, it is concluded that LP gives very optimistic results when bottleneck analysis were conducted. Importance of the study is that Faraji (2013) combined linear programming and simulation for an open pit coal mine.

Torkamani (2013) conducted a research on optimizing the short-term production plan of an open pit mine. Arena® Simulation Software was used to develop the model and it was verified in a real mine by means of measuring Key Performance Indicators (KPI) of the truck-shovel haulage system. There were two processing plants, two stockpiles, and two waste dump sites on site. The developed model in the study investigated the behaviour of the shovel and the mine trucks travelling between these destinations. In addition, the location of the extracted ore together with its tonnage and grades and maintenance schedule of the trucks according to different utilization rates were taken into consideration in the model. The study concluded 81% shovel utilization and 84% truck utilization (2 shovels and 8 trucks) in average for the best case when failures were not included and 89% shovel utilization and 67% truck utilization (3 shovel and 11 trucks) in average for the best case when failures were included. The significance of the research is that Torkamani (2013) combined short-term mine planing with truck-shovel production analysis.

Fjellström (2011) had a case study on an underground material transportation system of Renström Mine, Boliden Mineral by making a cost comparison between alternatives. The mining method used in the mine was cut-and-fill mining method and transportation of ore was realized by 1 mine truck and 3 highway trucks. Alternatives considered in the study were using only mine trucks, only highway trucks, and a combination of highway trucks and mine trucks in the haulage process of the mine. The model used in the study was developed in AutoMod™ Simulation Software. In the study, 52 different scenarios were investigated and ore transportation rates greater than actual production rate were selected. The first optimal scenario according to the simulation study after cost analysis was using 3 mine trucks with a reserve (76,663 t, unit cost of 26.44 SEK/t) when the production rate of the mine would not be increased (76,500 t). The second optimal scenario was using 4 mine trucks with a reserve (78,280 t, unit cost of 27.14 SEK/t) when production rate of the mine would be increased. Importance of this case study is that the research was an updated study for the

Renström Mine because the first simulation study for Renström had been realized in 1999, but after passing years, many changes occurred in the mine and these changes were considered in the study of Fjellström (2011).

Zhou (2010) showed an approach to mine-mill production system in combination of two different sides, mathematical modelling (Integer Programming-IP) and simulation modelling. The simulation model used results of the integer programming such as, inventory levels of unprocessed ore, and number of the shutdown days as a production scheduling input to examine the system performance. The model in the study was developed in Visual Basic for Applications environment. In the model, mean time between failures (MTBF) and mean time to repair (MTTR) were taken into consideration. ExpertFit Software was used to fit distributions for MTBF and MTTR. In the study, sensitivity analysis were performed according to the implemented maintenance model, increased mean time between failures, reduced mean time to repair, and increased arrival of ore. The base model used in the sensitivity analysis had no machine failures. Significance of the study is that investigation of mine-mill production system was realized by means of a combination of integer programming and simulation.

Yuriy and Vayenas (2008) had a research on maintenance analysis of LHD machines used in mining activities and the effect of maintenance time on production output of the mine. In the study, obtained results such as, time between failures from reliability assessment model, which was based on generic algorithm, were used as an input to discrete event simulation model. Simulation models were built in both AutoMod™ and Simul8. Thus, output differences between AutoMod™ and Simul8 were investigated. Validation of the model was realized by the data collected from a real underground mine. Although there were some differences between AutoMod™ and Simul8, these differences were in acceptable ranges. Thus, both models were considered to analyse the system. The most important part of the study is that Yuriy and Vayenas (2008) combined generic algorithm with discrete event simulation.

Şimşir and Özfırat (2008) studied on determination of the most effective longwall equipment configuration in an LTCC mine by using discrete event simulation. The aim of the study was to select the most effective equipment rather than increasing the system efficiency with the same equipment. In the study, simulation model was developed in Arena® Simulation Software. In the model, top coal production and face coal production were not modelled one by one. It was assumed that top coal production was a constant multiple of the face coal production. On the contrary to Şimşir and Özfırat (2008), in this thesis study, coal production is separated from each other but there is a connection between them. In other words, top coal production was considered as a process that does not have to be a certain multiple of face coal production, but top coal production was achieved as the shearer operations continue in the face coal operations. On the other hand, conveyors were modelled as resources having fixed capacities and delay time values in Şimşir and Özfırat's study. The researchers compared model outputs with daily production of a real-life mine for the validation of the model. Differences between model output (1,046 tons) and daily production (922.93 tons) of the mine were within acceptable limits. In the study, 320 different scenarios were assessed via developed model and the most logical scenarios were selected.

To sum up, simulation techniques have been developed since late 1950s and played an important role in the mining industry. Various researchers contributed to this development and by this way, discrete event simulation technique has become an essential part for the evaluation of different scenarios in different branches of mining activities.

2.1.4 Advantages, Disadvantages, and Effective Use of Simulation

While simulation techniques have still been improving since the beginning of simulation history, there is one unchanging subject in simulation, the presence of stochastic processes in general. If there is a stochastic process in the system, randomness occurs. In fact, simulation is a tool that does not satisfy 100% of reality due to stochastic processes. As a result of this phenomenon, simulation can be considered to have advantages and disadvantages in different cases.

Firstly, simulation of a system has many advantages. Some of them are listed below.

- ❖ Simulation helps engineers to test the probable results with every aspect of any change in the system without any change in real world. This is crucial especially when decisions have to be made in complex processes such as, mining activities and there is no chance to revert the changes as the related cost of this change would be costly.
- ❖ Simulation can be used to speed up or slow down the progress. This enables analysts to examine the system results thoroughly.
- ❖ Managers commonly demand to learn why the operation experiences certain issues and problems in the real system. Simulation software can be used to reconstruct the real system in a virtual world so that numerous scenarios can be evaluated.
- ❖ Without disrupting real world, people get a chance to improve simulation models, new policies, operating procedures or methods. The results of modifying operational conditions can be assessed in a computer software rather than the real world.
- ❖ People can improve their designing skills and perspectives by using the simulation software. In each study, they usually see and learn why they make mistakes by investigating the design of the system with the help of simulation software. As a summary, it can be said that simulation studies increase the operational experience of decision makers (Dindarloo and Siami-Irdemoosa, 2016).
- ❖ Interaction of variables can be understood. This enables analysts to understand the system better and decrease the time needed for the best design of the system.
- ❖ Importance of variables to the performance of the system is comprehensible via simulation software. Analysts can make sensitivity analysis and can see which variable is more important than others. This also decreases the time

spent for the best design because the analyst concentrates mostly on the variable affecting the system most.

- Bottleneck analysis can provide information to the analyst about where the operation reaches a critical inefficiency level in the system.
- The answer of "What if questions" can be obtained which is very useful for the prediction of results for a new system design (Pegden et al., 1995).

Although there are many advantages of simulation studies, sometimes it is not a good decision to simulate the system. Disadvantages of the simulation are listed as follows:

- Special training is necessary for model building. Model building ability of analysts directly increases with experience.
- Making comments about the results and interpretations of the simulation results can be difficult. Outputs are essentially and mostly random variables because input data is generally random. Therefore, it can be hard to differentiate whether observations are due to randomness or system interrelationship.
- Simulation modelling and process analysing can be time consuming and expensive.
- Generally, no exact solution is obtained in simulation studies. Results are generally estimated under given conditions (Pegden et al., 1995).

Effective use of simulation is also important. Simulation should not be used for the consideration of efficiency in such systems that:

- Problem can be solved with analytical solution easily.
- It is easier to make a change and experiment in real system than in virtual world.
- Simulation cost is bigger than profit after system change.
- There are not enough sources.
- There is not enough time for benefiting from simulation.
- There is not necessary information and data.

- There is no chance to validate model.
- Expectation from the project is not satisfied.
- System is so complex that there is no chance to model the system.

If the above situations are not valid for the system, simulation is the best way to understand and optimize the system.

2.1.5 Basic Flowchart in a Simulation Study

This chapter explains the basic planning of the simulation works conducted in a simulation study.

First of all, all of the simulation studies emerge from a problem. The problem should be put into a mathematical concept. This concept is known as “Problem Formulation” and it forms the first step of the simulation study.

In the second step, objectives and overall study plan are determined. Whether the methodology in the overall study plan is suitable for the study or not is checked in this step. On the other hand, objectives simply point out questions that are answered by simulation study. In other words, they can be considered as the aim of the investigated study.

The third and the fourth steps are “Model Conceptualization” and “Data Collection”, respectively. The model is characterized in model conceptualization stage in a way that should satisfy the system. For this purpose, modification of the primary assumptions that describe the system is continued until acceptable results are obtained. On the other part, data makes the connection between model and the real-world system. In data collection part, analysts collect data from the real-world system. The amount and quality of the data has a considerable impact on the reliability of the simulation results.

The fifth step in a simulation study is “Model Translation”. Data and information about the system are transformed into a specific format in this step. A computer program coded by analysts realizes this translation.

The next two steps are verification and validation. Verification step is related with whether the model works correctly or not. If the model is not verified, outputs of the model are not reliable. This step finishes when the system logic and input parameters are properly demonstrated in the computer environment. The validation step is related with the calibration of the model. The model in this part should be improved until the error between the model and the real system reaches an acceptable range.

In “Experimental Design” step, alternatives are specified and they are simulated in the computer. This step is needed to evaluate how the alternatives affect the entire system in the simulation model.

“Production Runs and Analysis” step is used to predict system performance for the system designs that are being simulated. Results of the experiments are evaluated in this step.

The next step is called “More Runs” which is not necessary for all simulation studies. It depends on the results of the analyst. When the confidence interval in the simulation study is satisfied, this step is not applied. However, if increase in the confidence level is necessary, more runs are needed in the study.

Every study should be documented systematically so that different analysts can obtain identical results in the same model and understand the relations between system components easily. On the other hand, the results of the simulation model including the results of comparison of the alternatives, experiments, and recommended solutions should be clearly reported in an understandable way for people determining whether the simulated results could be applicable or not in reality.

The last step in a simulation work is “Implementation”. The performance of implementation part depends on the correctness of all steps followed in a simulation study.

Relation of the steps mentioned above in a simulation study is given in Figure 2.3.

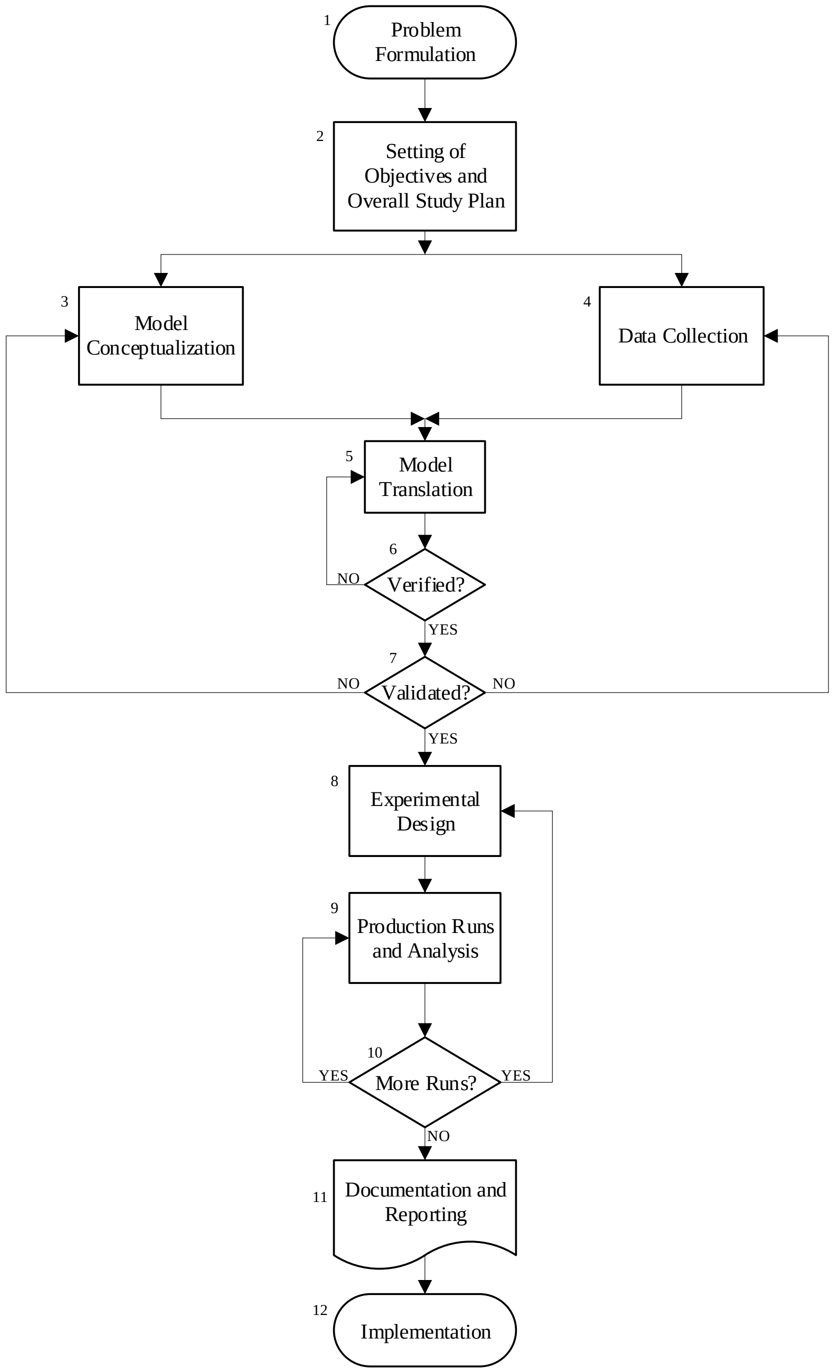

Figure 2.3 Basic flowchart in a simulation study (Banks et al., 2004)

2.1.6 General Information about Discrete Event Simulators

At the beginning of computer history, general-purpose programming languages were developed such as, C, Java, FORTRAN, Basic, Pascal, Python. Almost every problem in different aspects of subjects can be modelled by using general-purpose programming languages. Especially, general-purpose programming languages are better choices than simulation languages for complex problems. However, the required specialization required for using general-purpose programming languages makes it more difficult to use in some complex cases such as, the representation of mining activities.

Together with computers getting more common in the world, simulation languages such as, GPSS, GPSS/H, SLAM, SIMSCRIPT, and SIMAN were developed for creating simulation models easier in more flexible environments. According to these programming languages, several software packages, which have more visual and easy interfaces to use, have been developed. These types of software packages are called “simulators” and help analysts to find their mistakes in the models easily via their specialized debugging tools. Examples of these software types are Arena® Simulation Software, AutoMod™, CimStation, and GPSS/H with Proof Animation, Witness Simulation Software, and SLAM Simulations. To sum up, several simulation languages and simulators have been developed and improved up to now. Today, many of them are commonly used in the mining industry.

2.2 Statistical Data Analysis

Uncertainty in processes leads to inexact outputs. Their nature are described with statistical properties. Simulation studies are generally composed of stochastic processes and uncertainty in the processes greatly affect the output of the simulation. In fact, the output of the simulation study mainly depends on statistical analyses of uncertainty in processes. Improper data analysis causes inaccurate output of the simulation model. Therefore, statistical analysis of the system is the most important part of the simulation studies. Under this heading, hypothesis testing concept and goodness-of-fit tests will be discussed.

2.2.1 Hypothesis Testing Concept

Hypothesis testing is the basic concept of data analysis. In general, hypothesis testing procedure investigates two claims that are called “hypotheses”. The first one is called “null hypothesis” and the other one is called “alternative hypothesis”. Null hypothesis can be considered as initial assumption and alternative hypothesis is an opposite statement to null hypothesis. In hypothesis testing procedure, null hypothesis is tested by investigating random samples from population and consistency between null hypothesis and investigated sample results is checked. According to the hypothesis testing result, null hypothesis is either accepted or rejected. However, errors can sometimes occur according to the sample data. These errors are called “Type I Error” and “Type II Error” in statistics. Type I error occurs when null hypothesis is rejected although it is true. Type II error occurs when null hypothesis is accepted although it is false (Montgomery and Runger, 2014). Decisions in hypothesis testing concept is given in Table 2.1.

Table 2.1 Decisions in hypothesis testing (Montgomery and Runger, 2014)

Decision	**H_0 Is True**	**H_0 Is False**
Fail to reject H_0	No error	Type II error
Reject H_0	Type I error	No error

*H_0: Null hypothesis

In statistical testing concept, probability of type I error is represented by α (Alpha) and probability of type II error is represented by β (Beta).

Another denomination of α is “significance level” in statistics. Significance level represents confidence of the hypothesis testing. For example, if the sample data supports null hypothesis at 5% significance level, it indicates that hypothesis testing result supports the reality by 95% (95% Confidence Interval).

There are two ways for testing of hypothesis in general. In the first approach, critical region, i.e. a confidence level, is determined. Critical region can be called rejection region. This region represents significance level (α). If the test statistics falls into critical region, null hypothesis is rejected. Otherwise, failing to reject null hypothesis condition happens. The second approach for testing null hypothesis is significance testing method. In significance testing method, P-value is determined. P-value is the smallest level of significance which would cause null hypothesis rejection. If P-value is less than signicance level (α), null hypothesis is rejected. Otherwise, failing to reject null hypothesis condition happens.

2.2.2 Goodness-of-Fit Tests

Every statistical distribution has specific characteristics. Nature of the process should be represented according to these specific characteristics. This representation is realized by distribution fitting operations. Distribution fitting operations can be described as assigning specific distribution on discrete data. This process is needed for random number generations for a process. In fact, random numbers are generated according to statistical distributions.

According to available data, different types of distributions can be fitted in testing procedure. As it is mentioned before, fitted distributions should describe available data as much as possible. The better the distribution fits the discrete data, the more accurate random numbers are generated. Thus, output of the study approaches the real-life process. To sum up, the main aim in distribution fitting process is to obtain best fit to the available discrete data.

There are many tests are available to measure how successful the statistical distribution fits to the discrete data. These tests are known as “Goodness-of-Fit Tests”. The mostly known and used tests are Chi-square goodness of fit test, Kolmogorov-Smirnov goodness of fit test, and Anderson-Darling goodness of fit test. Chi-square goodness of fit test is applicable to both discrete and continuous distribution functions while Kolmogorov-Smirnov, and Anderson-Darling goodness of fit tests are only applicable to continuous distributions.

According to goodness of fit tests, there are many distributions that can be fitted to sample data. Aim of statistical analysis is to find the best fitted distribution. From this viewpoint, "sum of square errors" concept is used in statistics. Sum of square errors (SSE) can be considered as how far the sample data is from the distribution line (Montgomery and Runger, 2014). This concept is formulated as follows:

$$\mathrm{SSE} = \sum_{i=1}^{N} (e_i)^2 = \sum_{i=1}^{N} (y_i - Y_i)^2 \qquad (1)$$

where;

N is the sample size, y_i is the observed value and Y_i is the fitted values. As *SSE* value decreases, the distribution is getting better fitted.

After curve fitting operations, replication number should be determined in a simulation study. Replication number is an important parameter because simulation models give different outputs in every replication number. In this context, half-width (margin of error) term is commonly used in statistics. Half-width is defined as the radius of confidence level for the defined distribution. If a distribution is normally distributed with unknown population standard deviation, population mean in a level of (1-α) * 100% confidence interval is calculated as follows (Kelton et al., 2010):

$$\bar{x} \pm t_{\alpha/2,(n-1)} \cdot \frac{s}{\sqrt{n}} \qquad (2)$$

where;

s is the sample standard deviation, n is the number of replications, $t_{\alpha/2,(n-1)}$ is the critical value from t tables, and

$$\text{Half} - \text{width} = t_{\alpha/2,(n-1)} \cdot \frac{s}{\sqrt{n}} \tag{3}$$

As the number of replication increases, half-width decreases and hence, precision of the results approaches to reality. On the other hand, as the number of replication increases, run time of the simulation model increases. Therefore, both replication number and run time of the simulation model should be taken into consideration; as a result, optimum replication number should be determined in a simulation study.

In this study, collected data is evaluated in Arena® Input Analyzer (Arena Simulation Software, 2015) and Minitab® 18 (Minitab®, 2018).

2.3 Background on Underground Coal Extraction Operations

Underground mining methods in coal mining activities are room-and-pillar method or longwall mining method in general. Room-and-pillar mining method is used in relatively shallow mines. With the increase in depth of the mining, dimensions of the pillars have to be increased for the stability issues of the mine. As the dimension of the pillars is increased, amount of coal remaining in the pillars also increases. This situation causes the recovery of the coal to decrease. Therefore, longwall mining is one of the most commonly used methods when the depth of mine increases.

Sedimentary deposits have a uniform thickness with large longitudinal extent in general. Longwall mining method has been developed by taking advantage of this sedimentary rock property. In this mining method, rock characteristics of the hanging wall and footwall can be considered as minor criteria as the method can be implemented whether the footwall or hanging wall is weak or not as the hanging wall in the working area is artificially supported and the hanging wall tends to collapse. Mechanization can almost reach perfection in this type of mining method (Hustrulid and Bullock, 2001). However, some conditions affect the degree of mechanization. One of the most influential subject in the degree of mechanization in longwall mines is the geological condition of the deposit area. Structures including faults and folds affect the deposit continuity and as a result, shape of the deposit. In Turkey, Anatolia has many faulty areas and this can be considered as one of the main challenges of fully mechanized longwall operations in the coal deposits in Turkey.

Longwall mining is also defined as one of the simplest methods to excavate coal as production is realized by panels. Panels have a simple rectangular prism shape and their sizes depend on many conditions like the deposit shape and its characteristics, transportation capabilities of the mine, condition of ventilation, and capability of the power supply in the mine (Darling, 2011). Bottom edge of the panels is called "Main Gate" and the top edge of the panels are called "Tail Gate". Coal extraction in the panels is performed on the other remaining dimension of the panel, called "Coal Face".

2.3.1 Classifications of Longwall Mining Methods

Longwall mining methods can be classified as retreat method or advancing method according to the direction of production. In retreat mining, main gate and tail gate are created first. After reaching the planned panel length, main gate and tail gate are connected to each other. Production advances in the reverse direction. In advancing type mining, main gate and tail gate is advancing together with the longwall face. The collapsed region behind the coal face is called "goaf area". In spite of goaf area, main gate and tail gate must be stable for achieving adequate ventilation in advancing type longwall mining method. Generally, backfilling between the boundaries of goaf area and gates is needed to support main gate and tail gate. One of the main advantages of advancing type mining method over retreat type mining method is that production begins with gate operations. On the other hand, advancing type mining is also associated with many disadvantages. For example, backfilling is an expensive operation and ventilation problems may occur in the system due to air leakage to the goaf area. As a result, spontaneous combustion is a major risk that may be observed in the advancing type longwall mining method. In short, retreat type mining is more advantageous over advancing type mining by means of operation and safety in case the conditions are suitable. Typical plan views of longwall panels with advancing and retreat types mining direction are shown in Figures 2.4, and 2.5, respectively.

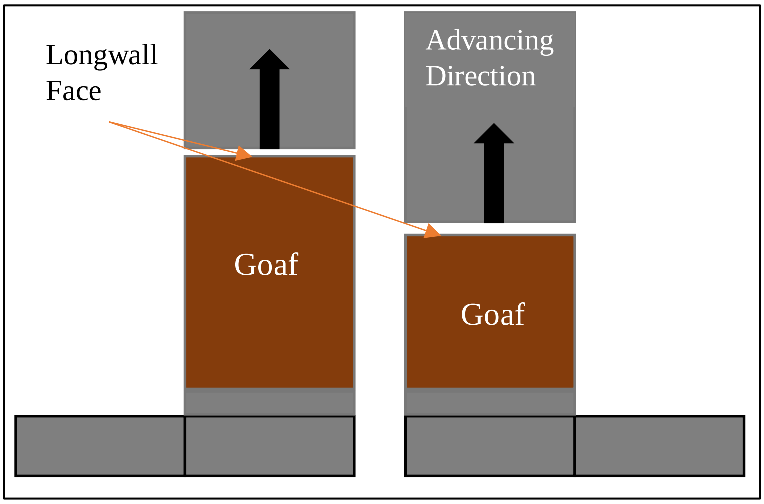

Figure 2.4 Typical plan view of longwall panels with advancing type mining direction

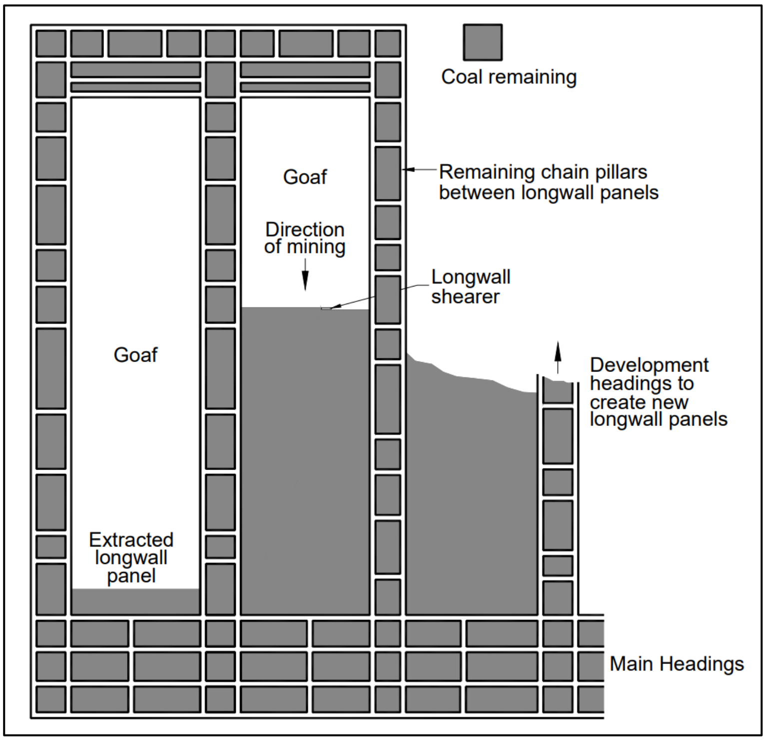

Figure 2.5 Typical plan view of longwall panels with retreat type mining direction (MSEC, 2007)

2.3.2 Operations on Coal Face

Generally, there is no need for drilling and blasting operations because soft materials can be easily cut mechanically. Special machines shaped as cutting plows or rotating drums with cutters moving back and forth along the faces cut a fresh slice of the seam every time. Although plow systems have also been developed for longwall mining, cutting machines used in longwall faces are mostly shearers especially for thick coal seams. Generally, shearers have a double-drum mounted on ranging arms. This property allows shearer to cut the coal especially when the coal seam dimension changes.

Shearers are mounted on armoured face conveyors (AFC) in the face. In fact, shearers move on the AFC. When AFC is pushed forward by shields, a transition area is formed. This area is called “snake area” and advance of shearers is performed within this area. Advance of the shearers in the coal face is mainly achieved by two systems according to the cutting type of shearers. These systems are uni-directional cutting system and bi-directional cutting system.

i. Uni-Directional Cutting System

Extraction of coal is performed with two shearer passes along the coal face between main gate and tail gate in this type of cutting system. In the first pass, shields are pushed forward. In the second pass, the AFC is pushed forward. Advancing on coal face is continued according to this cycle (Mitchell, 2009). One of the important parameters in production operations is the cycle time of the shearer. Cycle time can be defined as the time spent during one cycle of operation is performed.

Theoretical cycle time in uni-di cutting system is calculated as follows:

$$\text{Cycle Time} = 2 \text{ x main cut } + \ 2 \text{ x turnaround time} \qquad (4)$$

Uni-directional cutting system and movement of shields are shown in Figure 2.6.

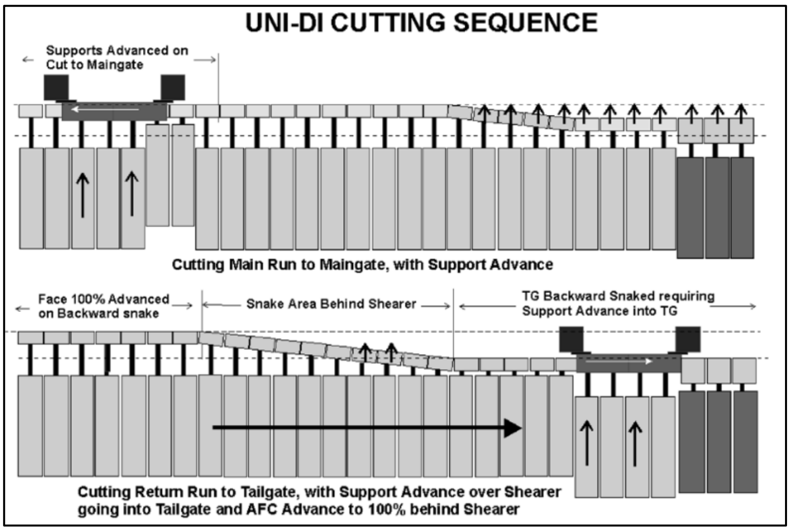

Figure 2.6 Uni-Di Cutting Sequence (Rutherford, 2001)

ii. Bi-Directional Cutting System

Extraction of coal is performed with single pass operations. In every pass from main gate to tail gate, advance of shearer is realized. In other words, AFC and supports are pushed forward in every pass. In this type of cutting system, “shuffle” is needed at each end of the coal face for advance of the shearer by moving back on the snake and then back to the end of the face (Mitchell, 2009). Bi-directional cutting system and movement of the shields are shown in Figure 2.7.

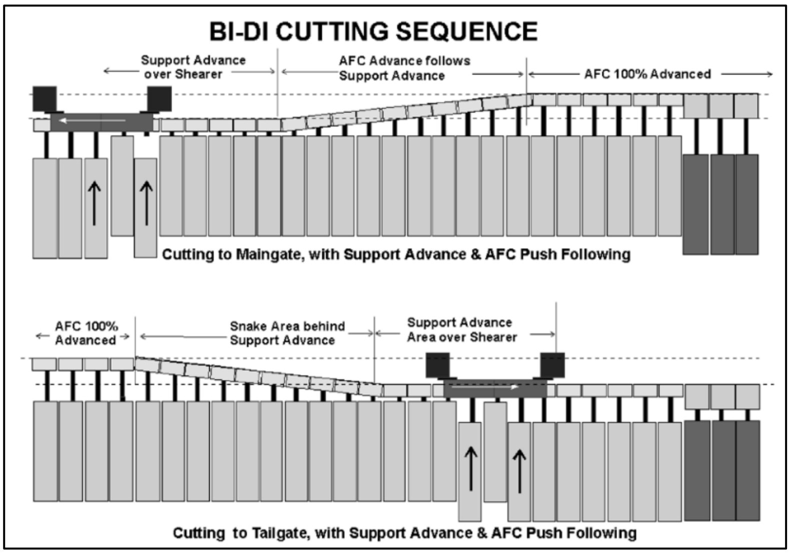

Figure 2.7 Bi-Di Cutting Sequence (Rutherford, 2001)

Theoretical cycle time in bi-di cutting system is calculated as follows:

$$\text{Cycle time} = \text{main cut} + 2 \text{ x shuffle time} + 3 \text{ x turnaround time} \quad (5)$$

2.3.3 Support and Transportation System in Longwall Mining Method

Protection of the working area is achieved by the roof support along the longwall face. Usually, hydraulically operated props are used for supporting the roof in longwall mining. As it is mentioned before, these operated props in the mechanized longwall mines are mining shields. Shields are moved forward during advances in mining and the roof behind can be allowed to collapse (Hustrulid and Bullock, 2001). One of the main advantages of mining shields is that no support remains in the collapsed area. In other words, supports are used in the panels to be operated in the future. This specific design of longwall mining method minimizes support expenses of the mining activities.

On the other hand, transportation of coal starts with the shearer action where excavation of coal begins. Due to the special design of shearers, the excavated coal falls onto the AFC when cut and then transported to the haulage drift. In the haulage drift, the beam stage loader (BSL) transports the coal to the crusher. The crusher reduces the size of the coal and other materials intercalated in the coal seam. This size reduction operation is required to transport the coal by belt conveyors. From the haulage drift, the broken coal is transported out of the mine by conveyors. Conveyor belts enable the flow of material to be continuous and therefore, conveyor belts in underground mines are commonly utilized for transportation of material. Major components of longwall mining systems can be seen in Figure 2.8.

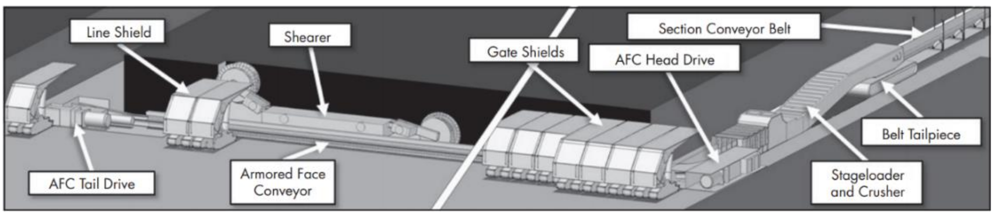

Figure 2.8 Major components of longwall mining systems (Darling, 2011)

Meanwhile, thickness of the coal seam is an important parameter in longwall mining method selection. Coal seams are divided into many subgroups according to their thicknesses. They are given in Table 2.2.

Table 2.2 Subgroups of coal seams according to their thickness (Darling, 2011)

Coal Seam Classifications	
Thin	$T \leq 1.75$ m
Moderate	$1.75 \text{ m} \leq T \leq 3.75$ m
Thick	$3.75 \text{ m} \leq T \leq 7.25$ m
Very Thick	$T \geq 7.25$ m

*T: Thickness of coal seam

When the seam thickness is less than 3.5 m, classical longwall mining method can be applied. However, this method is not suitable for thick and very thick coal seams. Several types of longwall mining methods have been developed for the extraction of deposits having thick coal seams. These methods can be considered as a kind of longwall mining method adaptations and examples are single pass longwall (SPL), multi-slice longwall (MSL), and longwall top coal caving (LTCC).

In SPL, extraction operations are realized by gradually increasing heights of the shearers and hydraulic supports up to 6 m (Hebblewhite and Cai, 2004). In other words, maximum seam height can be 6 m in SPL. In fact, this height limitation (6 m) occurs due to the equipment stability based on size, weight, and face conditions.

In MSL, production is realized by a series of classical longwall mining methods operated sequentially (Xu, 2001). These are called “longwall slices”. The number of slices depends on the height of the coal seam. Multi slicing longwall mining method is a risky extraction technique due to mining under the goaf area. This condition causes not only stability problems but also water and gas problems in the mining area (Hebblewhite and Cai, 2004).

The third applied method for thick coal seams is LTCC. In LTCC method, production is performed in two parts. In the first part, the shearer operates under the coal seam called "top coal" and the extraction process is performed following a classical longwall method. In the second part, top coal is caved behind the hydraulic supports as the shearer advances. This method is a cost-effective mining method because shearer only cuts a small portion of the coal and the remaining portion of the coal (top coal) is produced with the aid of gravity. In this mining method, recovery of the coal can be up to 80% when the thickness of the seam is between 5-9 m and operational height of shearer is 3 m (Le et al., 2017). Cross-sectional layout of top coal caving method is illustrated in Figure 2.9.

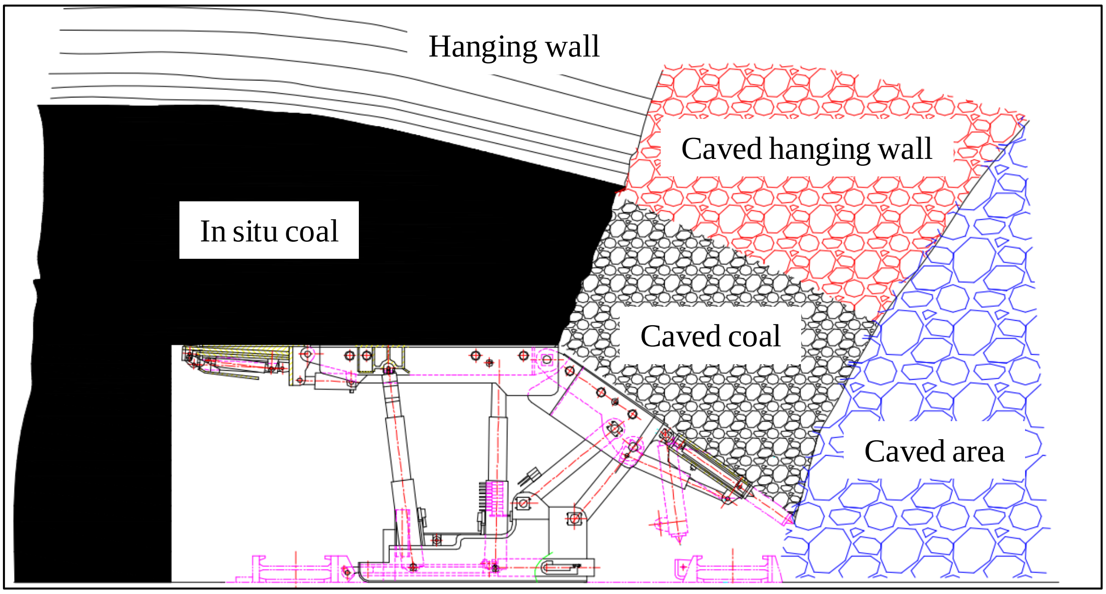

Figure 2.9 Cross-sectional view of LTCC method (Xie and Zhou, 2009)

2.3.4 LTCC History and Top Coal Cavability

The first applications of LTCC method are observed in 1950s and 1960s in France and the Soviet Union. Then, this thick coal extraction method was applied in other countries such as, Yugoslavia, Romania, Czechoslovakia, and Turkey. However, the main improvement in LTCC method was realized after LTCC method was used in China in the late 1980s. In its first implementations, transportation of coal was realized by single conveyor. Top coal was transferred to the AFC by means of the roof canopy and top coal together with face coal was transported by only one AFC. However, in China, an additional conveyor system, known as the rear conveyor (RC) system, was added to the transportation system. Thus, haulage of coal was achieved by two conveyors instead of one conveyor and as a result, production rate was increased. In the double conveyor system, coal that is cut by the shearer was hauled by the front conveyor and top coal was hauled by rear conveyor (Le et al., 2017). Single conveyor system and double conveyor system are illustrated in Figures 2.10, and 2.11, respectively.

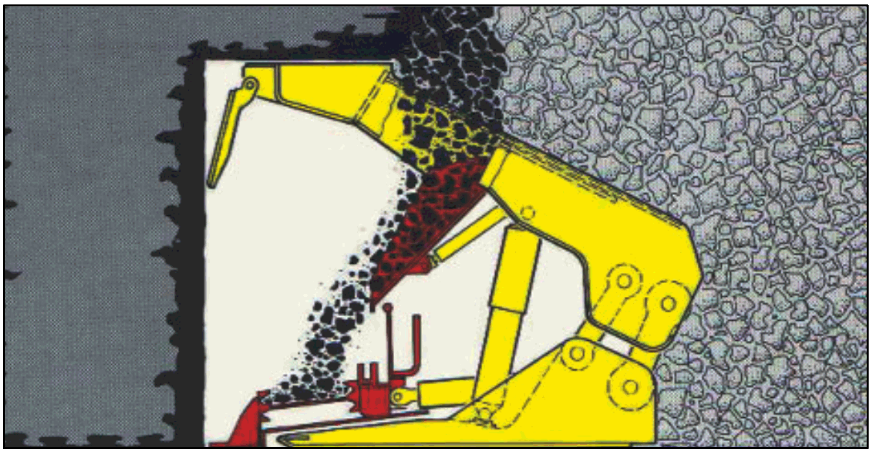

Figure 2.10 Single conveyor system in LTCC method (“Longwall Mining”, n.d.)

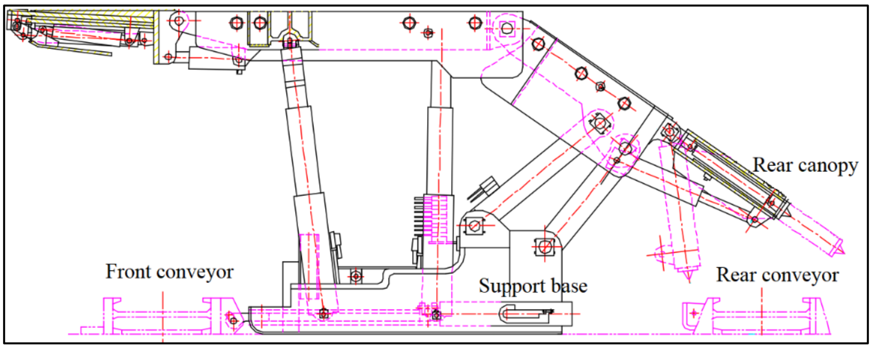

Figure 2.11 Double conveyor system in LTCC method (Xie and Zhao, 2009)

Currently, LTCC method is successfully applied to very thick coal seam with thickness of 20 m with a cutting height of 5 m. In addition, after further improvements in LTCC method, this method can also be applied in coal seams having a dip angle of 41^o (Le et al., 2017).

In research related to LTCC, cavability mechanism of top coal caving is an important subject. There are many factors affecting cavability of top coal caving method and some of the most influencial factors can be summarized as (Le et al., 2017):

- ❖ Coal seam properties i.e. uniaxial compressive strength of coal, discontinity characteristics, thickness of seam.
- ❖ Surrounding rock strata properties i.e. strata thickness and weakness.
- ❖ Stress condition of the caving area i.e. pre and post-mining stress distribution.
- ❖ Other factors i.e. panel design, water content of the strata.

Ease of top coal cavability is inversely proportional to the strength of the coal. In fact, cavability of top coal increases when the strength of the coal decreases. Discontinuties can be considered as weakness zones of strata. Therefore, it can control the caving mechanism of top coal. Thickness of the seam is an another important parameter in top coal caving. According to Dao (2010), the thinner coal seam fails easily when the strength of thinner coal and thicker coal are considered as the same.

Strata thickness and weakness is also inversely proportional to the capability of coal caving. When the roof strata is thin and weak, it converges to the top coal and as a result, stress on the top coal increases leading in ease of top coal caving (Le et al., 2017).

Stress condition of caving area is another influential characteristic of top coal caving. Stress conditions change before and after coal excavation where in pre-mining state, there is an equilibrium between stresses. With the beginning of the excavation, stresses form a new equilibrium state. Success of top coal caving depends on newly formed vertical stress that causes failing of top coal under the effect of gravity. However, effect of horizontal stresses on cavability of top coal is different from vertical stresses. On one hand, horizontal stress causes roof failure; on the other hand, it can reduce the effect of vertical stress on coal failure. As a result of this situation, cavability of coal decreases. Redistributed states of vertical stresses are illustrated in Figure 2.12.

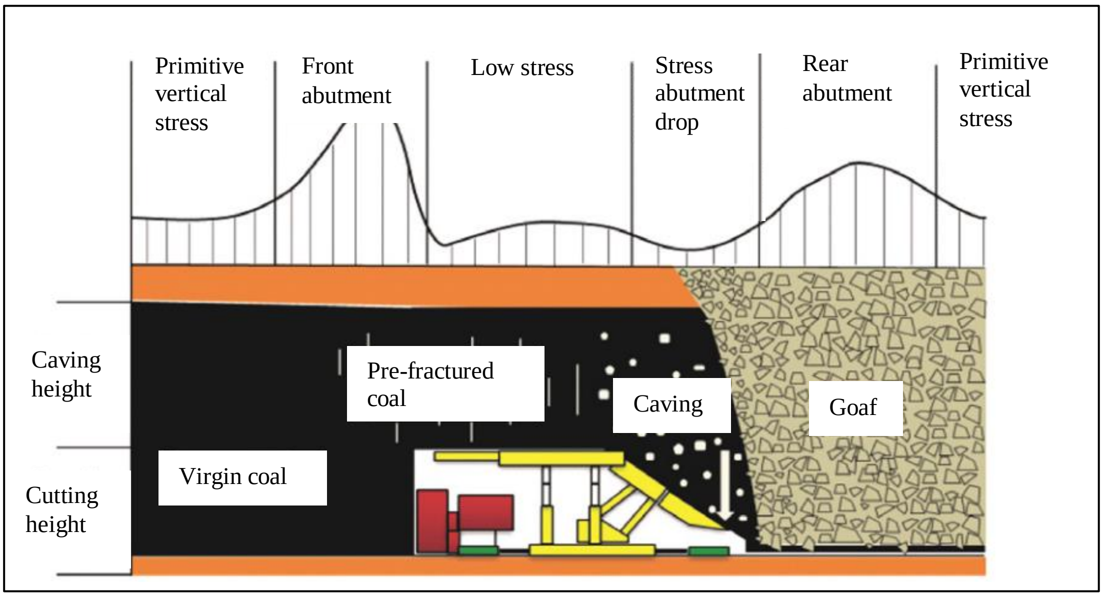

Figure 2.12 Illustration of stress distribution in LTCC zone (Xu, 2004)

Panel design also has an effect on top coal cavability as stated by Vakili and Hebblewhite (2010) who investigated the orientation of panels according to major horizontal stress and roadway designs. According to their study, 45^o face orientation to face vertical joints can increase top coal recovery at the center of the panel and as the angle between roadways and the major principle stress is getting higher, cavability of the top coal can increase at the gates. On the other hand, water content and strength of materials are inversely proportional to the cavability of coal. Water content decreases the strength of the rock mass and causes top coal to cave easier.

Particularly, cavability studies have been advanced by researchers in China. They have developed many methods based on empirical and observational approaches to assess the cavability of top coal in LTCC practice in China. These approaches include fracture index method, fuzzy cluster index method, and statistical analysis method. On the other hand, many researchers conducted various studies on cavability studies based on numerical approaches to estimate the caving mechanism of top coal. These approaches include discontinuum methods (Distinct Element Method) and continuum methods (Finite Difference Method, Finite Element Method, and Boundary Element Method). Yet, there is not a single method explaining cavability mechanism of top coal caving method (Le et al., 2017).

CHAPTER 3

MODELLING AND SIMULATION

In this chapter, general geological information about the mining area is given. In addition to this, data collection during the mine site visit, simulation in Underground Coal Talpac®, modelling algorithms, and its construction in Arena® will be explained in detail.

3.1 Geological Structure of the Mining Area

The mine is located in Soma district, Turkey. Satellite view of Soma region is given in Figure 3.1.

Figure 3.1 Overview on mining region, Soma, Manisa

The region subject to the research is known as “Soma basin”. Soma basin is composed of alluvial sediments and the rock formations formed after Palaeozoic Era. In general, Mesozoic crystallized limestone and Palaeozoic greywacke is at the base of the region. This structure is covered unconformably by Neogene sediments that contain economic lignite coal formation. The youngest structures in the region are Plio-Quaternary rock formation (Nebert, 1978).

Stratigraphic sequences of the rock formation from the bottom to top in the Soma basin is the Pre-Neogene rocks, Neogene sediments, and Post-Neogene sediments, respectively.

Pre-Neogene rocks are the oldest rock unit in the region. This formation is located at the base of Soma basin. Grey greywacke, meta-sandstone, arkose, schist and conglomerate form this unit. In some regions, carbonate rocks formed in Eocene Era are present. In addition, dark-coloured lenticular and banded limestones among the Palaeozoic rocks are present at the region. The Mesozoic units are represented by reddish coloured, thick-bedded or massive limestone-dolomitic limestone ranging from light to dark grey, reaching up to 400 m in thickness (Nebert, 1978).

Neogene rocks are divided into two groups according to their ages. The lower series is Miocene aged and indicated by the symbol “M”. The upper series is Pliocene aged and indicated by the symbol “P”. Lignite formation exists in both Miocene aged series and Pliocene aged series. Pliocene aged formations are composed of five formations, which are fine-grained silicified limestone-tuff formation, conglomerate-sandstone-clay formation, marl-tuff-clay-limestone-leaf fossils formation, top level lignite formation, and clay-sandstone-banded sericite (mottled) formation, from the top layer to the bottom layer. Miocene aged formations are also composed of five formations, which are intermediate level lignite formation, limestone-clay-gravel bands Gastropoda fossils formation, marl (leaf traces) formation, bottom level lignite formation and clay-sand-gravel formation from the top layer to the bottom layer (Nebert, 1978).

Post-Neogene rocks are formed after Pliocene age. Some of these rock formations are Pleistocene aged and others are Holocene aged. They are usually composed of reddish coloured, blocky-coarse conglomerates and pebbly sandstones (Nebert, 1978).

Stratigraphic section of the region is given in Figure 3.2.

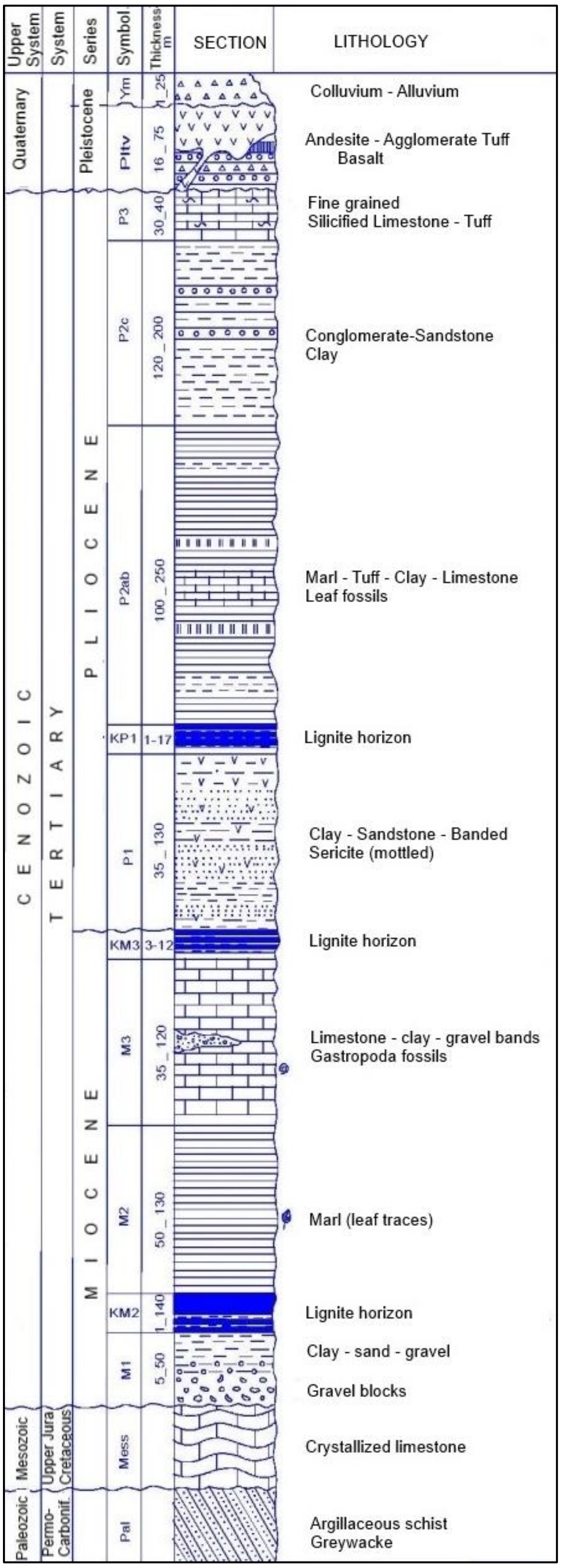

Figure 3.2 Stratigraphic section of the region (Karayiğit et al., 2017)

Coal reserves in the region are around 800 million tonnes. Calorific value of the coal changes between 4000 and 5000 kcal/kg. Moisture content of the coal changes from 10% to 20%. Ash content of coal is between 40% and 50%. Thickness of the coal formation changes between 15 m and 35 m, and inclination of the formation changes between 08º and 25º (Nebert, 1978). In the region, there are many faults, which are mostly high angle oblique-slip normal faults, intersect the coal formation. Strikes of the faults in the region are NW-SE, NE-SW, and E-W directions (İnci, 2002).

Coal mining activities in the region have been continued for 150 years with the advantageous features of the coal seam. It is considered that Soma basin will remain one of the main energy sources of Turkey in the near future.

3.2 Data Collection

Data was collected for six days during the mine site visit between July 07, 2018 and July 13, 2018. In the mine, an IT system was established, however; it does not allow providing access to the database of the equipment or other operations. All the data from the underground mining operations was visually represented in an information display and data was collected manually from this information display.

In the mine, data was collected in each location of the shearer. Followings were recorded in data collection from the information display:

- ❖ 231 data points for time between arrivals of the shearer delays
- ❖ 231 data points for duration of the shearer delays
- ❖ 119 data points for turnaround time of the shearer delays
- ❖ 484 data points for cutting speed of the shearer
- ❖ 1,082 data points for flit speed of the shearer

In the mine, there were many meetings with chef engineers related to coal production, and modelling of underground mining system. In addition, operations on the face coal were followed one day with chef engineers where the coal extraction operations were performed.

On the other hand, longwall top coal caving method with retreat type mining direction is applied in the mine. Cutting system of the shearer is bi-di cutting sequence. According to the data taken from the mechanical engineers related with the mining methods in the mine, there are

- one double-drum shearer in the panel,
- 91 shields along the coal face,
- one AFC on the coal face, and
- one rear conveyor behind the shields.

Production rate changes day by day in the mine. During the mine site visit, shearer utilization was considerably low in the mine. In the simulation models, data collected during the mine site visit was used for analysing underground system in the mine. In reality, shearer utilization can be higher in the mine than outputs of the simulation models. To obtain more accurate results, data should be collected from a longer time interval in the mine.

3.3 Construction of Simulation Modelling in Underground Coal Talpac®

Underground Coal Talpac® is easy to use software to develop simulation models for underground coal operations. This software deals with both bi-directional cutting systems and unidirectional cutting systems in underground longwall mining operations. However, the software has no specific functionality defined for top coal caving operations, and material transportation systems except for AFC.

Input parameters of the software are related with AFC, shearer, supports, cutting parameters, and ventilation. The input windows to define these parameters are given in Tables 3.1, 3.2, 3.3, 3.4, 3.5 and 3.6, respectively.

Table 3.1 Input parameters for AFC

Field	**Value**	**Unit**
AFC Speed	1.14	m/sec
AFC Capacity	1000	tonne/hr
Relate Speed and Capacity	Independent	
AFC Snake Length	22.5	
AFC Width	0.832	meters
AFC Fill Factor	1	
AFC Sigma Height	0.1	meters
Overall Grade of AFC	0	degrees
AFC Flight Bar Spacing	0.752	meters
Weight of Flight Bar	40	kg
AFC Chain Mass	29	kg/m

Table 3.2 Input parameters for shearer

Field	**Value**	**Unit**
Drum Width	0.8	meters
Web Depth Factor	1	
Drum Diameter	2	meters
Max Cutting Speed	11	m/min
Max Flit Speed	27	m/min
Length	12.5	meters
Underbody Clearance	0.5	meters
Drum Reversal Time	20	sec

Table 3.3 Input parameters for supports

Field	**Value**	**Unit**
Number of Supports	91	
Main Gate Supports	0	

Table 3.4 Input parameters for supports (cont'd)

Field	Value	Unit
Tail Gate Supports	0	
Cycle Time	10	sec
Num. of Supports per Batch	1	
Width	1.75	meters

Table 3.5 Input parameters for cutting parameters

Field	Value	Unit
Total Working Height	3	m
Dilution Thickness	0	m
Density of Coal in Seam	1.45	t/m^3
Density of Rock in Seam	2.70	t/m^3

Table 3.6 Input parameters for ventilation

Field	Value	Unit
Ventilation Factors	Intermediate	
Stat. Return Methane Limit	1	%
Coefficient A	23000	
Coefficient B	-0.7	
Seam Gas Capture	40	%
Working Time per Day	20	hr
Working Time per Week	140	hr
Return Air Quantity	40	m^3/sec
Irregularity Coefficient	1.5	

In Table 3.6, coefficient A and B are used for determining the rate of change of gas make with longwall production for a particular gas domain. Seam gas capture is the total percentage capture of seam gas from gas drainage activities. Irregularity coefficient is used for matching the average weekly gas concentrations to the daily peak gas concentrations. However, these factors are not included in this study.

On the other hand, a scenario that includes all steps in one cycle of the shearer cutting is created by using different types of steps in the software. There are four main step types in Underground Coal Talpac® Software, which are “Cut_in”, “Shearer”, “Delay”, and “Reposition_Drums”. “Cut_in” defines entrance to the new web cutting operations. “Shearer” defines movement of the shearer in the operations. “Delay” defines duration of the delay in the related operation. “Reposition_Drums” defines location of the shearer drums and turnaround time of the shearer. Examples of these step types are given in Tables 3.7, 3.8, 3.9, and 3.10.

Table 3.7 Cut_in step type in Underground Coal Talpac® Software

Field	**Value**	**Unit**
Step Type	Cut_in	
Step Name	Cut In	
End Support	mgend()+15	
Max Speed	5.5	m/min
Midstep Reposition Time	10	sec
Support Advance	No_Advance	

*mgend() is a formula for defining supports at the main gate end

Table 3.8 Shearer step type in Underground Coal Talpac® Software

Field	**Value**	**Unit**
Step Type	Shearer	
Step Name	Cut Back	
End Support	15	
Max Speed	6	m/min
Support Advance	Slow_Advance	

Table 3.9 Delay step type in Underground Coal Talpac® Software

Field	**Value**	**Unit**
Step Type	Shearer	
Step Name	Cut Back	
Delays	252	sec

Table 3.10 Reposition_Drum step type in Underground Coal Talpac® Software

Field	**Value**	**Unit**
Step Type	Reposition_Drum	
Step Name	Reverse Drum-1	
Front Drum Position	Top	
Back Drum Position	Bottom	
Delays	25.2	sec

The logic of the software can be considered as different from discrete event simulation defined in its conventional context. Minimum and maximum values are determined in each step. According to these values, the software tries to obtain optimum values by applying an incremental technique to each step. In fact, the software follows a deterministic approach to obtain optimum values for each step rather than a probabilistic approach. An example of optimization window of the software is given in Figure 3.3.

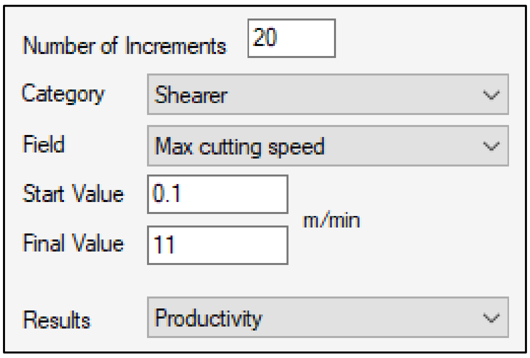

Figure 3.3 Optimization tool of Underground Coal Talpac® Software

The software shows the information about the shearer speed, AFC productivity, shearer productivity, AFC/Shearer production, cumulative production, methane level and optimized values by giving explanatory reports and graphs for each step. In addition, the animation tool available in the software benefits the user by exhibiting one cycle of the shearer movement. It is very useful for visually representing the shearer movement in the defined cutting algorithm. Representation of the animation tool of Underground Coal Talpac® Software is given in Figure 3.4.

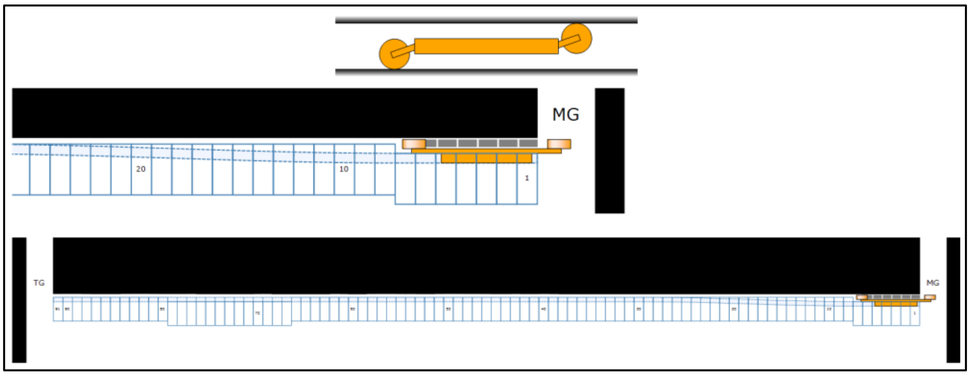

Figure 3.4 Animation tool of Underground Talpac® Software

Within the scope of this thesis, movement of the shearer in one cycle was introduced in steps. In the scenario, there are

- two “Cut in” operations in new web cutting at the main gate and tail gate,
- two “Cut back” operations in returning to the main gate and tail gate,
- two “Lower seam cutting” operations at the beginning of the shearer going from the main gate to tail gate and from tail gate to main gate, and
- two “Full seam cutting” operations.

On the other hand, cleaning operations are performed when coal spillage occurs in the coal face or when the base is not cut properly (increasing in the base elevation). In the model, there are

- eight cleaning operations in “Cut back”,
- four cleaning operations in “Lower seam cutting”, and

- ❖ thirty-three cleaning operations in “Full seam cutting”.

These steps were modelled in Underground Coal Talpac® Software and within the scope of this study, ventilation factors are not covered. After analysing in Underground Coal Talpac® Software, the underground longwall system was also modelled in Arena® because of probabilistic approach’s benefits as it is mentioned before.

3.4 Modelling Algorithms in Arena®

Several algorithms were developed in the simulation models that represent the material handling process, entry location of coal, and the movement cycle of shearer algorithm in bi-di cutting sequence.

3.4.1 Material Handling Algorithm

A double-drum shearer cuts the coal from the coal face that directly falls on the AFC. The AFC transfers the coal excavated from the face to the BSL. At the same time, as the shearer moves from one end to the other, shields are moved forward. When the shields are moved forward, top coal is directly passed to the RC that transfers the top coal to the BSL. BSL reduces the size of face coal together with top coal and transfers the material to the belt conveyor. The first belt conveyor transport the produced coal to the second belt conveyor and the coal is transferred to the last belt conveyor. At the end, coal is transported out of the mine to the surface facilities.

3.4.2 Entry Location of Coal Algorithm

Location of face coal production changes continuously between main gate and tail gate in the coal face and so, spent time of the face coal on the AFC is not constant. This situation is also valid for top coal caving operations. According to the entry location of the coal, the algorithm determines the locations where face coal and top coal enters the system. Thus, the varying time of face coal on the AFC and top coal on the RC can be estimated.

3.4.3 Movement Cycle of Shearer Algorithm in Bi-di Cutting Sequence

Cutting algorithm of the model is based on the cutting sequence of the coal in the longwall face. Cutting sequence of the coal depends on the movement of the shearer and the movement of the shearer is controlled by the shields in the model. Thus, advancing movement of the shields should directly be controlled by the cutting sequence algorithm of the coal. Therefore, cutting sequence of coal and movement of the shearer should be examined in detail. Steps in one cycle of the shearer movement are as follows:

1. First of all, shearer advances towards the gate by cutting the coal from the face (Completion of full seam cutting operation).
2. After excavating the coal at the gate, shearer stops, changes its direction, and returns back (Beginning of cut in operation). By means of advancing on "snake area", the shearer starts to dig the next web, also known as the advance of the shearer. When the shearer moves to the next web cutting, gate shields are moved forward. At the same time, when the shearer excavates the coal at the new web cutting operation, shields above the shearer are moved forward. Meanwhile, shields at the gate push the AFC forward and after the pushing operation, the shearer stops again (Completion of cut in operation).
3. Then, the shearer changes its direction (Beginning of cut back operation) and excavates the coal by returning to the related gate. This is the second cut of the shearer at the related gate. When the shearer excavates the coal at the gate, shields above the shearer are moved forward at the same time (Completion of cut back operation).
4. After excavating the coal at the gate, shearer again stops, changes its direction (Beginning of lower seam cutting operations) and excavates the base coal at the gate (Completion of lower seam cutting operations).
5. After that, the shearer continues to go to the other gate and when it passes the place where the cut in operation is completed, the shearer starts to excavate the coal in the web (Beginning of the full seam cutting operation) and moves on to the other gate. While the shearer goes to the other gate, shields above the

shearer and shields at the gate are moved forward for the second time. Then, advanced shields at the back of the shearer push the AFC forward. Thus, snake area is formed behind the shearer and it follows the shearer until the shearer cuts the coal at the other gate. When the shearer arrives that gate of the longwall (Completion of full seam cutting operation), the steps mentioned above are repeated. Thus, one cycle of the shearer movement is completed.

In the cycle of shearer movement mentioned above, extraction processes at the gates are performed twice. Cycle of the shearer movement at each end is called "shuffle cycle". The movement of the shearer can be seen in Figure 3.5. In the figure, steps mentioned above are given in their numbers. In addition, position of the AFC is represented as a solid line and movement of the shearer is represented as a dashed line in the figure.

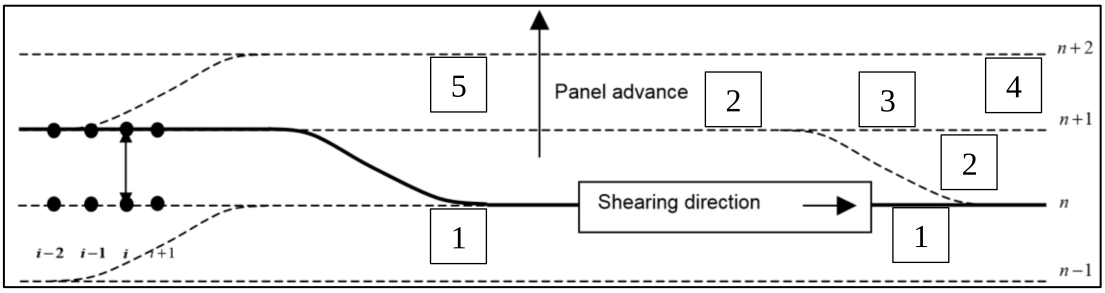

Figure 3.5 Shearer movement and the position of AFC according to shearer movement (Reid et al., 2003)

3.5 Construction of Simulation Modelling in Arena®

In this chapter, entities, resources, variables, and attributes used in the developed model are explained. In addition, applications of the developed algorithms to the simulation model are clarified.

3.5.1 Entities

There are two types of entities used in this study. One is for the face coal and the other is for the top coal. Both entities represent one tonne of produced coal. While production of face coal entity depends on movement of the shearer, production of top coal entity depends on the movement of shields. In the simulation model, shearer movement and shield movement are related to each other as it is mentioned before. In other words, production of face coal entities and top coal entities are dependent on each other in the simulation model.

3.5.2 Resources and Conveyors

In the developed model, shearer is modelled as a source of coal production instead of a resource that entities use. This means that if shearer cuts coal, coal is produced. Otherwise, coal production had to be represented in a more complex structure in the developed model. AFC and RC are modelled as resources. BSL, belt conveyor 1, belt conveyor 2 and belt conveyor 3 are modelled as conveyors in the simulation model.

3.5.3 Variables

Variables are divided into two subgroups in simulation modelling. The first group is the input variables and the second group is the output variables. Input variables are used for the construction of the model algorithms and store input information. On the other hand, output variables are used to represent the outcome of the simulation model according to the different model inputs.

i. Input Variables

Input variables will be examined in three parts. The first part is for face coal operations, the second part is for top coal caving operations and the last part is for transportation of the coal via AFC and RC.

The first part of the model is the production of face coal via shearer activity. List of input variables used for controlling face coal production in the model according to the shearer movement is explained in Tables 3.11, and 3.12.

Table 3.11 Input variables used in controlling face coal operations

Variable Name	Stored Information
Longwall Information Variable	Density of the coal (t/m^3) Cutting height of the coal face (m) Face length (m) Shield length (m) Total shield number Arm length of the shearer
Shearer Information Variable	Direction of the shearer Location of the shearer Speed of the shearer at the current location (m/min) Speed of the shearer at the next location (m/min)
Shuffle Information Variable	Current shuffle number Entry location of the shearer for new web cutting at the main gate Entry location of the shearer for new web cutting at the tail gate
Delay Time Variable	Time between arrivals of the shearer delays (min) Duration of the shearer delays (min) Turnaround time of the shearer (min)
Shearer Limits Variable	Stop station of the shearer when shuffle number is 0 and direction of the shearer is 1 Stop station of the shearer when shuffle number is 1 and direction of the shearer is 2 Stop station of the shearer when shuffle number is 2 and direction of the shearer is 1 Stop station of the shearer when shuffle number is 0 and direction of the shearer is 2 Stop station of the shearer when shuffle number is 1 and direction of the shearer is 1 Stop station of the shearer when shuffle number is 2 and direction of the shearer is 2.
Top-Bottom Variable	Entity (produced coal) comes from top cutter drum Entity (produced coal) comes from bottom cutter drum
Minimum and Maximum Delay Time Variable	Minimum time between arrivals of the shearer delays (min) Minimum duration of the shearer delays (min) Minimum turnaround time of the shearer (min) Maximum duration of the shearer delays (min) Maximum turnaround time of the shearer (min)

Table 3.12 Input variables used in controlling face coal operations (cont'd)

Variable Name	**Stored Information**
Minimum and Maximum Speed Variable	Minimum cutting speed of the shearer (m/min) Minimum flit speed of the shearer (m/min) Maximum cutting speed of the shearer (m/min) Maximum flit speed of the shearer (m/min)
Temporary Shuffle Counter Variable	Current tonnage of the face coal production from the shearer location according to the related shield
Coal Production Variable	Total tonnage of the coal production from the current location of the shearer (t) Total tonnage of the coal production from the next location of the shearer (t)
Cleaning Operations Variable	Total number of cleaning operations at the main gate Total number of cleaning operations at the tail gate Total number of cleaning operations in the main cut operations Current cleaning operation number at the main gate Current cleaning operation number at the tail gate Current cleaning operation number in the main cut operations Location of returning station of the shearer at the main gate for beginning the cleaning operations Location of returning station of the shearer at the tail gate for beginning the cleaning operations Location of returning station of the shearer in the main cut operations for beginning the cleaning operations Location of returning station of the shearer at the main gate for ending the cleaning operations Location of returning station of the shearer at the tail gate for ending the cleaning operations Location of returning station of the shearer in the main cut operations for ending the cleaning operations

The second part of the model is the production of top coal. These variables are used mainly for arranging top coal production according to the face coal production. They are presented in Table 3.13.

Table 3.13 Input variables used in controlling the top coal caving operations

Variable Name	**Stored Information**
Shearer Arranger Variable	Direction of the shearer Location of the shearer Speed of the shearer at the current location (m/min) Speed of the shearer at the next location (m/min)
Top Coal Delay Time Variable	Duration of the shearer delays (min) Turnaround time of the shearer (min)
Shield Location Variable	Advancing shield number
Top Coal Production Variable	Total tonnage of the top coal production from the related shield
Temporary Top Coal Counter Variable	Current tonnage of the top coal production from the related shield
Shuffle Arranger Variable	Current shuffle number Entry location of the shearer for new web cutting at the main gate Entry location of the shearer for new web cutting at the tail gate

The third part of the model represents the transportation of face coal and top coal via AFC and RC. Variables used in this part are presented in Tables 3.14, and 3.15.

Table 3.14 Input variables used in transportation of the face coal via AFC

Variable Name	**Stored Information**
AFC Temporary Counter Variable	Separation of two consecutive entities one by one before entrance of entities to the AFC
AFC Property Variable	Capacity of the AFC (tph) Speed of the AFC (m/sec) Cross-sectional area of the material on the AFC (m^2) Distance covered by one entity on the AFC (m)
AFC Variable	Production time of the previous entity Production time of the current entity
AFC Entry Time Variable	Entry time of the previous entity to the AFC Entry time of the current entity to the AFC

Table 3.15 Input variables used in transportation of the top coal via RC

Variable Name	Stored Information
RC Temporary Counter Variable	Separation of two consecutive entities one by one before entrance of entities to the RC
RC Property Variable	Capacity of the RC (tph) Speed of the RC (m/sec) Cross-sectional area of the material on the RC (m^2) Distance covered by one entity on the RC (m)
RC Variable	Production time of the previous entity Production time of the current entity
RC Entry Time Variable	Entry time of the previous entity to the RC Entry time of the current entity to the RC

The reason why processes related to face coal activities and top coal activities are separated and handled individually in the simulation model although some variables store the same data value (e.g. shearer speed) is that they might be related to different portions of the coal production both from coal face and top coal. These differences occur due to the differences between caving height and cutting height in the mine (Caving height > Cutting height). In fact, variable values change earlier in the face coal operations than top coal operations. Therefore, different variables are given for face coal and top coal operations so that the modelled system is not affected by the variable value changes.

ii. Output Variables

As it is mentioned before, output variables are used for the system output under the different input conditions. These variables are needed to evaluate the alternatives investigated in the simulation model. On the other hand, there is a specific module named as “ReadWrite” in Arena® Software. This module is used for reading data from a file or writing data to a file in a simulation run. In this study, output variables together with “ReadWrite modules were used for obtaining system outputs. Output variables used in the model are listed in Table 3.16.

Table 3.16 Output variables for obtaining results of the system change

Variable Name	Stored Information
Shearer Usage Variable	Total usage of the shearer (min)
Total Production Variable	Total face coal production (t) Total top coal production (t) Total system production (t)

3.5.4 Attributes

There are several attributes used in the model. Attributes play a major role in the system construction similar to variables. In addition, attributes are used in obtaining output data from the simulation model. Attributes used in the model are listed in Table 3.17.

Table 3.17 Attributes used in the simulation model

Attribute Name	Stored Information
Face Coal Production Time Attribute	Production time of the face coal
Top Coal Production Time Attribute	Production time of the top coal
AFC Delay Time Attribute	Spent time of the face coal on the AFC
RC Delay Time Attribute	Spent time of the top coal on the RC
Entity Sequence of Face Coal Attribute	Sequence of the face coal entities produced from the same shearer location
Entity Sequence of Top Coal Attribute	Sequence of the top coal entities produced from the same shield location
Face Coal Entry Location Attribute	Entry location of the face coal
Top Coal Entry Location Attribute	Entry location of the top coal

3.5.5 Modelling Applications

Modelling applications, construction of the modelling algorithms by using entities, resources, variables, and attributes, are summarized in four subsections in this chapter as “Creation of Entities”, “Movement of Shearer”, “Advance of Shields”, and “Modelling of AFC, RC, BSL, Belt Conveyor 1, Belt Conveyor 2, and Belt Conveyor 3”.

i. Creation of Entities

Regardless of the simulation software environment, models commonly start with a Create module, as it is the case in Arena® Simulation Software. Create module determines the production of entities and includes entity types, time between arrivals, and its unit, entities per arrival, max arrivals, and first creation time of the entity. Time between arrivals of the face coal entities are modelled according to the shearer operations in the model. The equation of time between arrivals (TBA) for face coal (FC) entities as a result of the shearer cutting operations is as follows:

$$\text{TBA} = \frac{\text{Shield Length (m)}}{\text{Shearer Speed (m/min) x 0.5 x No. of FC Entities}} + \text{DT (min)} \qquad (6)$$

*DT: Delay time

The reason why the shearer speed is multiplied by 0.5 is that the shearer is a double-drum shearer and it is assumed that the two drums produce coal simultaneously. In other words, two entities enter the system at the same time in the model. Therefore, entities per arrival as a result of the double-drum shearer’s cutting operations are selected as two in the developed model. However, the condition for top coal entities is a bit different as the entity production is one by one and it is modelled according to the total spent time to total entity production ratio in the related shield. In the light of this information, the equation of time between arrivals for top coal (TC) entities is as follows:

$$\text{TBA} = \frac{\text{Shield Length (m)}}{\text{Shearer Speed (m/min) x No. of TC Entities}} + \frac{\text{DT (min)}}{\text{No. of TC Entities}} \qquad (7)$$

The shearer speed value used in this formula is transferred from the face coal operations when the last entity enters the system at the top coal operations. Thus, face coal and top coal operations work in coordination in the simulation model to represent longwall mining as close to reality as possible.

To sum up, there are two Create modules in the simulation model, one represents the face coal operations and the other generates the entities for the top coal operations.

ii. Movement of Shearer

Movement of the shearer is divided into four main parts in one cycle. The first part is the movement of the shearer between gates and is modelled as shuffle number 0. The second part is the movement of the shearer between the related gate and the next web stop station, modelled as shuffle number 1. The third part is the movement of the shearer between the next web stop station and the related gate, modelled as shuffle number 2. The last part is the movement of the shearer for cleaning operations and is modelled as shuffle number 3. The cleaning operations are performed when coal spillage occurs in the coal face or when the base is not cut properly (increase in the base elevation). The movement of the shearer is represented by shield numbers where the first face coal entity produced from the related shield makes the shearer move. The shearer location remains the same until the last face coal entity produced from the related shield enters the system.

The direction of the shearer is modelled as 1 and 2 when the shearer moves the tail gate from main gate and main gate from tail gate, respectively. In other words, shearer direction is 1 when the shearer approaches tail gate and shearer direction is 2 when the shearer approaches main gate.

The speed of the shearer is divided into two groups according to whether the movement of the shearer is a flit movement or not. Flit movement refers to the movement of the shearer without cutting operations. It is modelled according to shuffle numbers and the direction of the shearer. Conditions for flit movement of the shearer in the model are as follows:

- ❖ Condition 1: Following conditions in Table 3.18 explain the flit movement when the shearer moves from main gate to tail gate.

Table 3.18 Flit movement (Condition 1)

Stored Information	**Conditional Description**	
Shuffle Number	==	0
Shearer Direction	==	1
Shearer Location	≤	(Stop station of the shearer when shuffle number is 1 and direction of the shearer is 1)
Shearer Location	≥	(Stop station of the shearer when shuffle number is 2 and direction of the shearer is 2) + 2 * (Arm length of the shearer)

- ❖ Condition 2: Following conditions in Table 3.19 explain the flit movement before the beginning of the new web cutting at the tail gate.

Table 3.19 Flit movement (Condition 2)

Stored Information	**Conditional Description**	
Shuffle Number	==	1
Shearer Direction	==	2
Shearer Location	>	(Entry location of the shearer for the new web cutting at the tail gate) + (Arm length of the shearer)
Shearer Location	≤	(Stop station of the shearer when shuffle number is 0 and direction of the shearer is 1) – 2 * (Arm length of the shearer)

❖ Condition 3: Following conditions in Table 3.20 explain the flit movement after the shearer returns to the tail gate in the shuffle cycle.

Table 3.20 Flit movement (Condition 3)

Stored Information	**Conditional Description**	
Shuffle Number	==	2
Shearer Direction	==	1
Shearer Location	≤	(Entry location of the shearer for the new web cutting at the tail gate) - (Arm length of the shearer)
Shearer Location	≥	(Stop station of the shearer when shuffle number is 1 and direction of the shearer is 2) + 2 * (Arm length of the shearer)

❖ Condition 4: Following conditions in Table 3.21 explain the flit movement when the shearer moves from tail gate to main gate.

Table 3.21 Flit movement (Condition 4)

Stored Information	**Conditional Description**	
Shuffle Number	==	0
Shearer Direction	==	2
Shearer Location	≥	(Stop station of the shearer when shuffle number is 1 and direction of the shearer is 2)
Shearer Location	≤	(Stop station of the shearer when shuffle number is 2 and direction of the shearer is 1) – 2 * (Arm length of the shearer)

❖ Condition 5: Following conditions in Table 3.22 explain the flit movement before the beginning of the new web cutting at the main gate.

Table 3.22 Flit movement (Condition 5)

Stored Information	Conditional Description	
Shuffle Number	==	1
Shearer Direction	==	1
Shearer Location	<	(Entry location of the shearer for the new web cutting at the main gate) – (Arm length of the shearer)
Shearer Location	≥	(Stop station of the shearer when shuffle number is 0 and direction of the shearer is 2) + 2 * (Arm length of the shearer)

❖ Condition 6: Following conditions in Table 3.23 explain the flit movement after the shearer returns to the main gate in the shuffle cycle.

Table 3.23 Flit movement (Condition 6)

Stored Information	Conditional Description	
Shuffle Number	==	2
Shearer Direction	==	2
Shearer Location	≤	(Stop station of the shearer when shuffle number is 1 and direction of the shearer is 1) – 2 * (Arm length of the shearer)
Shearer Location	≥	(Entry location of the shearer for the new web cutting at the main gate) + (Arm length of the shearer)

According to the model, when the shearer moves without cutting operations, flit speed is assigned to the shearer. Otherwise, cutting speed is assigned to the shearer. On the other hand, new speed values, which are different from the speeds in flit movement or cutting movement, can be assigned to the shearer in cleaning operations if necessary. Assignment of the shearer speed is realized at each location of the shearer.

General delay time in the movement of the shearer is determined by delay time duration and time between arrivals of shearer delays. Delay time duration is the period of the shearer inactivity. Time between arrivals of the shearer delays is the time duration between beginning of the shearer activity and inactivity. It can be simply considered as time duration of the shearer activity. In the simulation model, shearer speed is never assigned as zero. The shearer inactivity is modelled by adding delay time to time between arrivals of two consecutive face coal entities. In this model, general delay time in the movement of the shearer is assigned at the end of the shearer locations. Turnaround time is assigned at each stop station of the shearer.

iii. Advance of Shields

Advance of shields follows the movement of the shearers. It is controlled by variables used in top coal operations and performed according to the following conditions:

- Condition 1: This condition explains advancing shields when the shearer moves from main gate to tail gate. At the beginning of the movement, advancing shield number increases from 1 to the number of gate shields. After passing the stop station of the shearer (when shuffle number is 1 and direction of the shearer is 1), advancing shield number increases until the shearer arrives the stop station of the shearer in this movement. Conditions for advance of shields are given in Tables 3.24, and 3.25.

Table 3.24 Advance of the shields (Condition 1-1)

Stored Information	Conditional Description	
Shuffle Number	==	0
Shearer Direction	==	1
Shearer Location	>	(Stop station of the shearer when shuffle number is 2 and direction of the shearer is 2)
Shearer Location	≤	(Stop station of the shearer when shuffle number is 2 and direction of the shearer is 2) + (Number of the gate shields)

Table 3.25 Advance of the shields (Condition 1-2)

Stored Information	Conditional Description	
Shuffle Number	==	0
Shearer Direction	==	1
Shearer Location	>	(Stop station of the shearer when shuffle number is 1 and direction of the shearer is 1)
Shearer Location	≤	(Stop station of the shearer when shuffle number is 0 and direction of the shearer is 1)

❖ Condition 2: This condition explains advancing shields when the shearer moves from tail gate to the stop station of the shearer in the new web cutting operation. At the beginning of the movement, advancing shield number decreases from the number of the shields to the number of shields minus the number of gate shields. After the shearer passes the entry location of the new web cutting operations, advancing shield number decreases from the entry location of the new web cutting operations to stop station of the shearer in this movement. Conditions for advance of shields are given in Tables 3.26, and 3.27.

Table 3.26 Advance of shields (Condition 2-1)

Stored Information	Conditional Description	
Shuffle Number	==	1
Shearer Direction	==	2
Shearer Location	<	(Stop station of the shearer when shuffle number is 0 and direction of the shearer is 1)
Shearer Location	≥	(Stop station of the shearer when shuffle number is 0 and direction of the shearer is 1) – (Number of gate shields)

Table 3.27 Advance of shields (Condition 2-2)

Stored Information	**Conditional Description**	
Shuffle Number	==	1
Shearer Direction	==	2
Shearer Location	≤	(Entry location of the shearer for new web cutting at the tail gate)
Shearer Location	≥	(Stop station of the shearer when shuffle number is 1 and direction of the shearer is 2)

- Condition 3: This condition explains advancing shields when the shearer moves from the stop station of the shearer in the new web cutting operation to the tail gate. This is the second cut of the shearer at the tail gate. Advancing shield number increases from the entry location of the new web cutting operations at the tail gate to the stop station of the shearer in this movement. Condition for advance of shields is given in Table 3.28.

Table 3.28 Advance of shields (Condition 3)

Stored Information	**Conditional Description**	
Shuffle Number	==	2
Shearer Direction	==	1
Shearer Location	>	(Entry location of the shearer for new web cutting at the tail gate)
Shearer Location	≤	(Stop station of the shearer when shuffle number is 2 and direction of the shearer is 1)

- Condition 4: This condition explains advancing shields when the shearer moves from tail gate to main gate. At the beginning of the movement, advancing shield number decreases from the number of the shields to the number of shields minus the number of gate shields. After passing the stop station of the shearer (when shuffle number is 1 and direction of the shearer is 2), advancing shield number decreases until the shearer arrives the stop station of the shearer in this movement. Conditions for advance of shields are given in Tables 3.29, and 3.30.

Table 3.29 Advance of shields (Condition 4-1)

Stored Information	Conditional Description	
Shuffle Number	==	0
Shearer Direction	==	2
Shearer Location	<	(Stop station of the shearer when shuffle number is 2 and direction of the shearer is 1)
Shearer Location	≥	(Stop station of the shearer when shuffle number is 2 and direction of the shearer is 1) – (Number of gate shields)

Table 3.30 Advance of shields (Condition 4-2)

Stored Information	Conditional Description	
Shuffle Number	==	0
Shearer Direction	==	2
Shearer Location	<	(Stop station of the shearer when shuffle number is 1 and direction of the shearer is 2)
Shearer Location	≥	(Stop station of the shearer when shuffle number is 0 and direction of the shearer is 2)

❖ Condition 5: This condition explains advancing shields when the shearer moves from main gate to the stop station of the shearer in the new web cutting operation. At the beginning of the movement, advancing shield number increases from 1 to the number of gate shields. After the shearer passes the entry location of the new web cutting operations, advancing shield number increases from the entry location of the new web cutting operations to the stop station of the shearer in this movement. Conditions for advance of shields are given in Tables 3.31, and 3.32.

Table 3.31 Advance of shields (Condition 5-1)

Stored Information	Conditional Description	
Shuffle Number	==	1
Shearer Direction	==	1
Shearer Location	>	(Stop station of the shearer when shuffle number is 0 and direction of the shearer is 2)
Shearer Location	≤	(Stop station of the shearer when shuffle number is 0 and direction of the shearer is 2) + (Number of gate shields)

Table 3.32 Advance of shields (Condition 5-2)

Stored Information	Conditional Description	
Shuffle Number	==	1
Shearer Direction	==	1
Shearer Location	≥	(Entry location of the shearer for new web cutting at the main gate)
Shearer Location	≤	(Stop station of the shearer when shuffle number is 1 and direction of the shearer is 1)

- Condition 6: This condition explains advancing shields when the shearer moves from the stop station of the shearer in the new web cutting operation to the main gate. This is the second cut of the shearer at the main gate. Advancing shield number decreases from the entry location of the new web cutting operations at the main gate to the stop station of the shearer in this movement. Condition for advance of shields is given in Tables 3.33, and 3.34.

Table 3.33 Advance of shields (Condition 6)

Stored Information	Conditional Description	
Shuffle Number	==	2
Shearer Direction	==	2

Table 3.34 Advance of shields (Condition 6, cont'd)

Stored Information	Conditional Description	
Shearer Location	<	(Entry location of the shearer for new web cutting at the main gate)
Shearer Location	≥	(Stop station of the shearer when shuffle number is 2 and direction of the shearer is 2)

Generally, shields above the shearer are moved forward when shearer cuts the coal. Aim of the shields advance is to protect the shearer from coal or rock spillage from the hanging wall.

As it is mentioned before, shearer's data is stored in the variables controlling the face coal operations and is transferred to the variables controlling the top coal operations. In this way, advance of shields works in coordination with movement of the shearer.

iv. Modelling of AFC, RC, BSL, Belt Conveyor 1, Belt Conveyor 2 and Belt Conveyor 3

In Arena® Software, conveyors have fixed lengths and velocities that consist of cells. Entities seize a definite number of conveyor cells according to ratio of their size to the cell size. They can move on the cells by seizing and releasing the cells from the first cell to the last cell. In other words, every entity uses every cell of the conveyor during the transportation stage.

In the simulation model, BSL, belt conveyor 1, belt conveyor 2, and belt conveyor 3 are defined as conveyors. All the entities arrive these conveyors are transported by conveyor module in Arena® Software. Illustration of an entity movement on the Arena® conveyor module is represented in Figure 3.6. For a better understanding of the concept, movement of an entity having a size of two cells on the conveyor is illustrated in Figure 3.6.

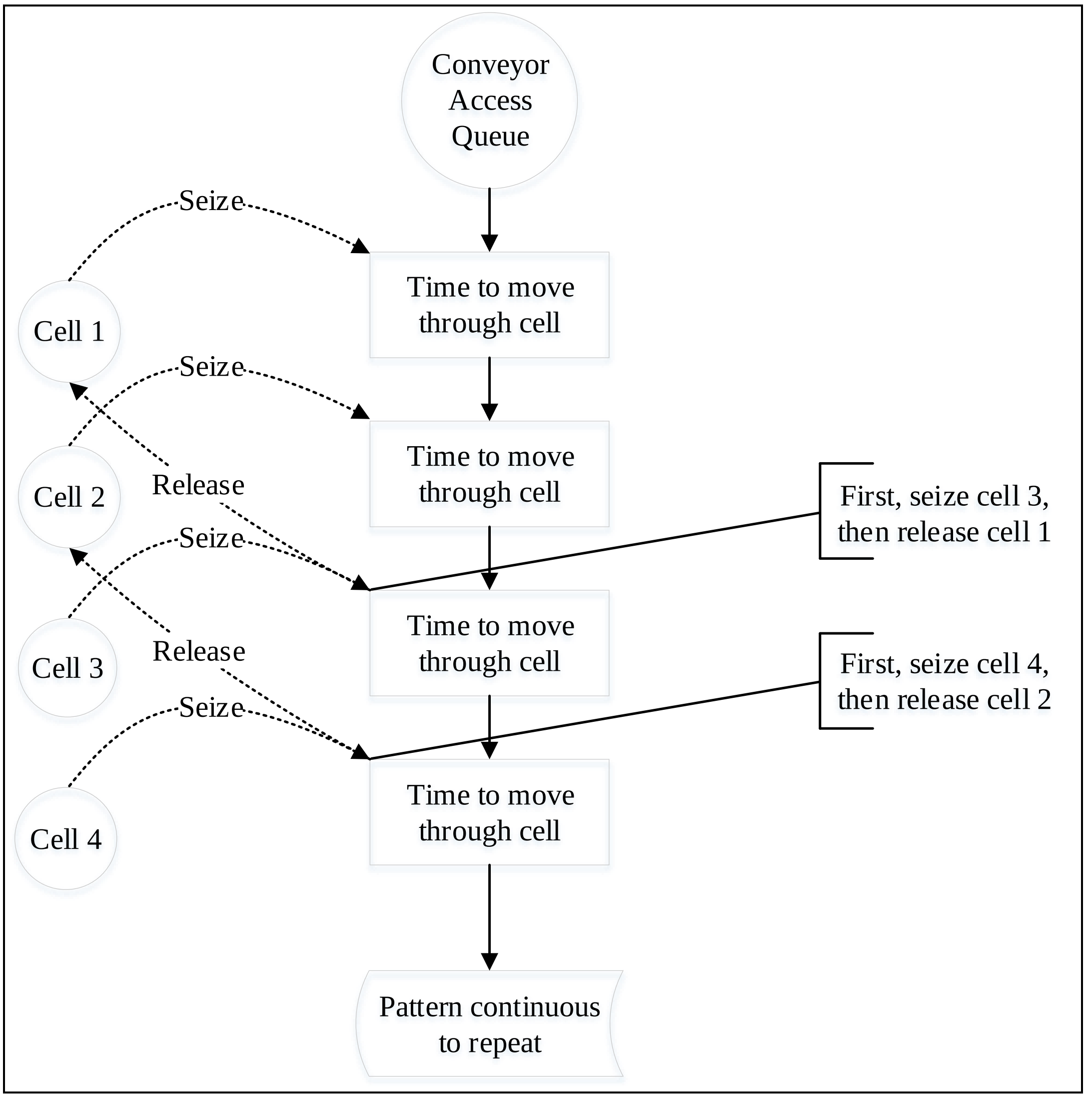

Figure 3.6 Movement of the entity on the conveyor (Rossetti, 2016)

Spent time of the entities on the conveyor do not change for the same entities as seen in Figure 3.6. However, in real cases, production place of the coal changes continuously. As a result, spent time of the entities on the conveyor changes continuously. Therefore, transportation of the produced coal via conveyor block does not represent the real case. For that reason, AFC and RC are defined as resources having infinite capacities with varying delay times according to the mathematical equations. The reason why they have infinite capacities is about the capacity concept of Arena® Simulation Software. The capacity of a resource is the number of entities using the resource at the same time. The problem here occurs when many entities enters the system in a considerably short period. In such situations, number of entities equal to the resource capacity seize the resource and all the entities are transported at the same time. However, in real cases, entities entering the system use the conveyors in an order. Thus, resources having fixed capacities are not considered as suitable to define AFC and RC systems. Therefore, a system is developed for defining the AFC and RC where according to the logic of this system, AFC and RC have infinite capacities. All entities utilize the AFC or RC but the model determines the spent time of entities on the AFC or RC. For the determination of the spent time process, the model controls whether there is enough space on the AFC or RC for the current entity according to the previous entity. The aim of developing such this system is to transport the face coal or top coal to the BSL at the right time. The equation for the spent time of the entities on the conveyor is as follows:

$$\text{ST/C} = \text{Shield Entry (No.) x } \frac{\text{Shield Length (m)}}{\text{Conveyor Speed (m/sec) x 60}} + \text{TNFES (min)} \quad (8)$$

*TNFES: Time needed for enough space
*ST/C: Spent time on the conveyor

TNFES calculation is based on the distance covered by one tonne of coal on the conveyor, the entity production time of the last two entities, which are the previous entity and the current entity, and the time needed for creating one entity space according to the conveyor speed. Calculation for the cross-sectional area of the material on the conveyor is as follows:

$$\text{Area } (\text{m}^2) = \frac{\text{Conveyor Capacity (tph)}}{\text{Density } (\text{t/m}^3) \text{ x Conveyor Speed (m/sec) x 3600}} \quad (9)$$

*Area: Cross-sectional area of the material on the conveyor

According to the cross-sectional area of the material, the distance covered by one tonne of coal on the conveyor can be calculated as,

$$\text{Distance (m/t)} = \frac{1}{\text{Density } (\text{t/m}^3) \text{ x Area } (\text{m}^2)} \quad (10)$$

*Distance: Distance covered by one tonne of coal on the conveyor

After calculation of the distance covered by one tonne of coal on the conveyor, time needed for creating one entity space on the conveyor can be calculated as,

$$\text{TNFC1ES/C (min/t)} = \frac{\text{Distance (m/t)}}{\text{Conveyor Speed (m/sec) x 60}} \quad (11)$$

*TNFC1ES/C: Time needed for creating one entity space on the conveyor

According to these calculations, there are two conditions depending on whether there is enough space on the conveyor or not in material transportation process on the conveyors.

- ❖ Condition 1: When the current entity is produced, there is no material accumulation in front of the conveyor and so, the current entity directly passes to the conveyor.

$$\text{PTCE} > (\text{ETPE/C} + \text{TNFC1ES/C}) \quad (12)$$

*PTCE: Production time of the current entity
*ETPE/C: Entry time of the previous entity to conveyor

In other words, there is enough space for the entity on the conveyor and so,

$$\text{ETCE/C} = \text{PTCE} \quad (13)$$

*ETCE/C: Entry time of the current entity to conveyor

This condition also states that,

$$\text{TNFES} = 0 \quad (14)$$

- ❖ Condition 2: When the current entity is produced, there is a material accumulation in front of the conveyor and so, the current entity cannot directly pass to the conveyor.

$$\text{PTCE} < (\text{ETPE/C} + \text{TNFC1ES/C}) \quad (15)$$

In other words, there is not enough space for the entity on the conveyor and so,

$$\mathrm{ETCE/C} = (\mathrm{ETPE/C} + \mathrm{TNFC1ES/C}) \quad (16)$$

This condition also states that,

$$\mathrm{TNFES} = (\mathrm{ETPE/C} + \mathrm{TNFC1ES/C}) \quad (17)$$

The model continuously controls these two conditions. According to these conditions, spent time is assigned as “AFC Delay Time” or “RC Delay Time” attribute on the entity and AFC or RC use these attributes in their delay blocks. Thus, it is provided that every entity arrives the BSL at the right time.

Modelling applications in Arena® Software are presented in Appendix C.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, results of statistical analysis, simulation modelling in Underground Coal Talpac® and Arena® including model limitations and assumptions used in the construction of the simulation modelling, outputs of the simulation model, verification and validation processes are given. In addition, sensitivity analysis and discussion about these results are presented.

4.1 Results of Statistical Data Analysis

All the data collected during the mine site visit is evaluated in Arena® Input Analyzer (Arena Simulation Software, 2015), and Minitab® 18 (Minitab®, 2018). After analysing raw data, descriptive statistics on time between arrivals of the shearer delays is presented in Table 4.1.

Table 4.1 Descriptive statistics of TBA of the shearer delays (min)

N	Mean	St.Dev	Median	Min.	Max.	Skewness	Kurtosis
231	3.584	4.365	2.050	0.150	33.683	3.055	13.255

Goodness of fit test reports, and square error analysis on time between arrivals of the shearer delays are presented in Figures 4.1, and 4.2. According to the goodness of fit test results, corresponding P-value (0.345) is greater than significance level (5%) and so, lognormal distribution is a good choice for time between arrivals of the shearer delays. In addition, according to the square error analysis, lognormal distribution has the minimum square errors. Therefore, lognormal distribution is best fitted to time between arrivals of the shearer delays. Histogram of the time between arrivals of the shearer delays, and lognormal distribution fit on the histogram are presented in Figure 4.3.

```
        Distribution Summary

Distribution:   Lognormal
Expression:     LOGN(3.67, 5.4)
Square Error:   0.000738

Chi Square Test
  Number of intervals   = 5
  Degrees of freedom    = 2
  Test Statistic        = 2.25
  Corresponding p-value = 0.345

Kolmogorov-Smirnov Test
  Test Statistic        = 0.0396
  Corresponding p-value > 0.15

        Data Summary

Number of Data Points   = 231
Min Data Value          = 0.15
Max Data Value          = 33.7
Sample Mean             = 3.58
Sample Std Dev          = 4.36

        Histogram Summary

Histogram Range         = 0 to 34
Number of Intervals     = 15
```

Figure 4.1 Goodness of fit test report - TBA of the shearer delays

Function	Sq Error
Lognormal	0.000738
Weibull	0.00438
Erlang	0.00609
Exponential	0.00609
Beta	0.00742
Gamma	0.00922
Normal	0.139
Triangular	0.225
Uniform	0.281

Figure 4.2 Square error analysis - TBA of the shearer delays

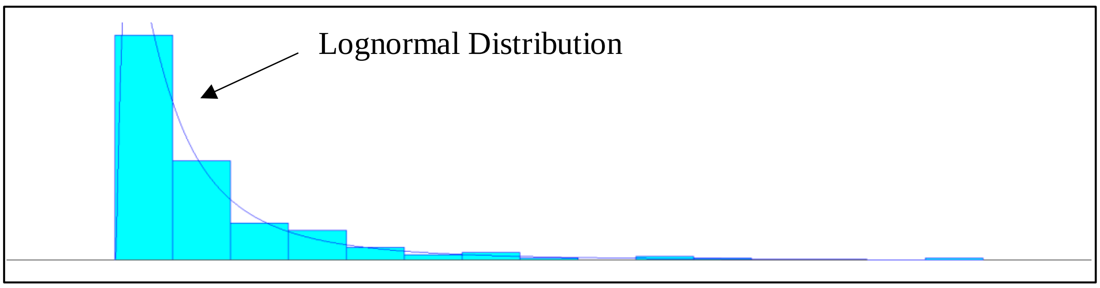

Figure 4.3 TBA of the shearer delays

Details about statistical analysis are presented in Appendix B.1, B.2 and B3.

4.2 Results of Simulation Modelling in Underground Coal Talpac®

In Underground Coal Talpac® Software, a scenario that includes one cycle of shearer operations was created. According to the data collected from the mine site, the shearer cannot always complete one cycle in a day. One cycle completion time of the shearer during the mine site visit took approximately 2.5 days. Shearer movement during the mine site visit were modelled in Underground Coal Talpac® and outputs of model after completion of one cycle is presented in Table 4.2.

Table 4.2 Model outputs of Underground Coal Talpac® Software

Information (One Cycle)	Model Outputs	Unit
Total Time	3,700.29	min
Total Production	17.97	tph
Face Length	159.25	m
Weight Sheared	1,108.38	t
AFC Power	767.85	kW

Maximum speed of the shearer changes between 0 and 11.50 m/min in the mine. Maximum shearer speeds according to the steps in one cycle of the shearer are presented in Tables 4.3, and 4.4.

Table 4.3 Maximum shearer speed according to the steps

Name of the Step	Max Shearer Speed (m/min)
Cut In-1	5.50
Cut Back-1	4.35
Cleaning Operations in Cut Back-1	2.60
Lower Seam Cutting-1	5.30
Cleaning Operations in Lower Seam Cutting-1	4.70
Full Seam Cutting-1	6.60

Table 4.4 Maximum shearer speed according to the steps (cont'd)

Name of the Step	Max Shearer Speed (m/min)
Cleaning Operations in Full Seam Cutting	11.50
Cut In-2 (Return)	8.40
Cut Back-2	6.50
Cleaning Operations in Cut Back-2	8.00
Lower Seam Cutting-2 (Return)	7.80
Cleaning Operations in Lower Seam Cutting-2	8.30
Full Seam Cutting-2	5.80
Cleaning Operations in Full Seam Cutting-2	7.60

According to Underground Coal Talpac®, shearer production rates can reach 1,075.29 tph shown in Figure 4.4. Gaps in the figure indicate that there is no coal production and there are many gaps in Figure 4.4, which implies that shearer utilization rate is considerably low in the mine.

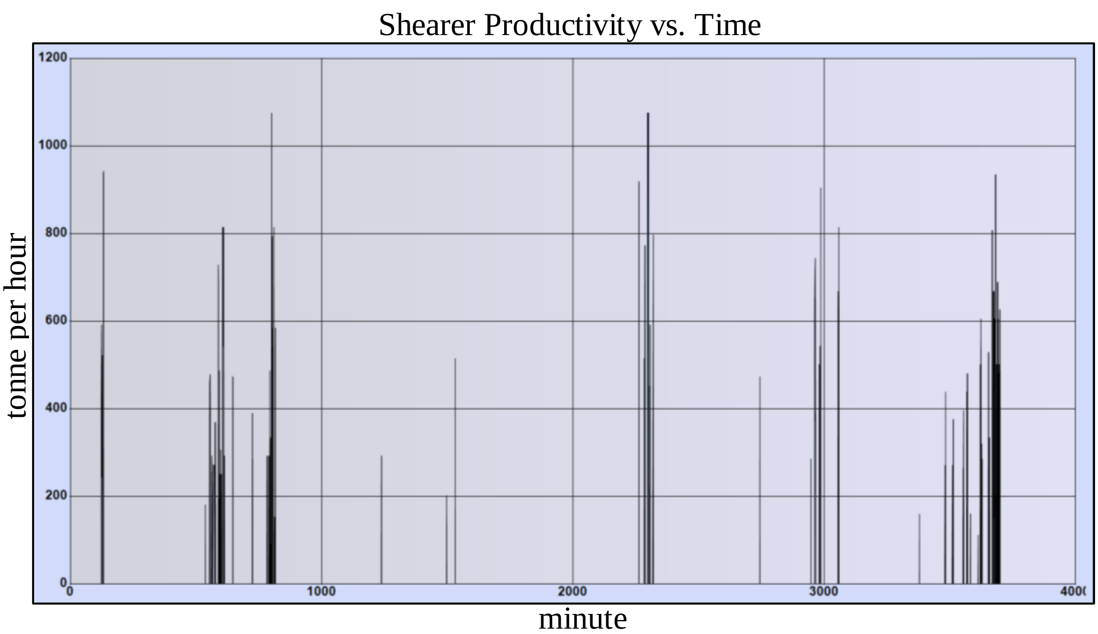

Figure 4.4 Shearer productivity (tph) in one cycle of the shearer

The cumulative production of the shearer starts with the first shearer action and ends after the completion of one cycle of the shearer. According to the model, total shearer production is 1,108.38 t and the completion time of the shearer cycle is 3,700.29 min. Cumulative coal production (t) according to the simulation time (min) is presented in Figure 4.5. In the figure, horizontal lines represent that the cumulative production is not changing. In other words, shearer utilization rate is considerably low, as it can be inferred from Figure 4.4.

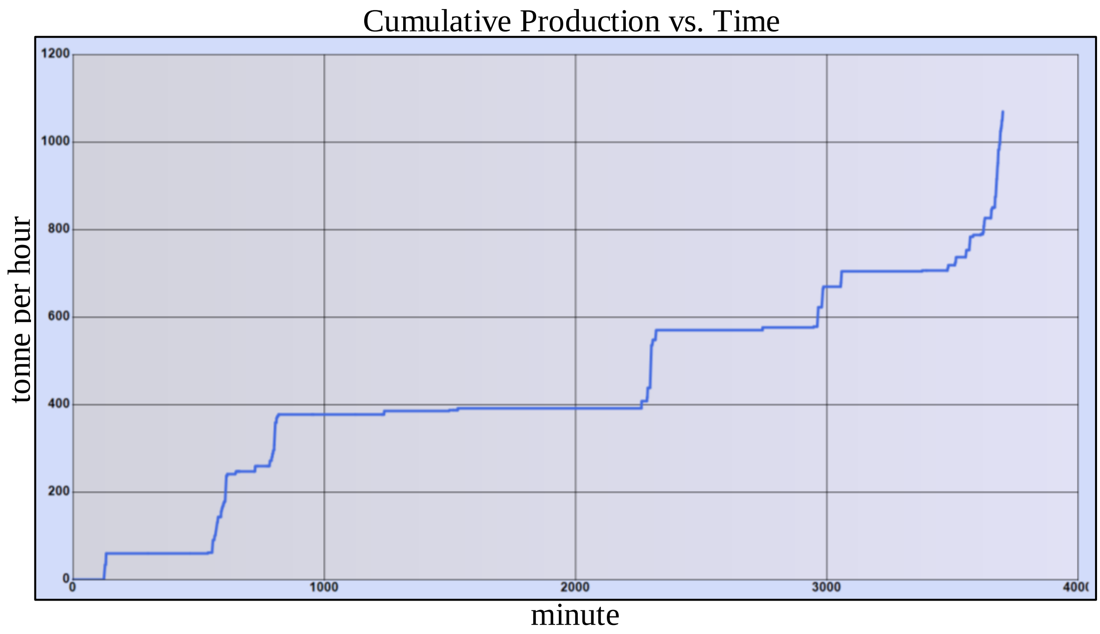

Figure 4.5 Cumulative production of the shearer (t) in one cycle of the shearer

4.3 Results of Simulation Modelling in Arena®

In Arena® Software, data collected from the mine were used after statistical analysis. In the model, 20 different scenarios were assessed. On the other hand, hardware specifications of the computer where simulation models were run are important parameters for considering run time of the simulation model. Hardware specifications of the computer used in this study, and simulation batch run (No animation) time are presented in below:

Table 4.5 Computer specifications

Hardware Name	**Specification**
Processor	Intel® Core™ i5-6500 CPU @3.20 GHz (4 CPUs)
RAM	8192 MB
Simulation Batch Run Time	01:31 (mm:ss)

4.3.1 Assumptions and Limitations

There are several assumptions in the developed model. They are as follows:

- Coal left behind the longwall face can cause spontaneous combustion fires when it is in contact with air. To prevent spontaneous combustion of coal, no coal should be left in the goaf area. In the mine, certain amount of impurities are extracted in top coal operations to extract all the coal. In the simulation model, coal and impurities are not separated from each other so that all of the production is assumed to be "coal".
- In the simulation model, the movement of the shearer is modelled according to shield numbers (e.g., the current location of shearer is the 1st shield and the next location of the shearer is the 2nd shield). In this model, production place of the coal (entity) is the same for the entities entering the system from the same shearer location. In addition, shearer speed changes only when location of the shearer changes. Thus, time between arrivals is constant for the entities entering the system from the same location of the shearer.
- When there are cleaning operations in the mine, it is assumed that there is no coal production.
- Shearer usage is considered as the total activity time in coal cutting operations in a day. In the model, spent time in cleaning operations are not considered as part of the shearer utilization.
- Top coal production is only achieved when the related shield is moved forward.
- TBA of the top coal entities is assumed to be the ratio between total spent time in the related shield advancing and total entity production.

On the other hand, there are some limitations in the model. They are as follows:

- Simulation model is developed for one panel in longwall mining operations. However, it can be adapted to longwall mines having several panels by making structural changes in the model.
- Simulation model is developed for the longwall mines having bi-directional cutting sequence. Therefore, uni-directional systems cannot be simulated in this study via the developed model unless the model is modified.

4.3.2 Verification and Validation

Verification processes are achieved by controlling of the model outputs under certain conditions of inputs to investigate the behaviour of the system. If the logic of the system works properly, verification process is completed. Besides, animations are very useful for the verification of the model as a preliminary check. With the aid of the animations, behaviour of each entity in the system can be followed. Thus, analysts can get information about whether the system works properly or not. In this thesis study, verification process is completed with simple animations and examination of the model outputs under known circumstances. Validation processes are achieved by comparison of model outputs with the real-life system. In Table 4.6, model outputs are given under different replication numbers (RN).

Table 4.6 Daily average coal production according to different replication numbers

Daily Coal Production (t) ± Half-width (95% CI)			**RN**
FC	**TC**	**Total**	
733.90 ± 64.00	9,281.44 ± 789.89	10,035.34 ± 853.80	50
717.49 ± 44.58	9,044.25 ± 556.78	9,761.74 ± 601.28	100
726.73 ± (< 36.31)	9,154.19 ± (< 453.20)	9,880.92 ± (< 489.45)	150
725.03 ± (< 31.72)	9,114.20 ± (< 393.34)	9,839.23 ± (< 425.00)	200

*CI: Confidence Interval

As it is shown in Table 4.6, half-width of the model output decreases with increasing replication number. After 150 replications, there are no remarkable changes in terms of half-widths of the model outputs. Therefore, replication number is chosen as 150 in this study. According to Arena® Software outputs, minimum and maximum productions of the shearer are 21 t and 1,177 t, respectively.

In Table 4.7, daily coal productions during the mine site visit are given and comparison of model outputs and daily coal production is presented in Table 4.8.

Table 4.7 Daily coal productions of the mine

Day No	**Daily Coal Productions (t)**		
	FC	**TC**	**Total**
1	736.89	9,307.32	10,044.21
2*	267.96	3,384.48	3,652.44
3	785.61	9,922.68	10,708.29
4	499.38	6,307.44	6,806.82
5	353.22	4,461.36	4,814.58
6	773.43	9,768.84	10,542.27

*: In the 2nd day, the mine operates with two shifts (16 hrs). Hence, there is a significant difference between 2nd day and other days in terms of coal daily production.

Table 4.8 Model outputs vs. Daily coal production of the mine in average

Types of Results	**FC**	**TC**	**Total**
Model Output in Average (t)	726.73	9,154.19	9,880.92
Daily Coal Production of the Mine in Average (t)	629.71	7,953.53	8,523.83
Differences (%)	15.41%	15.10%	15.92%

In Table 4.8, calculation of average daily coal productions in the mine is based on the productions in days 1, 3, 4, 5, and 6 because the mine operates two shifts in day 2.

According to Table 4.8, the differences between average daily face coal production, top coal production and the sum of face coal production and top coal production of the mine and model outputs are 15.41%, 15.10%, and 15.92%, respectively. These results indicate that simulation outputs and average daily production of the mine are compatible with each other. Hence, verification and validation processes are completed.

4.3.3 Model Outputs

Model outputs give that daily coal production on the longwall face is 726.73 t and daily shearer usage is 89.07 min in average. In addition, cleaning operations are performed 13 times in a day.

According to the model, spent time in different operations is presented in Table 4.9.

Table 4.9 Daily time breakdown in average

Name of the Duration	**Duration (min)**
Total Duration of the Shearer Delays	1,242.06
Total Turnaround Time of the Shearer	14.55
Total Cutting Time of the Shearer	89.07
Total Flit Time of the Shearer	94.32
Total Time in a Day	1,440

In the context of the daily time breakdown, it was observed that the shearer spent most of its time to delays. Following this, flit time of the shearer was seen as the second important duration parameter. Also, cutting time of the shearer was seen to be close to the flit time. Based on the fundamental principles of the shearer production, shearer spent relatively lower time to turnaround operation as it was expected. In order to evaluate the daily shearer time breakdown in more details, pie chart was constructed according to the time duration of the shearer operations mentioned above. Constructed pie chart is given in Figure 4.6.

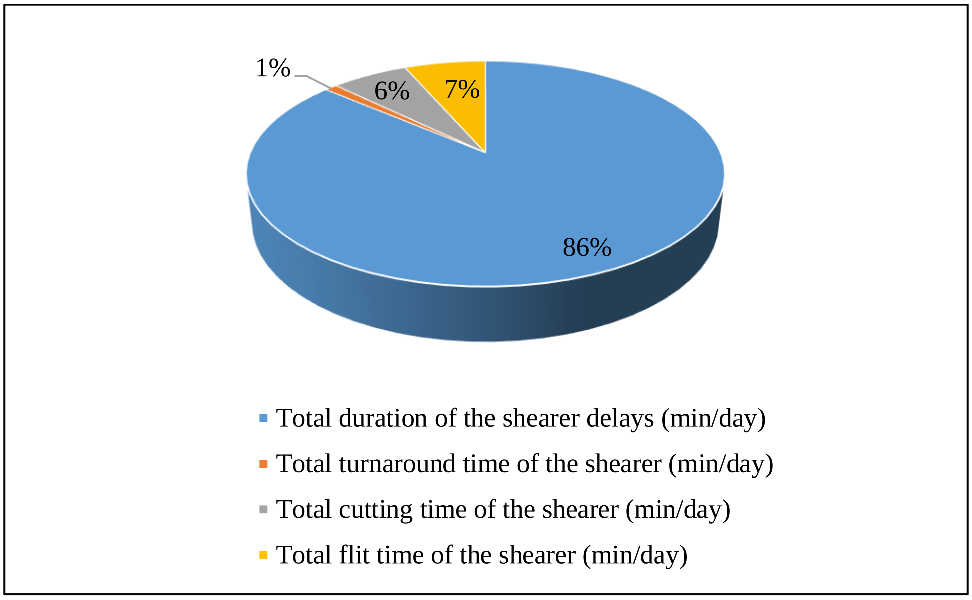

Figure 4.6 Daily time breakdown in average

Total duration of the shearer delays in the mine is 1,242.06 min/day in average. It changes between 1,106.73 min/day and 1,404.42 min/day. Outputs on total duration of the shearer delays in the mine are presented in Figure 4.7.

Total turnaround time of the shearer in the mine is 14.55 min/day in average. It changes between 5.09 min/day and 25.74 min/day. Outputs on total turnaround time of the shearer in the mine are presented in Figure 4.8.

Total cutting time of the shearer in the mine is 89.07 min/day in average. It changes between 3.11 min/day and 155.33 min/day. Outputs on total cutting time of the shearer in the mine are presented in Figure 4.9.

Total flit time of the shearer in the mine is 94.32 min/day in average. It changes between 27.37 min/day and 154.54 min/day. Outputs on total flit time of the shearer in the mine are presented in Figure 4.10.

Total number of the cleaning operations in the mine is 13.05 in average. It changes between 4 and 20. Outputs on total number of cleaning operations in the mine are presented in Figure 4.11.

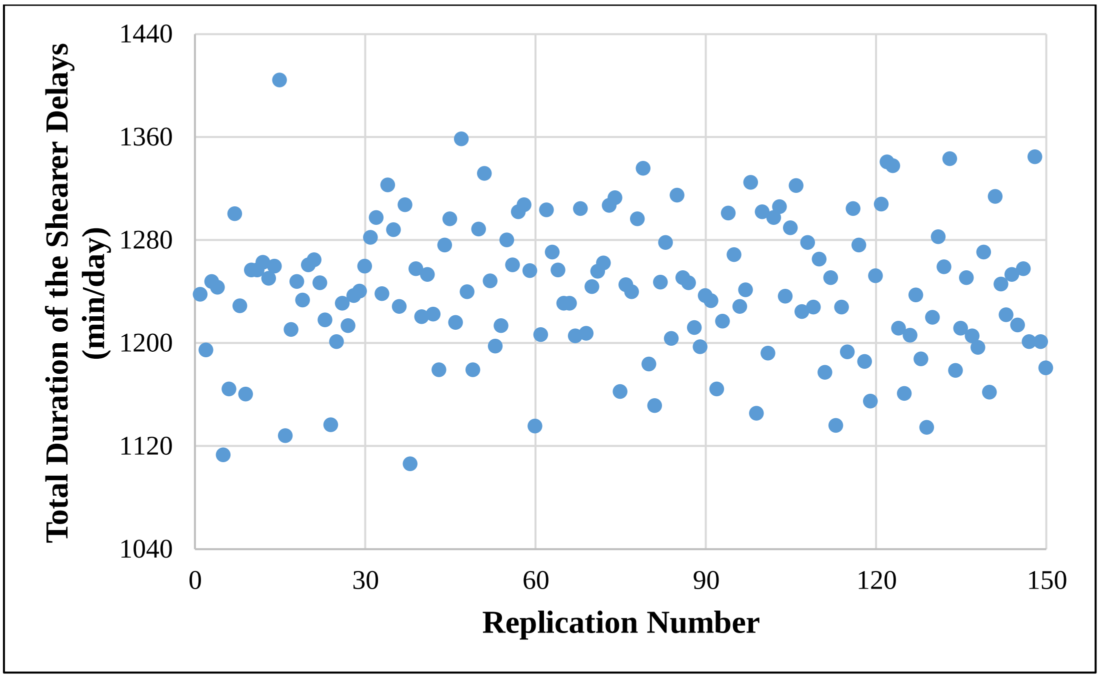

Figure 4.7 Total duration of the shearer delays (min/day) according to the different replication numbers

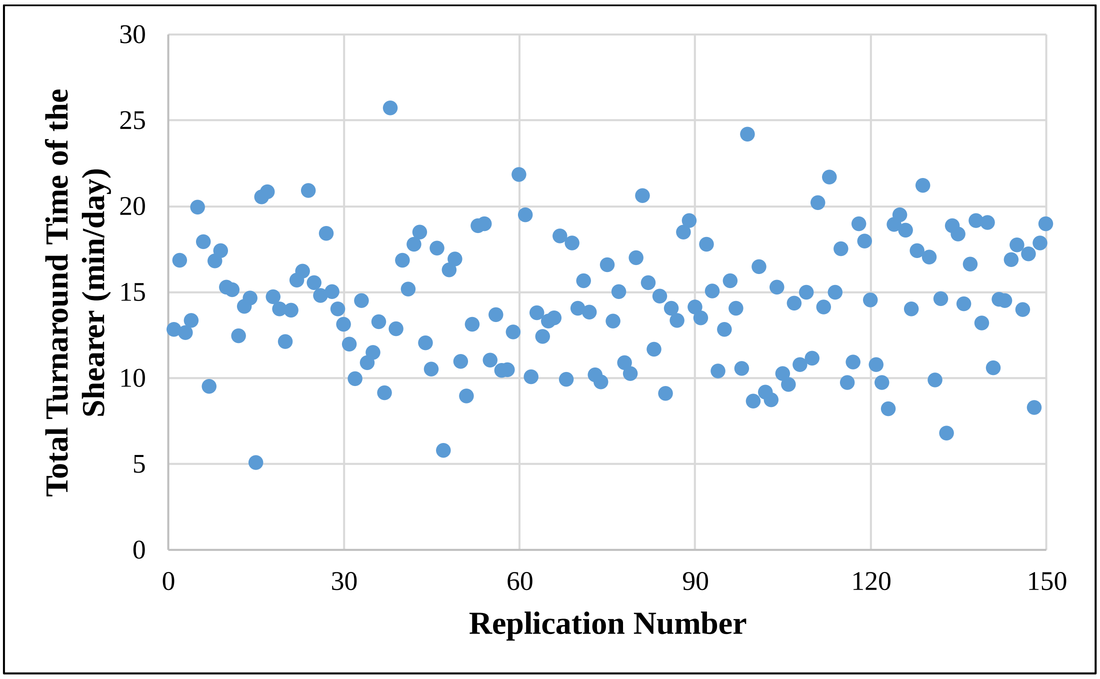

Figure 4.8 Total turnaround time of the shearer (min/day) according to the different replication numbers

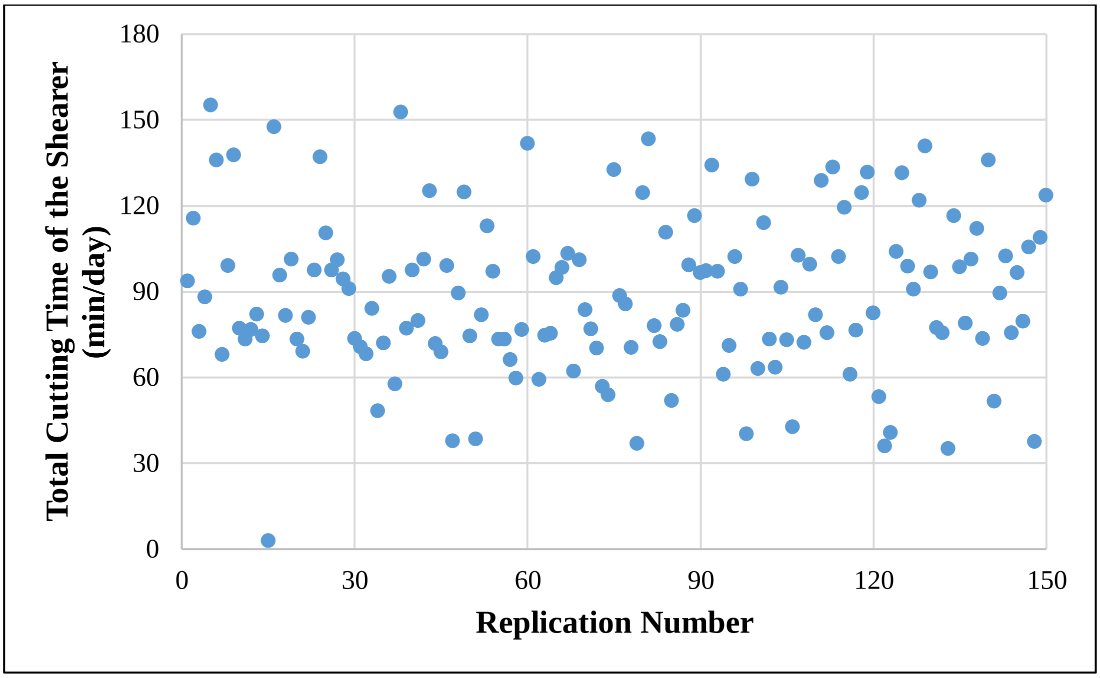

Figure 4.9 Total cutting time of the shearer (min/day) according to the different replication numbers

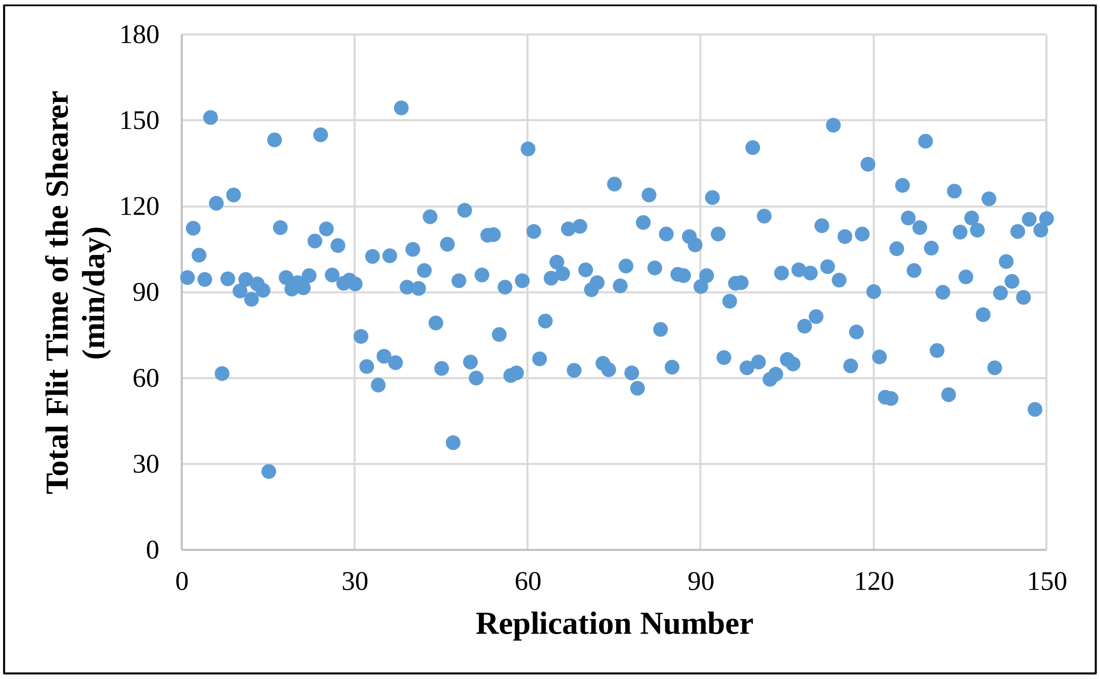

Figure 4.10 Total flit time of the shearer (min/day) according to the different replication numbers

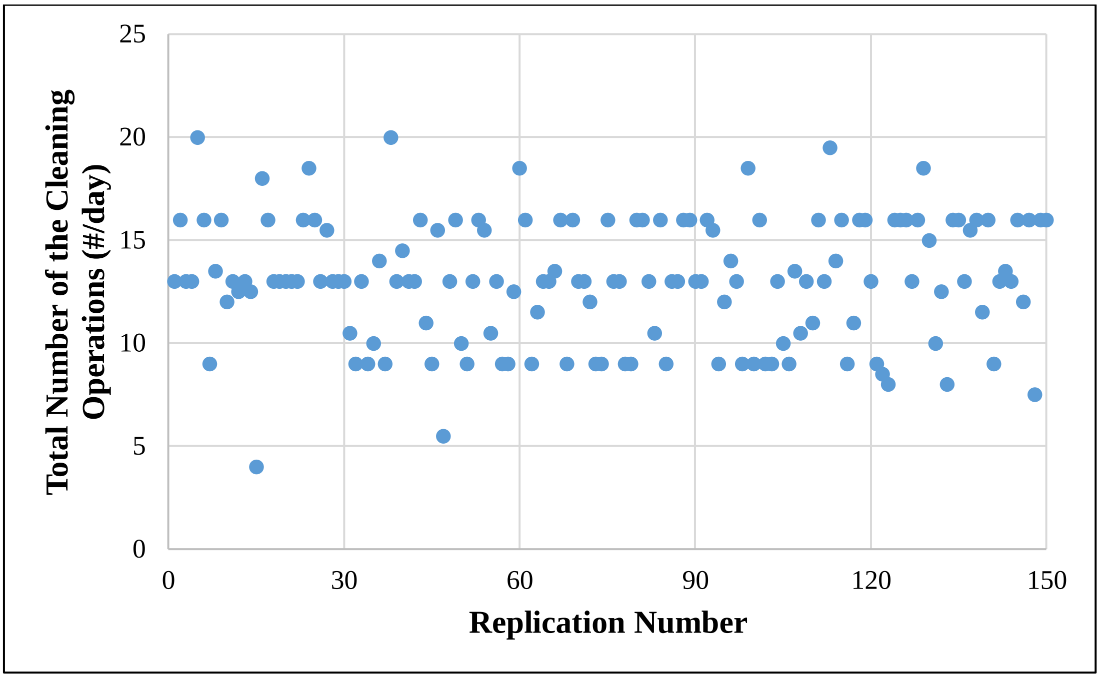

Figure 4.11 Total number of the cleaning operations (#/day) according to the different replication numbers

Daily shearer production of the mine is 726.73 t in average. It changes between 21 t and 1,177 t. Outputs on daily shearer production are presented in Figure 4.12.

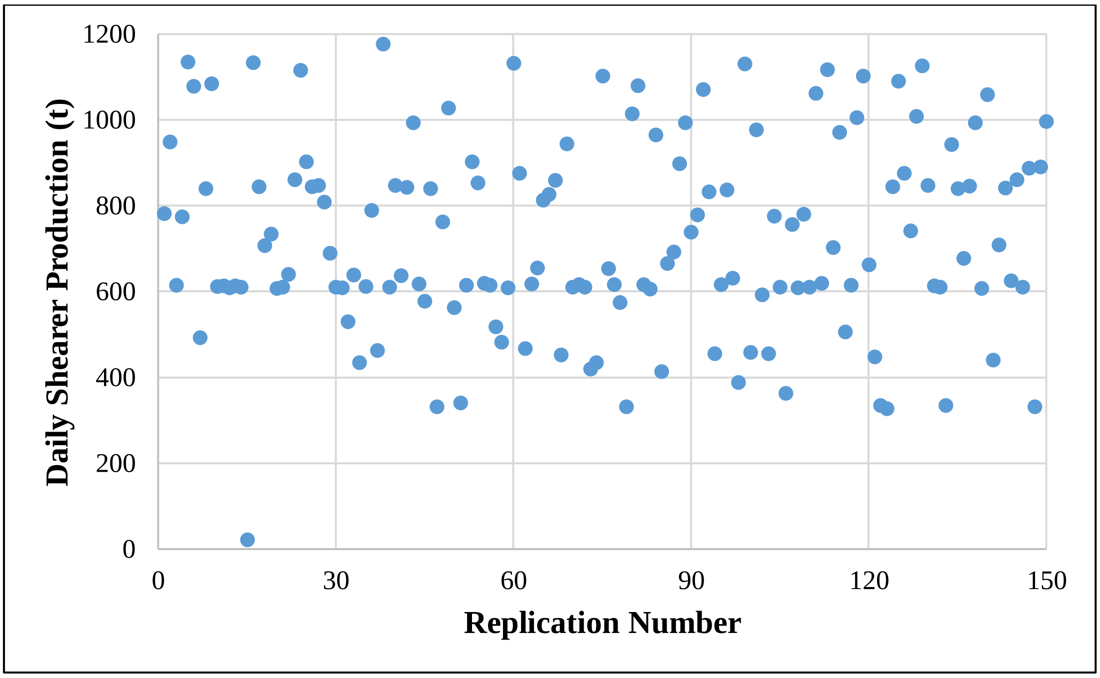

Figure 4.12 Daily shearer production in the mine according to different replication numbers

Change in parameters affects daily shearer production in the mine. The relation between change in the investigated parameters and shearer production is presented in Table 4.10.

Table 4.10 Daily shearer production (t) according to the % change in parameters

Parameter Name	**% Change in Parameters**				
	-20%	**-10%**	**0%**	**10%**	**20%**
TBA of the shearer delays	606.55	638.21	726.73	794.62	834.79
Duration of the shearer delays	888.76	803.62	726.73	688.97	614.43
Turnaround time of the shearer	716.09	710.64	726.73	685.37	708.55
Cutting speed of the shearer	678.65	677.00	726.73	773.11	759.09
Flit speed of the shearer	641.33	696.97	726.73	743.98	785.51

According to the model outputs in Table 4.10,

- ❖ Daily shearer production in the mine increases 108.06 t/day in average in case time between arrivals of the shearer delays is increased by 20%. However, in case time between arrivals of the shearer delays is decreased by 20%, daily shearer production in the mine decreases 120.18 t/day in average.
- ❖ Daily shearer production in the mine increases 162.03 t/day in average in case duration of the shearer delays is decreased by 20%. However, in case duration of the shearer delays is increased by 20%, daily shearer production in the mine decreases 112.30 t/day in average.
- ❖ Turnaround time of the shearer do not have a significant effect on daily shearer production in the mine due to very short turnaround time and not many turnaround operations in the shearer movement.
- ❖ Daily shearer production in the mine increases 32.36 t/day in average in case cutting speed of the shearer is increased by 20%. However, in case cutting speed of the shearer is decreased by 20%, daily shearer production in the mine decreases 48.08 t/day in average.
- ❖ Daily shearer production in the mine increases 58.78 t/day in average in case flit speed of the shearer is increased by 20%. However, in case flit speed of the

shearer is decreased by 20%, daily shearer production in the mine decreases 85.40 t/day in average.

According to the simulation model, daily shearer usage in the mine is 89.07 min/day in average as it is mentioned before. It changes between 3.11 min and 155.33 min/day. Outputs on daily shearer usage in the mine are presented in Figure 4.13.

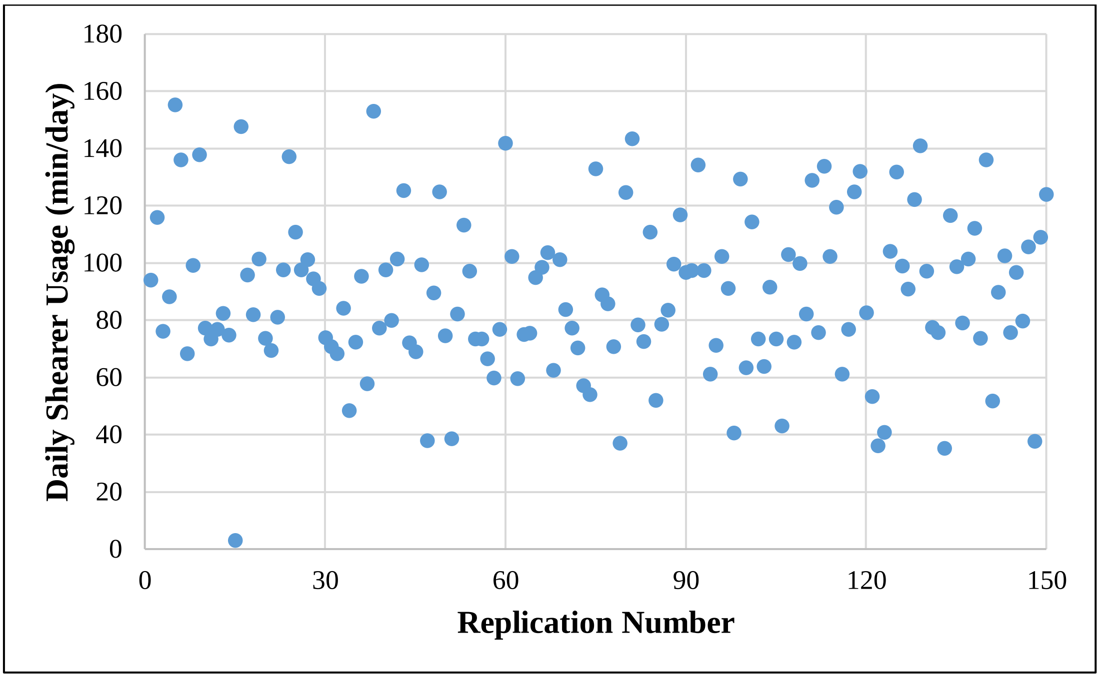

Figure 4.13 Daily shearer usage (min) according to the different replication numbers

Change in parameters affects daily shearer usage in the mine. The relation between change in the investigated parameters and shearer production is given in Table 4.11.

Table 4.11 Daily shearer usage according to the % change in parameters

Parameter Name	% Change in Parameters				
	-20%	**-10%**	**0%**	**10%**	**20%**
TBA of the shearer delays	73.40	77.77	89.07	96.56	102.19
Duration of the shearer delays	108.65	97.68	89.07	83.26	73.93
Turnaround time of the shearer	87.00	85.79	89.07	83.18	86.35
Flit speed of the shearer	77.58	84.78	89.07	90.31	96.09

According to the model outputs in Table 4.11,

- ❖ Daily shearer usage in the mine increases 13.12 min/day in average in case time between arrivals of the shearer delays is increased by 20%. However, in case time between arrivals of the shearer delays is decreased by 20%, daily shearer usage in the mine decreases 15.67 min/day in average.
- ❖ Daily shearer usage in the mine increases 19.58 min/day in average in case duration of the shearer delays is decreased by 20%. However, in case duration of the shearer delays is increased by 20%, daily shearer usage in the mine decreases 15.14 min/day in average.
- ❖ Turnaround time of the shearer do not have a significant effect on daily shearer usage in the mine as in the effect on daily shearer production in the mine.
- ❖ Daily shearer usage in the mine increases 7.02 min/day in average in case flit speed of the shearer is increased by 20%. However, in case flit speed of the shearer is decreased by 20%, daily shearer usage in the mine decreases 11.49 min/day in average.

4.3.4 Sensitivity Analysis

Sensitivity analysis is used for examining the effect of the independent variable on the dependent variable under certain assumptions. The most influential factor is determined by conducting sensitivity analysis in a simulation study. Within the scope of this thesis, 20 different scenarios were assessed and impact of time between arrivals of the shearer delays, duration of the shearer delays, turnaround time of the shearer, flit speed of the shearer, and cutting speed of the shearer on the daily shearer production in the mine were investigated. Sensitivity analysis was performed by assigning a specific distribution for every condition that was investigated. Results of the sensitivity analysis on the daily production rate of the mine are shown in Figure 4.14.

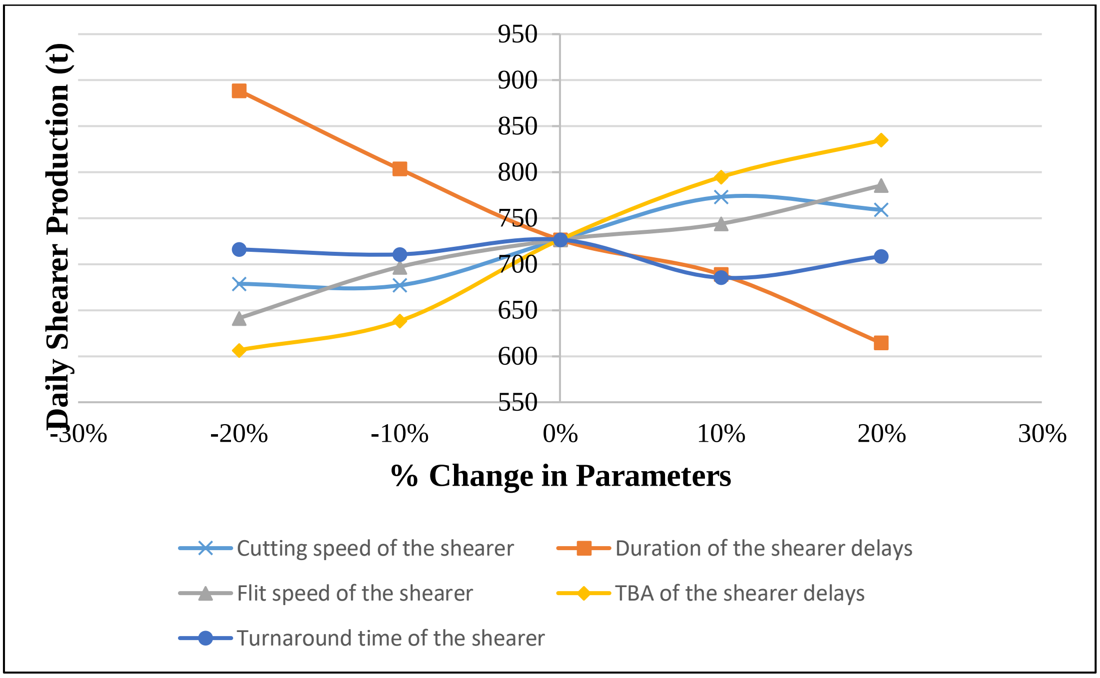

Figure 4.14 Sensitivity analysis on the daily production rate of the mine

According to the conducted sensitivity analysis, factors are listed below from the most effective to the least effective on the production rate of the shearer in the mine.

- Duration of the shearer delays
- Time between arrivals of the sharer delays
- Flit speed of the shearer
- Cutting speed of the shearer
- Turnaround time of the shearer

As it is shown in the Figure 4.14, although duration of the shearer delays has the steepest slope, slope of time between of the shearer delays is close to it. This means that production rate is mostly affected by the interruption of the shearer operations. Therefore, precautions should be primarily taken against interruption of the shearer operations.

As the flit speed increases, shearer passes the non-cutting zone faster and spends less time in that zone. As a result, there is a longer time available for cutting operations.

Hence, production rate of the shearer increases. However, the effect of this increment in flit movement is much less than the duration of the shearer delays and the time between arrivals of the shearer delays. On the other hand, cutting speed has a similar effect with flit speed on the production rate of the mine. As it has increased, production rate of the shearer in the mine increases as expected.

Turnaround time of the shearer has the least effect on production rate of the shearer. There are two complementary reasons for that. One is that the shearer spends very short time for turnaround operations in this operation and the other is that there are not so many turnaround operations in the system. Hence, turnaround time of the shearer has a negligible effect on production rate of the shearer in this mine.

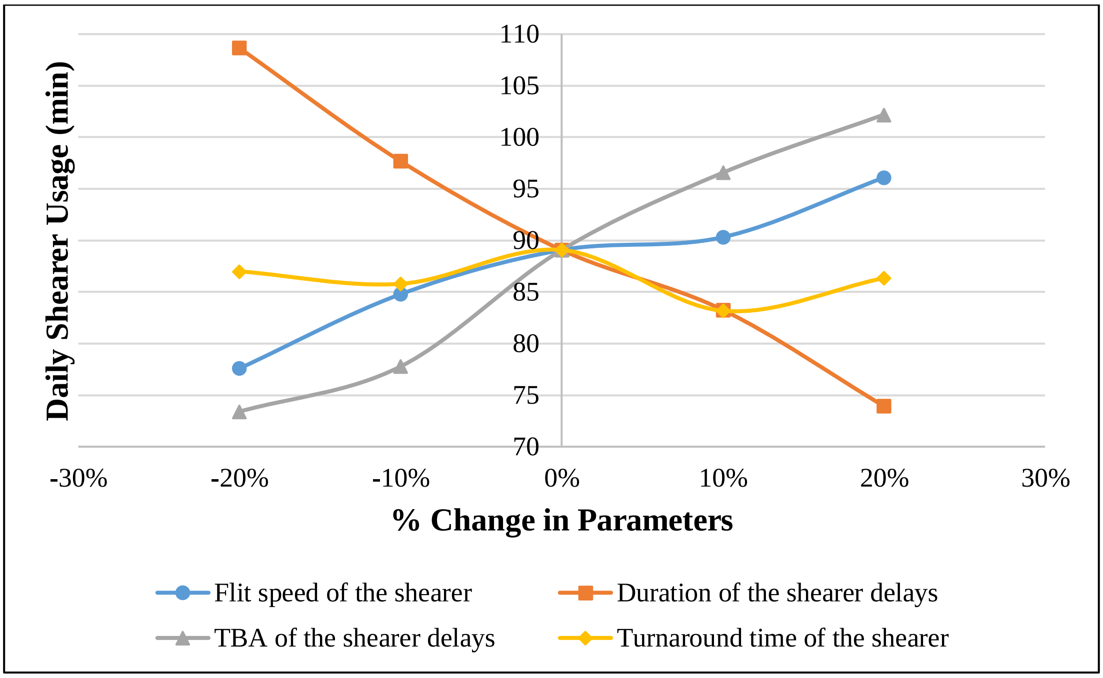

Figure 4.15 Sensitivity analysis on daily shearer usage (min)

Outputs of total activity time of the shearer (shearer usage) is compatible with the sensitivity analysis results on the daily production rate of the shearer. Duration of the shearer delays are inversely proportional to the total activity time of the shearer. Time between arrivals of the shearer delays and flit speed are directly proportional to total activity time of the shearer. Turnaround time of the shearer has a negligible effect on shearer total activity as in the daily production rate of the shearer. Sensitivity analysis on daily shearer usage is shown in Figure 4.15.

On the other hand, in coal mining activities, conveyor systems are commonly used and in these systems, coal is continuously transported out of the mine. One of the main disadvantages in these systems is that if there is any failure in any component of the transportation system, all machines including shearer, AFC, RC, and belt conveyors are stopped. This situation is commonly described as an “operational delay”. In the mine, it is obvious that there are many breakdowns in different sections of the mine. For that reason, production rate decreases in the mine. To minimize mechanical breakdowns, maintenance of the all machines should always be done periodically. In this way, efficiency of the system and production rate can be increased to the theoretical maximum in the mine. On the other hand, operational delays can also occur during the extraction of top coal when large particles obstruct the spillage of smaller particles on the RC. In this situation, it becomes a bottleneck in real cases.

In the mine, an IT infrastructure exists but it does not allow providing access to the database of the operations. The reliability of the any operational data depends on the person collecting the data. In order to achieve realistic and reliable results, data should be preferably collected automatically. Therefore, IT systems, which enable access to the database of the operations, should be set up in the mine for a better system analysis.

Underground Coal Talpac® is easy to use software that can be adapted to different cutting operations in underground longwall mining activities. This software provides visual interfaces and supports the animation of the shearer operations. To examine the shearer operations, one cycle of the shearer movement is created by means of using step types that are defined in the software. This situation may restrict the analysts in their studies. In addition, the software uses deterministic approach to model the shearer operations. In fact, the software cannot handle stochastic processes thoroughly. Moreover, the software has no specific functionality defined for top coal caving operations, and material transportation systems except for AFC. On the other hand, Arena® is a discrete event simulation software where the user can define the entities in much more detail. This can also be considered as the fact that Arena® is more flexible for developing simulation models and stochastic approaches of shearer operations can be defined. However, the construction of the simulation model in Arena® might be more complex and can take more effort and time.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Bi-di cutting system in underground longwall mining method is combined with simulation studies in this study. In addition, top coal operations is modelled according to the shield movements in Arena® Simulation Software. In the model, top coal production is achieved only from the shield, which is currently moved forward. However, top coal production may continue in other shields in reality. On the other hand, a new modelling system is developed for AFC and RC so that entities arrive BSL on time.

In the study, data was collected from six days in an underground longwall coal mining operation in Turkey. According to Underground Coal Talpac® outputs, one cycle completion time of the shearer during the mine site visit is 3,700.29 min. Maximum shearer production rate can reach 1,075.29 tph and total shearer production rate is 17.97 tph in the mine. Maximum shearer speed in the mine is 11.50 m/min. Total sheared weight in one cycle of the shearer is 1,108.38 t. After all, shearer utilization in the mine is considerably low.

According to Arena® outputs, daily shearer usage is 89.07 min/day, daily shearer production is 726.73 t and daily top coal production is 9,154.19 t in the mine. Within the scope of this thesis, the shearer performance were investigated and the most influential factor in the production operations was also determined by discrete event simulation. This factor is duration of the shearer delays. When the duration of the shearer delays is decreased to 80% of actual situation, daily shearer usage could increase 19.58 min/day. As a result of this situation, daily shearer production could increase 162.03 t/day.

Outputs of the simulation models, and data collected during the mine site visit show that shearer utilization is considerably low in the mine. During the mine site visit, extraordinary conditions may have occurred. Thus, shearer utilization may have been lower than reality during the mine site visit. Therefore, data should be collected from a longer time interval in the mine for obtaining more accurate results from the simulation study.

5.2 Recommendations

Every branch of mining works can be simulated via simulation packages. Simulation studies can be used in interdisciplinary research areas. In fact, different branches of mining activities can be combined in simulation studies. The list presented below can be future works of LTCC simulation studies.

- ❖ Geotechnical conditions of the coal zone can be included and optimization of top coal policy of the mine can be investigated in accordance with the top coal caving principles in the mine. As a result, cavability studies and simulation studies can be integrated by this way.
- ❖ The uni-directional cutting system with bi-directional cutting system can be compared in real cases. For better comparison, real data should be obtained from the same mining activity for both uni-directional cutting system and bi-directional cutting system.
- ❖ Causes of the shearer stops can be examined in detail. In this way, equipment breakdowns and operational delays can be separated from each other and different delays can be assigned to them. In addition, service time of the equipment can be optimized in the mine according to this investigation. As a result, breakdowns of the equipment can be minimized. Thus, usage of the equipment can be maximized and more accurate results can be obtained in the mine.

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APPENDICES

APPENDIX A: COAL POWER GENERATION

A.1 Power Generation from Coal in the World (2014)

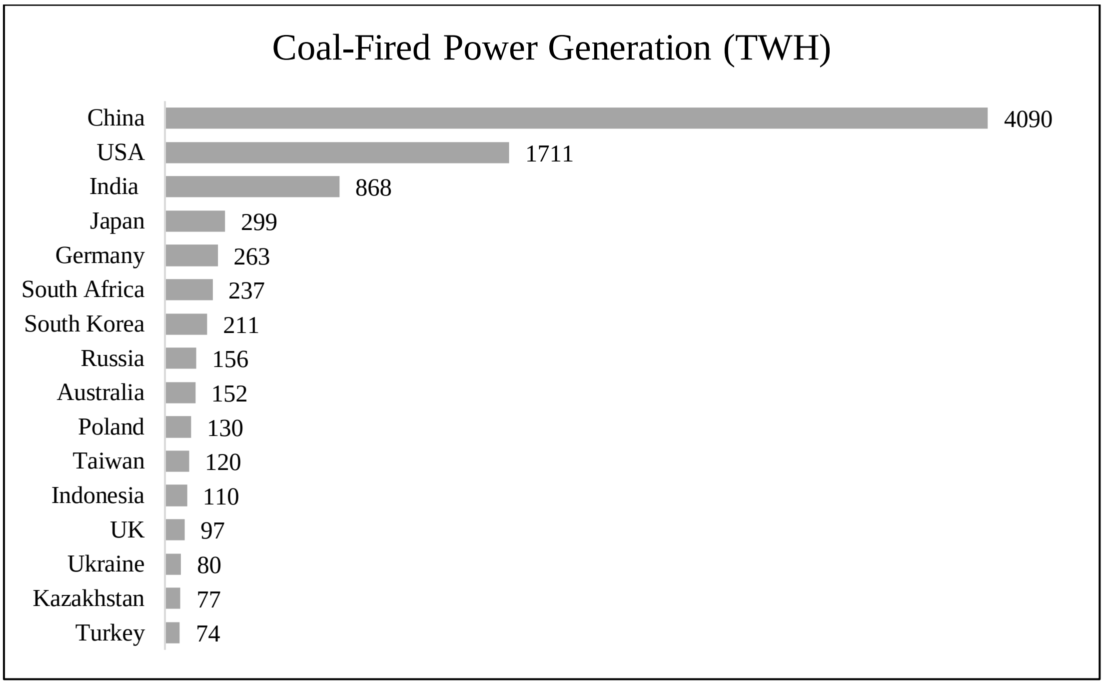

Figure A.1 Coal-fired power generation in 2014 (World Energy Council, 2016)

APPENDIX B: DISTRIBUTION IDENTIFICATIONS

B.1 Descriptive Statistics of the Input Data

Table B.1 Descriptive statistics of duration of the shearer delays (min)

N	Mean	St.Dev	Median	Min.	Max.	Skewness	Kurtosis
231	30.530	83.879	2.017	0.083	551.983	3.904	16.008

Table B.2 Descriptive statistics of turnaround time of the shearer (min)

N	Mean	St.Dev	Median	Min.	Max.	Skewness	Kurtosis
119	0.303	0.203	0.250	0.070	0.980	1.551	2.080

Table B.3 Descriptive statistics of cutting speed of the shearer (m/min)

N	Mean	St.Dev	Median	Min.	Max.	Skewness	Kurtosis
484	3.378	1.610	3.088	1.000	13.400	1.725	5.604

Table B.4 Descriptive statistics of flit speed of the shearer (m/min)

N	Mean	St.Dev	Median	Min.	Max.	Skewness	Kurtosis
1,082	5.363	2.931	4.900	1.000	25.800	2.445	11.584

B.2 Probability Distributions of Operations

Table B.5 Probability distributions used in the model

Variable Name	Unit	Distributional Expression
TBA of the shearer delays	min	LOGN(3.67, 5.40)
Duration of shearer delays	min	WEIB(9.41, 0.45)
Turnaround time of the shearer	min	LOGN(0.30, 0.20)
Cutting speed of the shearer	m/min	1.00 + 13 * BETA(1.81, 8.08)
Flit speed of the shearer	m/min	1.00 + 25 * BETA(2.27, 10.80)

B.3. Probability Distributions of Alternatives

Table B.6 TBA of the shearer delays under certain conditions

Description	Unit	Distributional Expression
80% of TBA of the shearer delays	min	LOGN(2.94, 4.32)
90% of TBA of the shearer delays	min	LOGN(3.30, 4.85)
100% of TBA of the shearer delays	min	LOGN(3.67, 5.40)
110% of TBA of the shearer delays	min	LOGN(4.03, 5.92)
120% of TBA of the shearer delays	min	LOGN(4.40, 6.47)

Table B.7 Duration of the shearer delays under certain conditions

Description	Unit	Distributional Expression
80% of duration of shearer delays	min	WEIB(7.52, 0.45)
90% of duration of shearer delays	min	WEIB(8.48, 0.45)
100% of duration of shearer delays	min	WEIB(9.41, 0.45)
110% of duration of shearer delays	min	WEIB(10.40, 0.45)
120% of duration of shearer delays	min	WEIB(11.30, 0.45)

Table B.8 Turnaround time of the shearer under certain conditions

Description	Unit	Distributional Expression
80% of turnaround time of the shearer	min	LOGN(0.24, 0.16)
90% of turnaround time of the shearer	min	LOGN(0.27, 0.18)
100% of turnaround time of the shearer	min	LOGN(0.30, 0.20)
110% of turnaround time of the shearer	min	LOGN(0.33, 0.22)
120% of turnaround time of the shearer	min	LOGN(0.36, 0.24)

Table B.9 Cutting speed of the shearer under certain conditions

Description	Unit	Distributional Expression
80% of cutting speed of the shearer	m/min	LOGN(2.70, 1.27)
90% of cutting speed of the shearer	m/min	GAMM(0.59, 5.14)
100% of cutting speed of the shearer	m/min	1.00 + 13 * BETA(1.81, 8.08)
110% of cutting speed of the shearer	m/min	1.00 + 14 * BETA(2.20, 8.88)
120% of cutting speed of the shearer	m/min	1.00 + ERLA(1.02, 3.00)

Table B.10 Flit speed of the shearer under certain conditions

Description	Unit	Distributional Expression
80% of flit speed of the shearer	m/min	ERLA(1.07, 4.00)
90% of flit speed of the shearer	m/min	ERLA(1.21, 4.00)
100% of flit speed of the shearer	m/min	1.00 + 25 * BETA(2.27, 10.80)
110% of flit speed of the shearer	m/min	1.00 + 28 * BETA(2.56, 12.20)
120% of flit speed of the shearer	m/min	1.00 + ERLA(1.81, 3.00)

APPENDIX C: MODELLING OVERVIEW

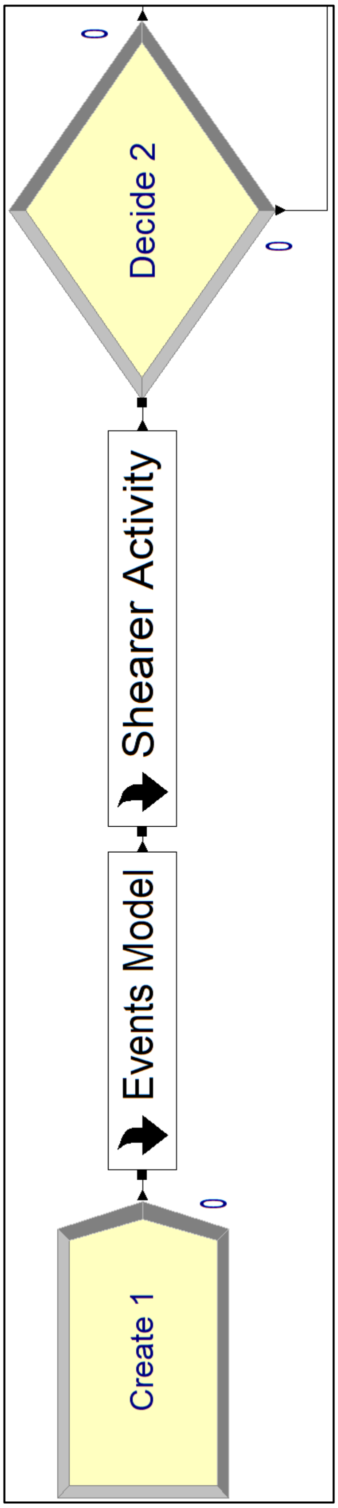

Figure C.1 Arena model of LTCC method

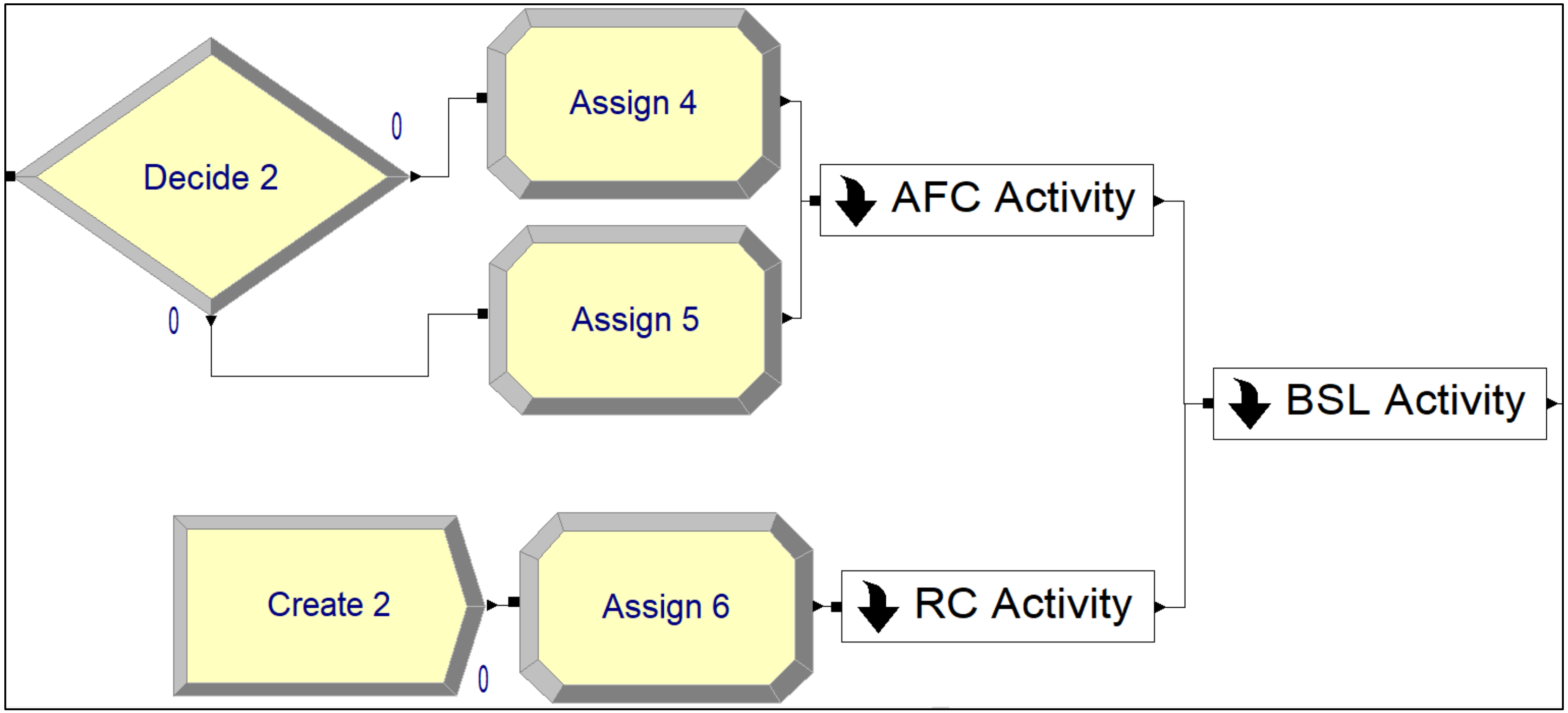

Figure C.2 Arena model of LTCC method (cont'd)

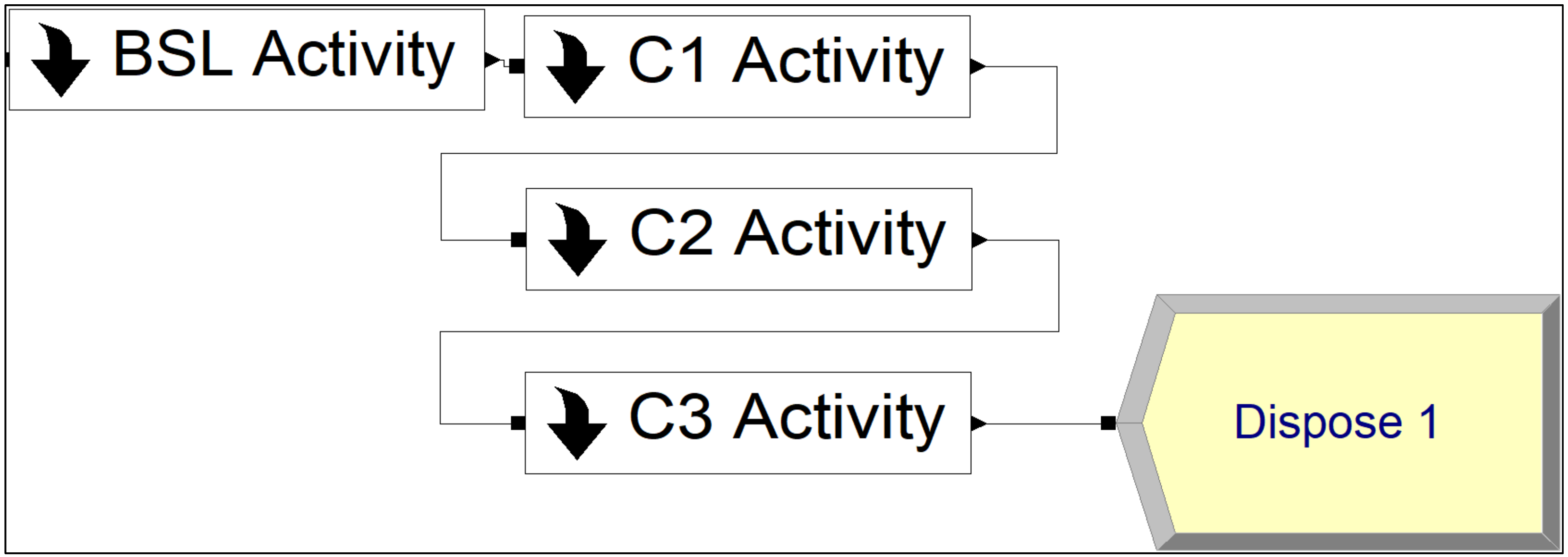

Figure C.3 Arena model of LTCC method (cont'd)

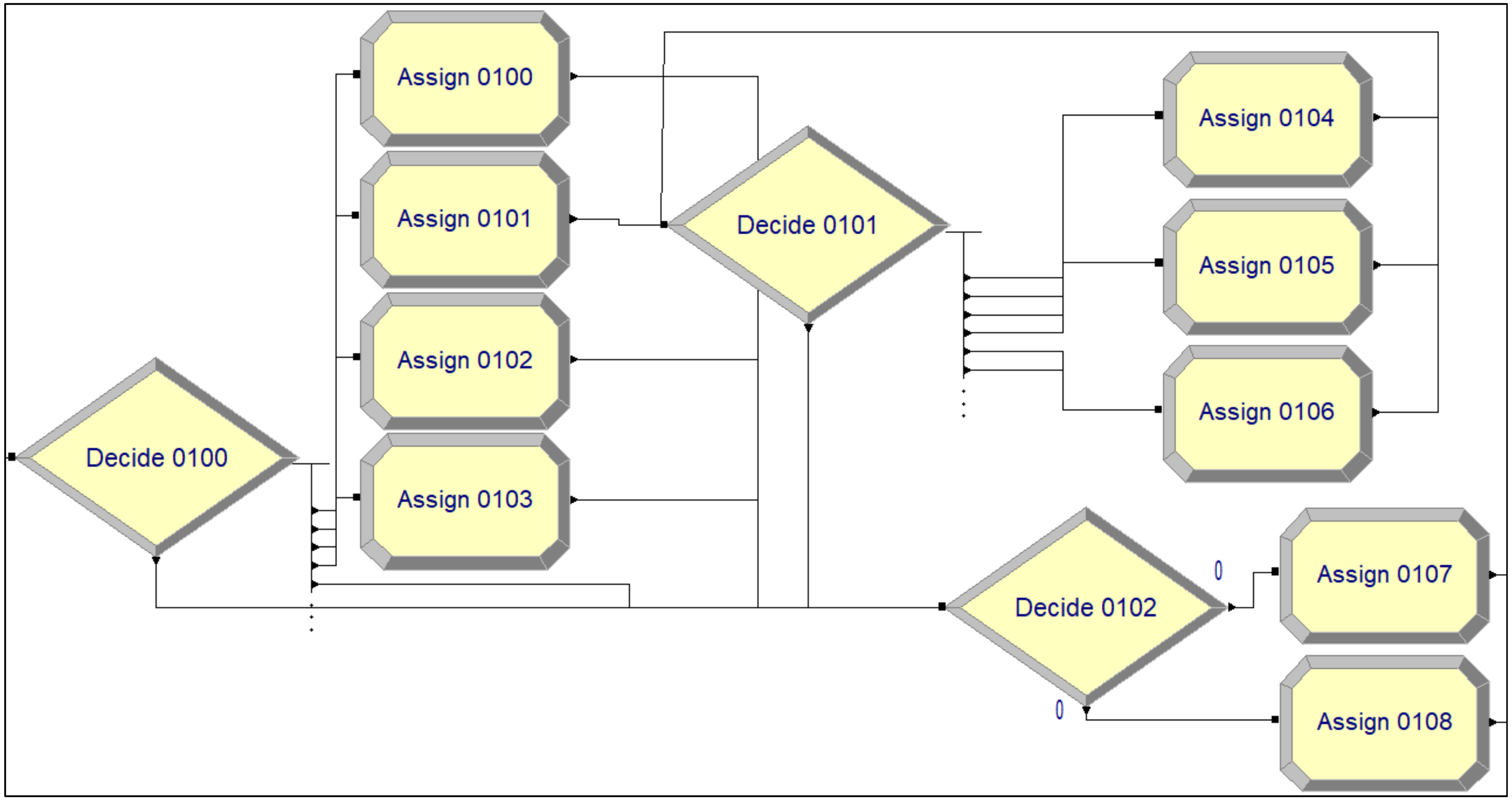

Figure C.4 Submodel for the shearer movement between gates (Full seam cutting and lower seam cutting) for one direction

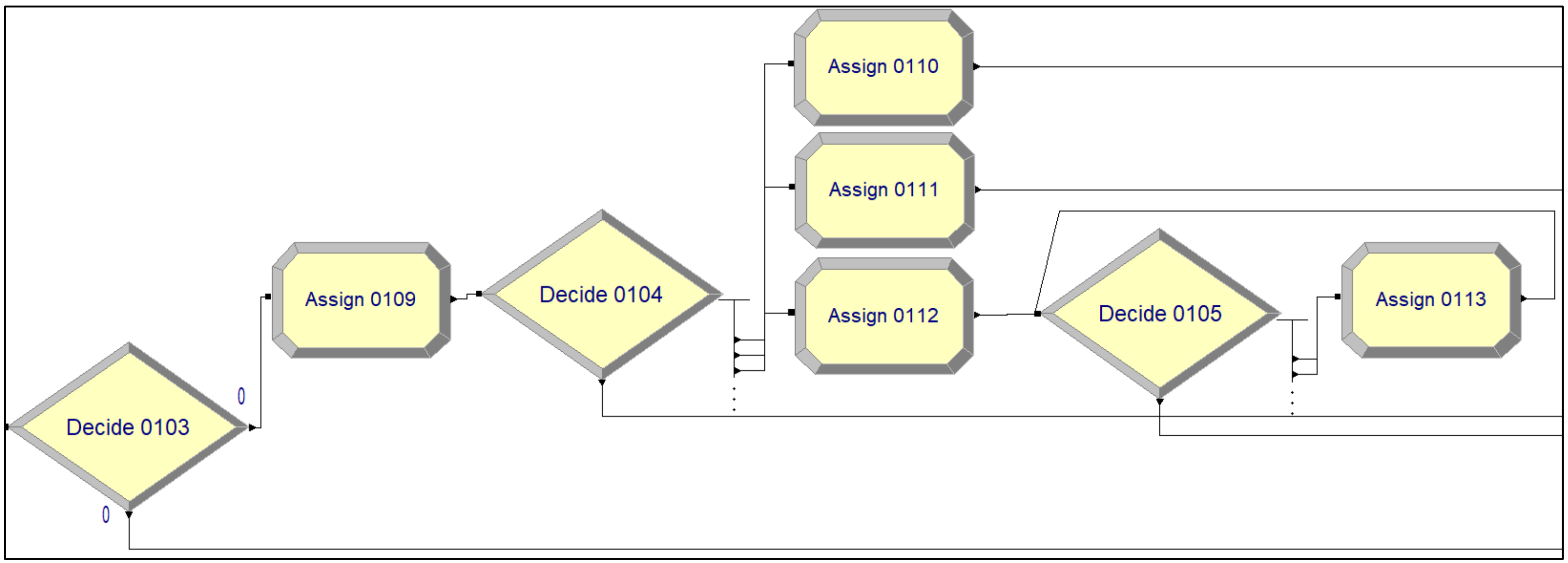

Figure C.5 Submodel for determination of cleaning operations in the shearer movements between gates for one direction

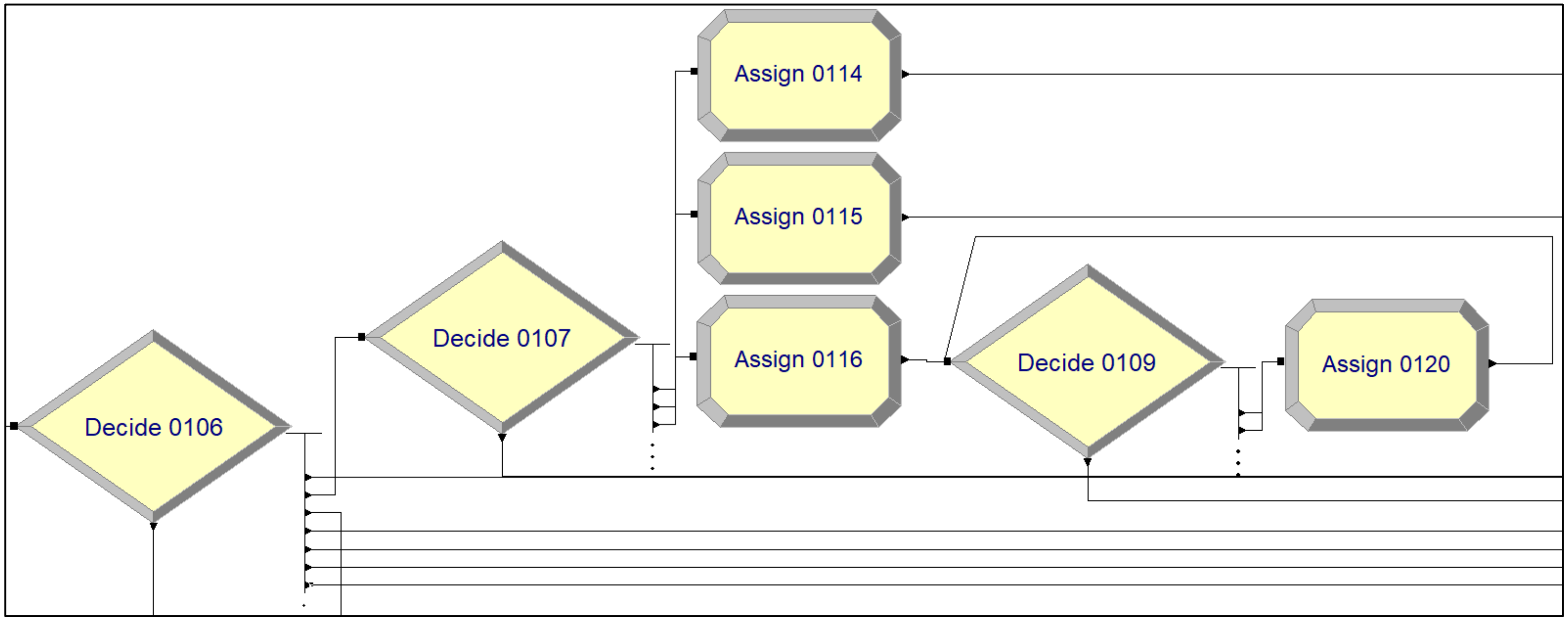

Figure C.6 Submodel for completion of the shearer movement between gates for one direction

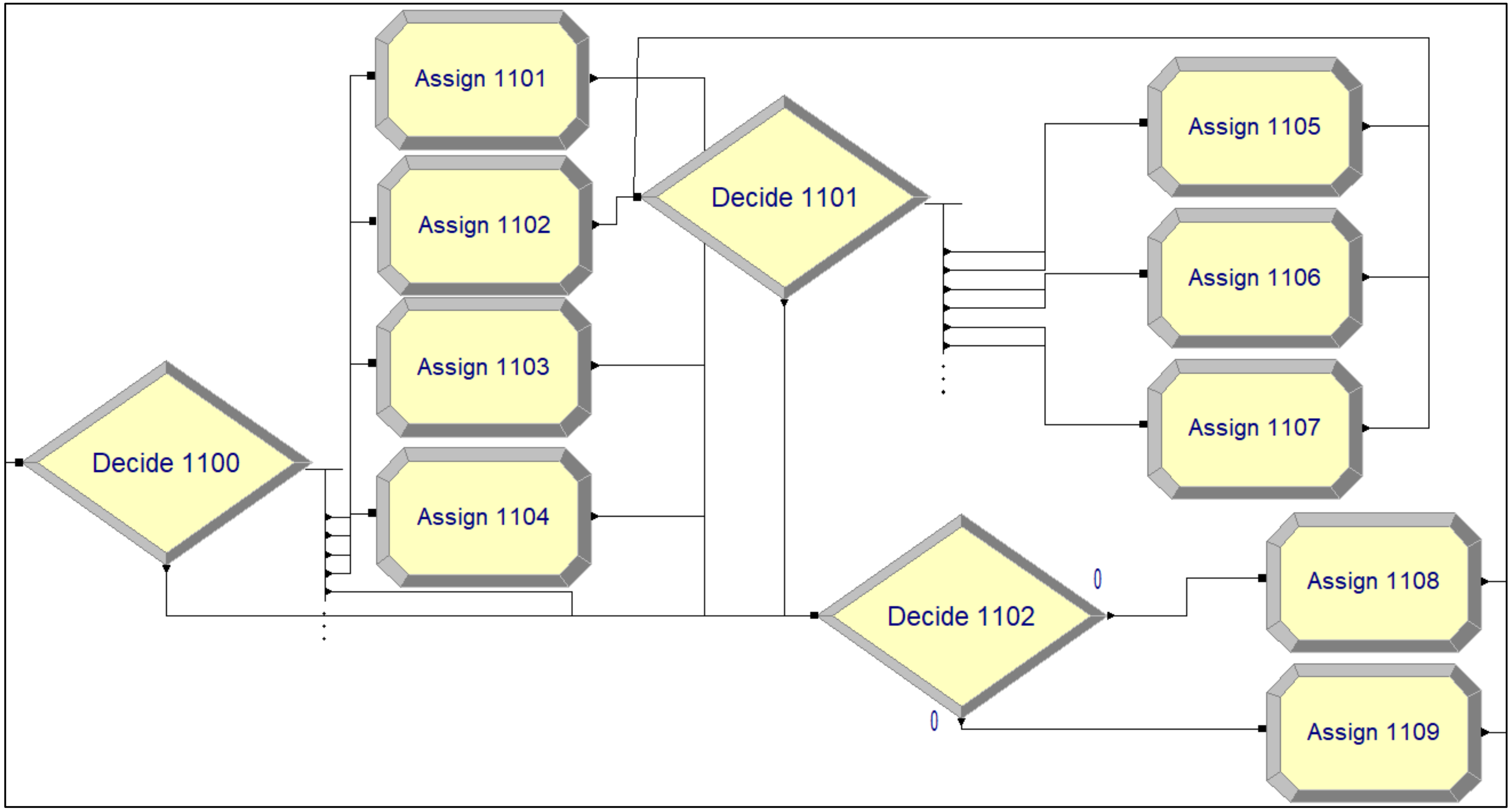

Figure C.7 Submodel for the shearer movement in new web cutting operations (Cut in) for one direction

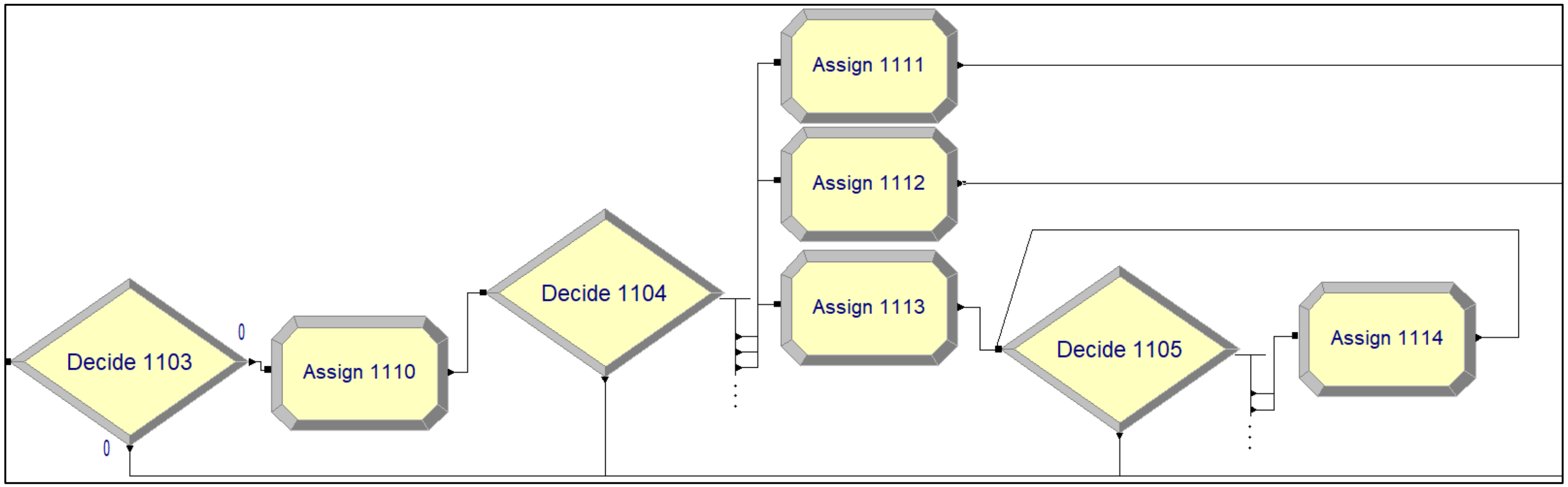

Figure C.8 Submodel for determination of cleaning operations in new web cutting operations for one direction

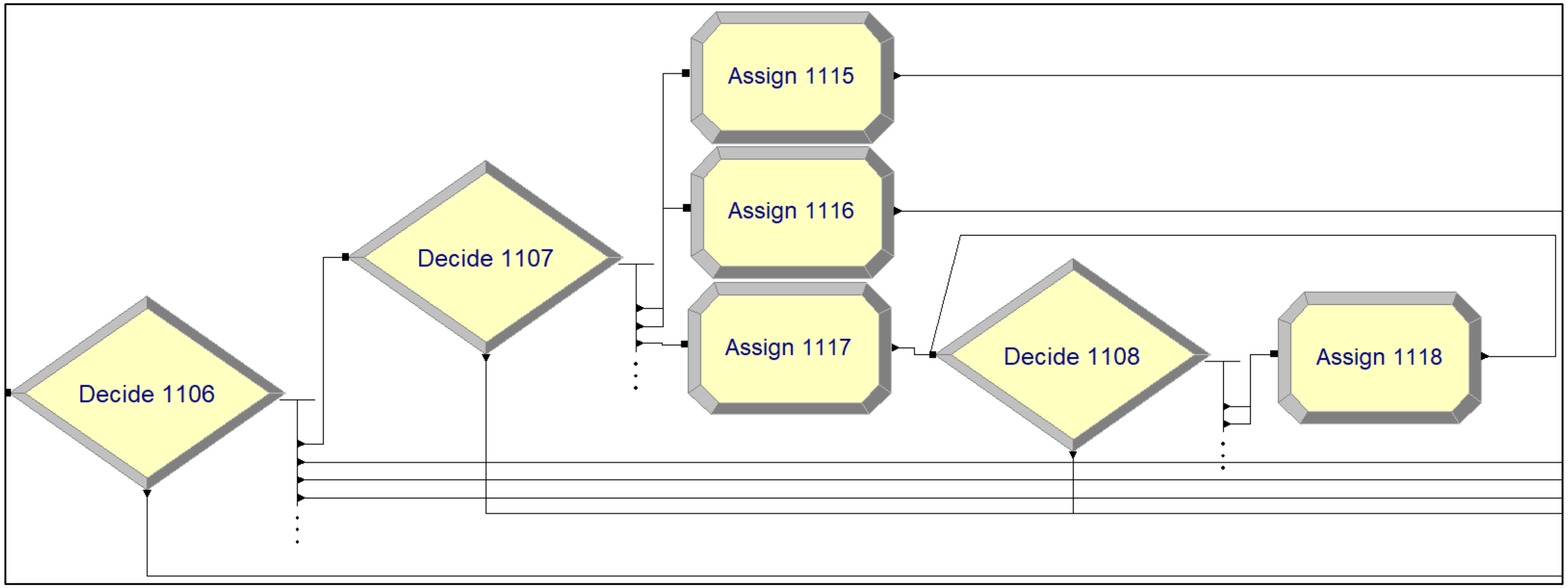

Figure C.9 Submodel for completion of the shearer movement in new web cutting operations for one direction

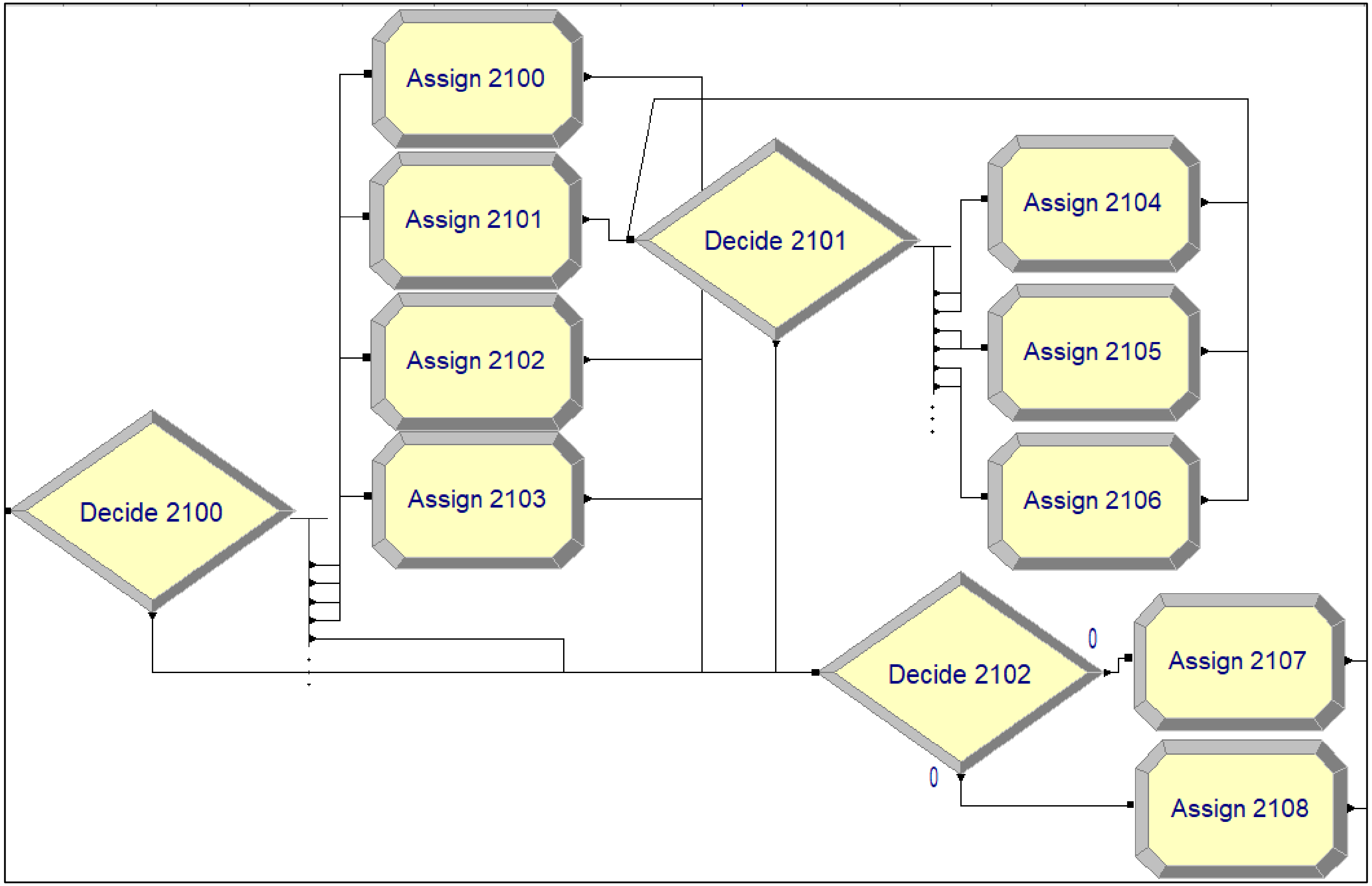

Figure C.10 Submodel for the shearer movement in returning to the gate operations (Cut back) for one direction

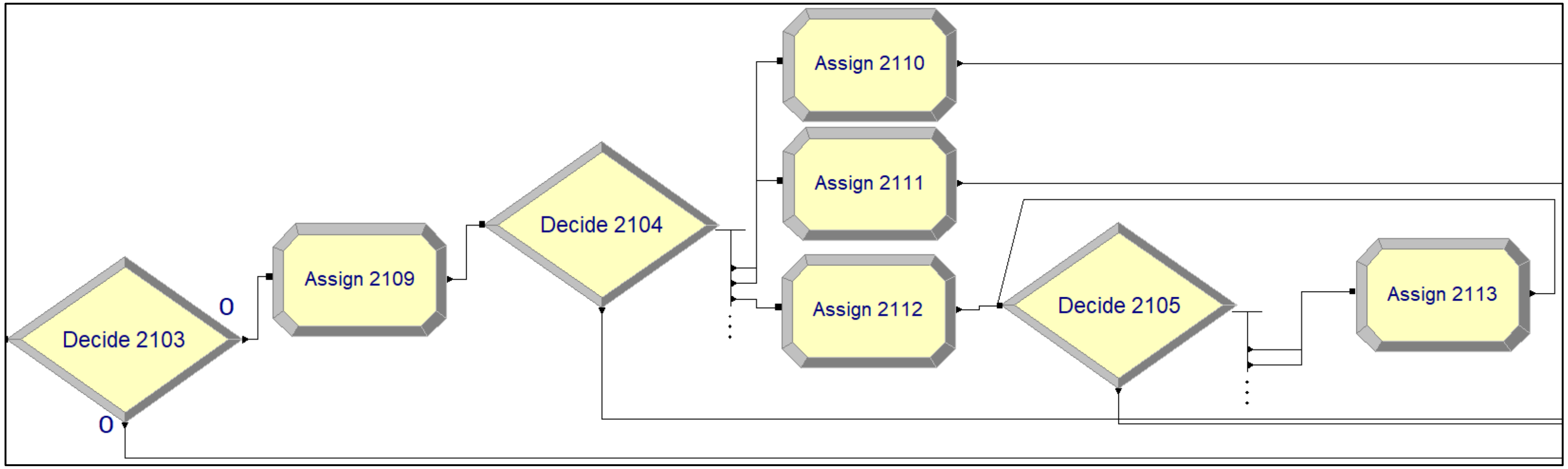

Figure C.11 Submodel for determination of cleaning operations in returning to the gate operations for one direction

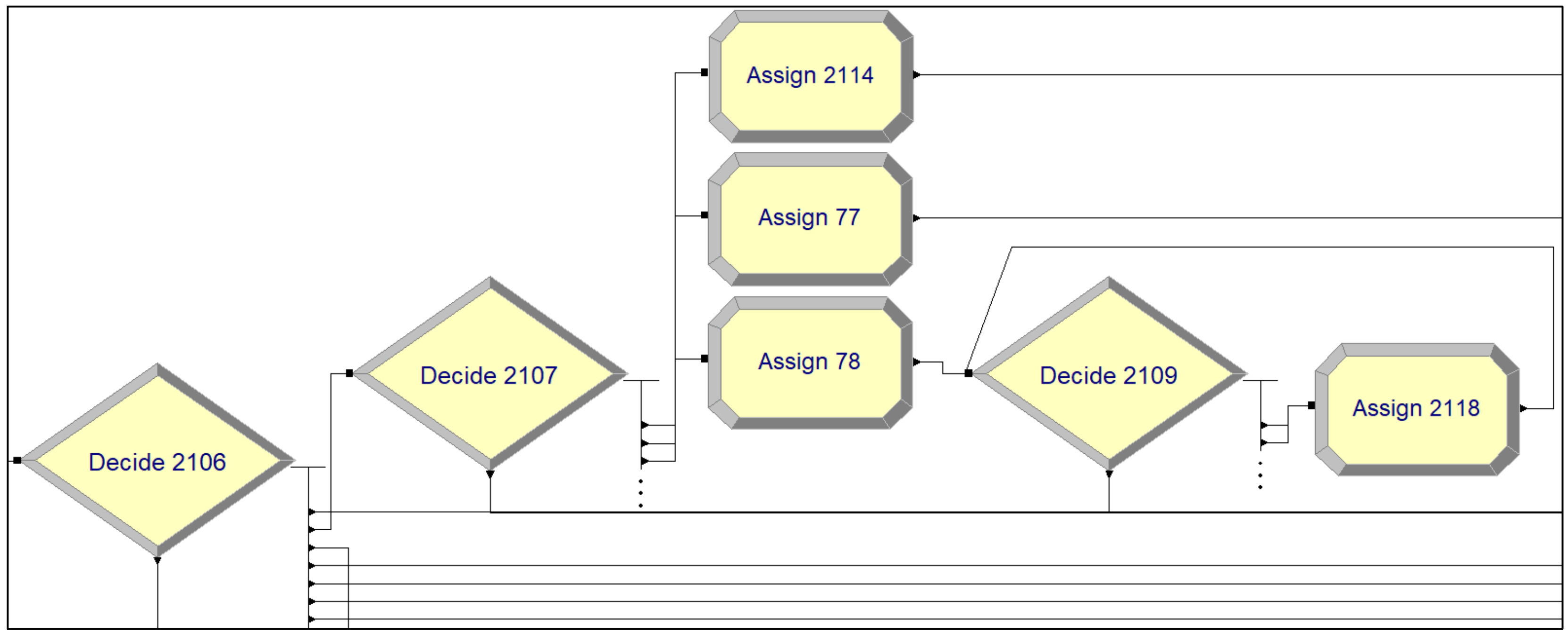

Figure C.12 Submodel for completion of the shearer movement in returning to the gate operations for one direction

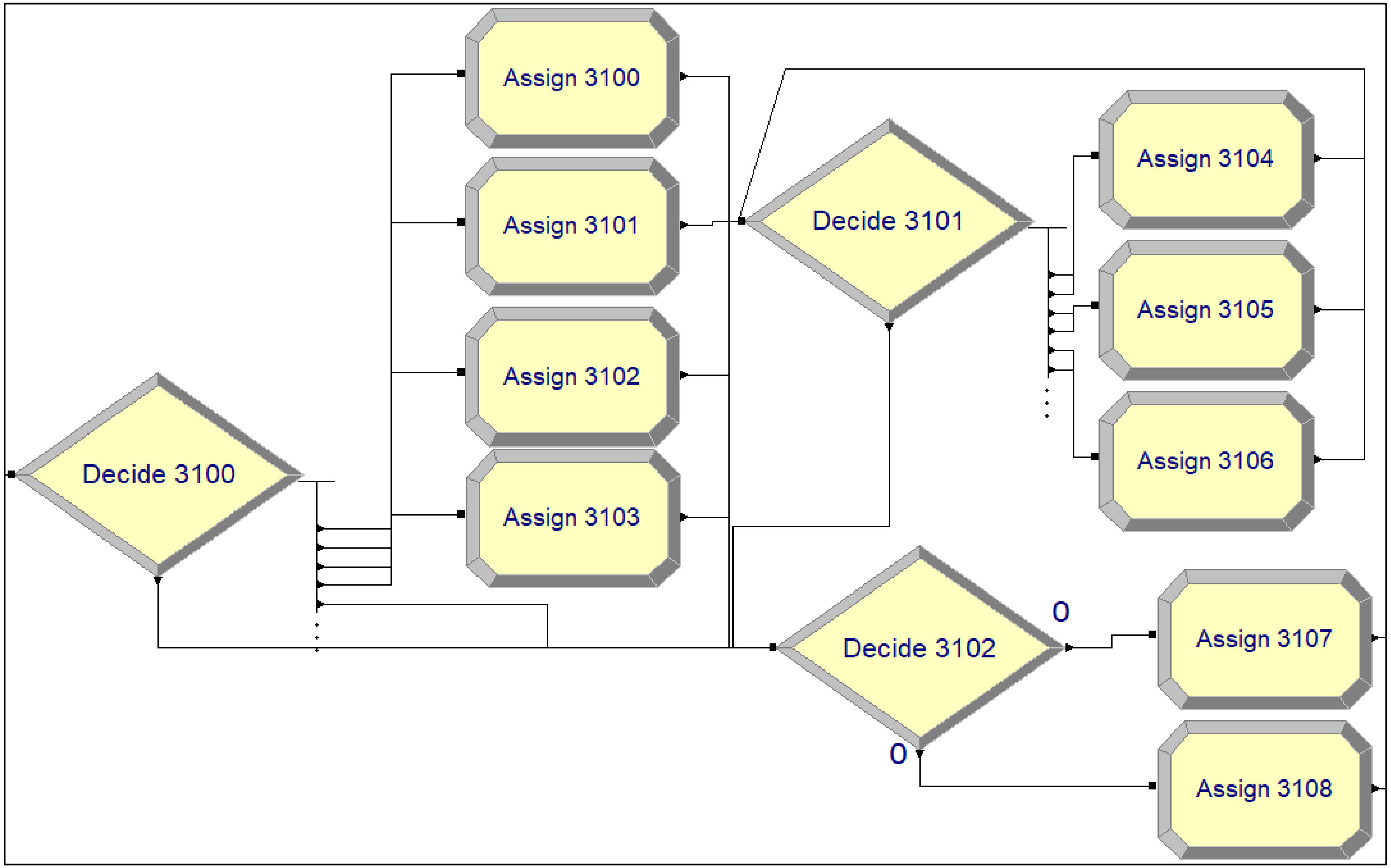

Figure C.13 Submodel for the shearer movement in cleaning operations for one direction

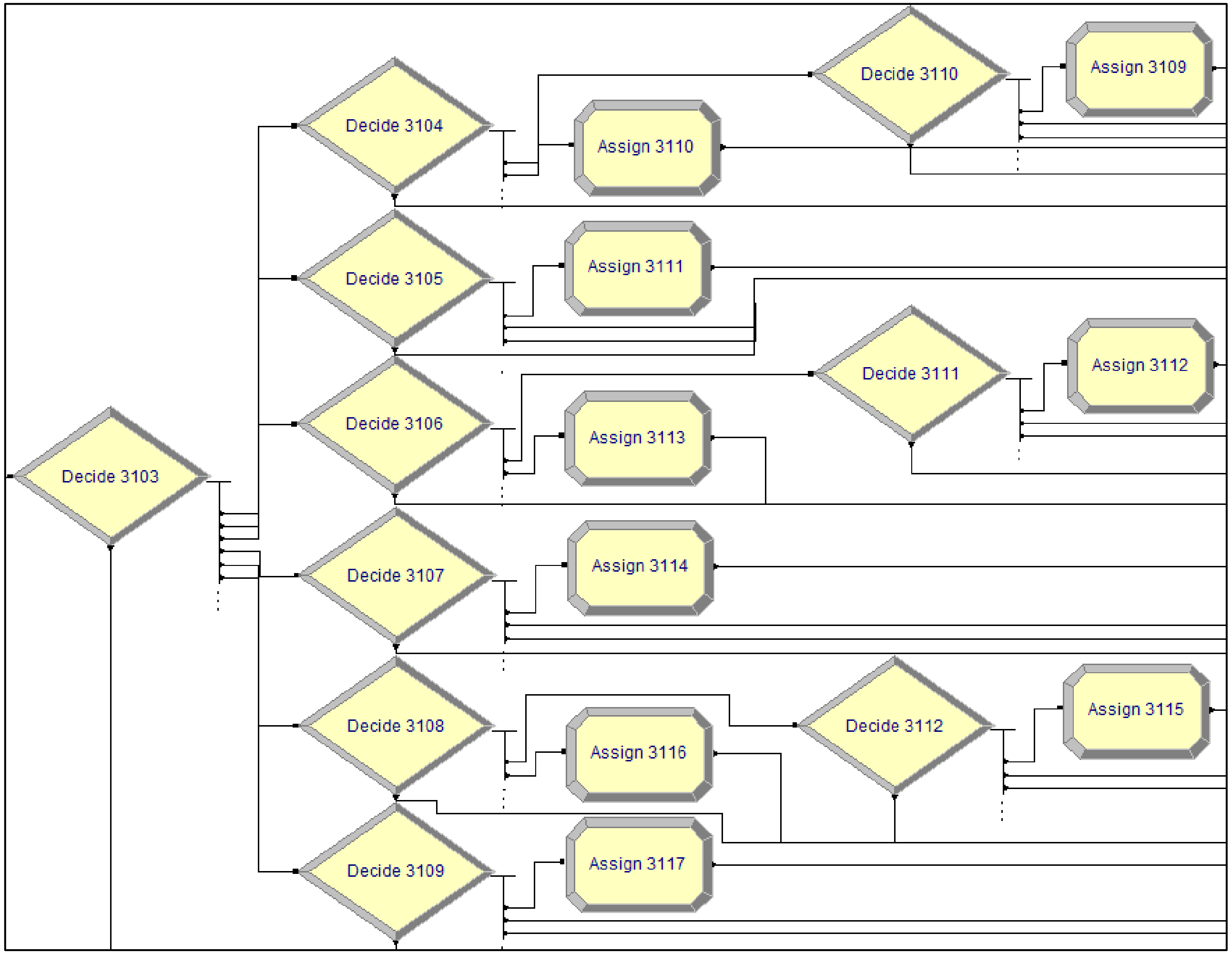

Figure C.14 Submodel for determining whether cleaning operations are over or not in the related shearer operation for one direction

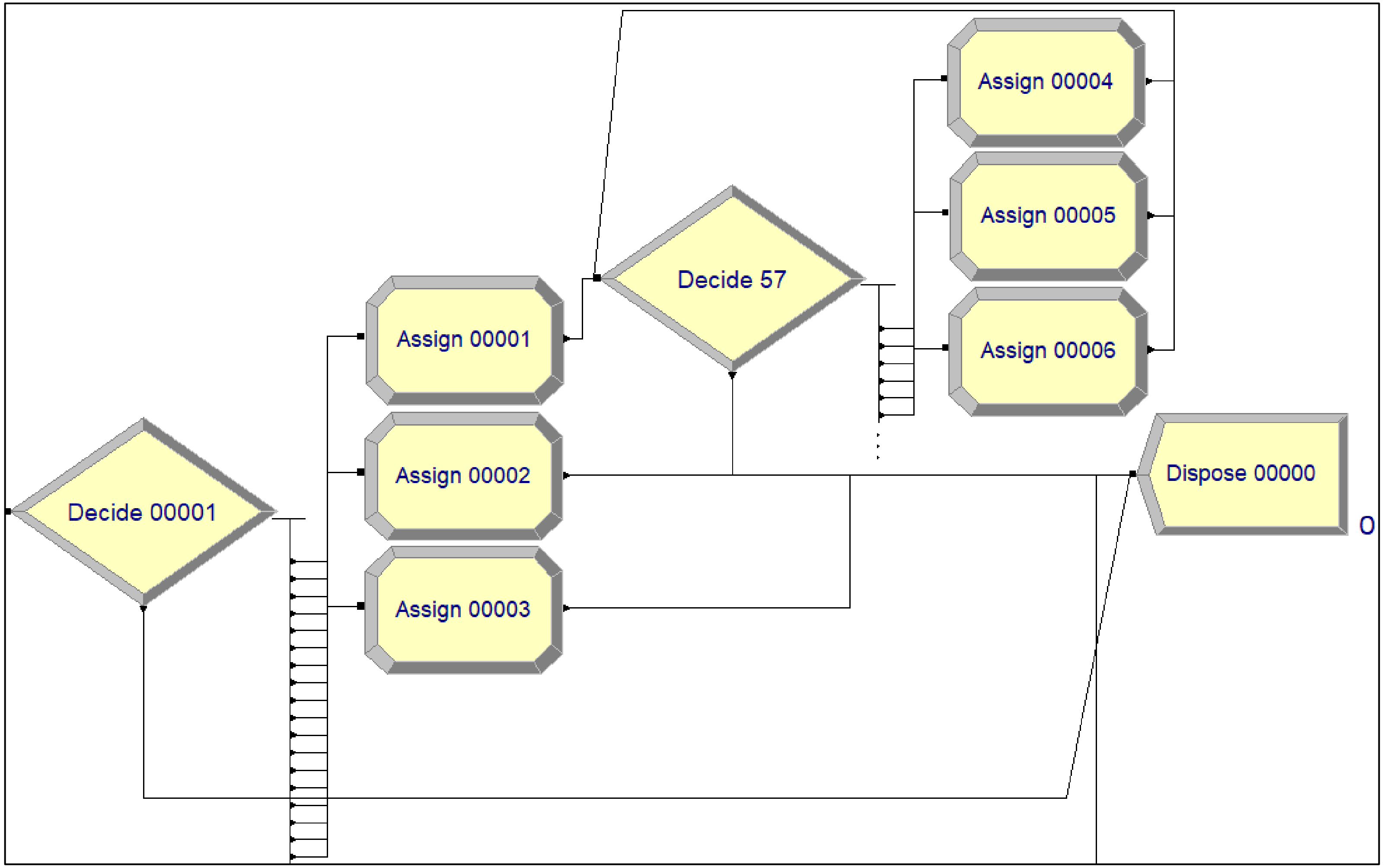

Figure C.15 Submodel for determination of the flit movement

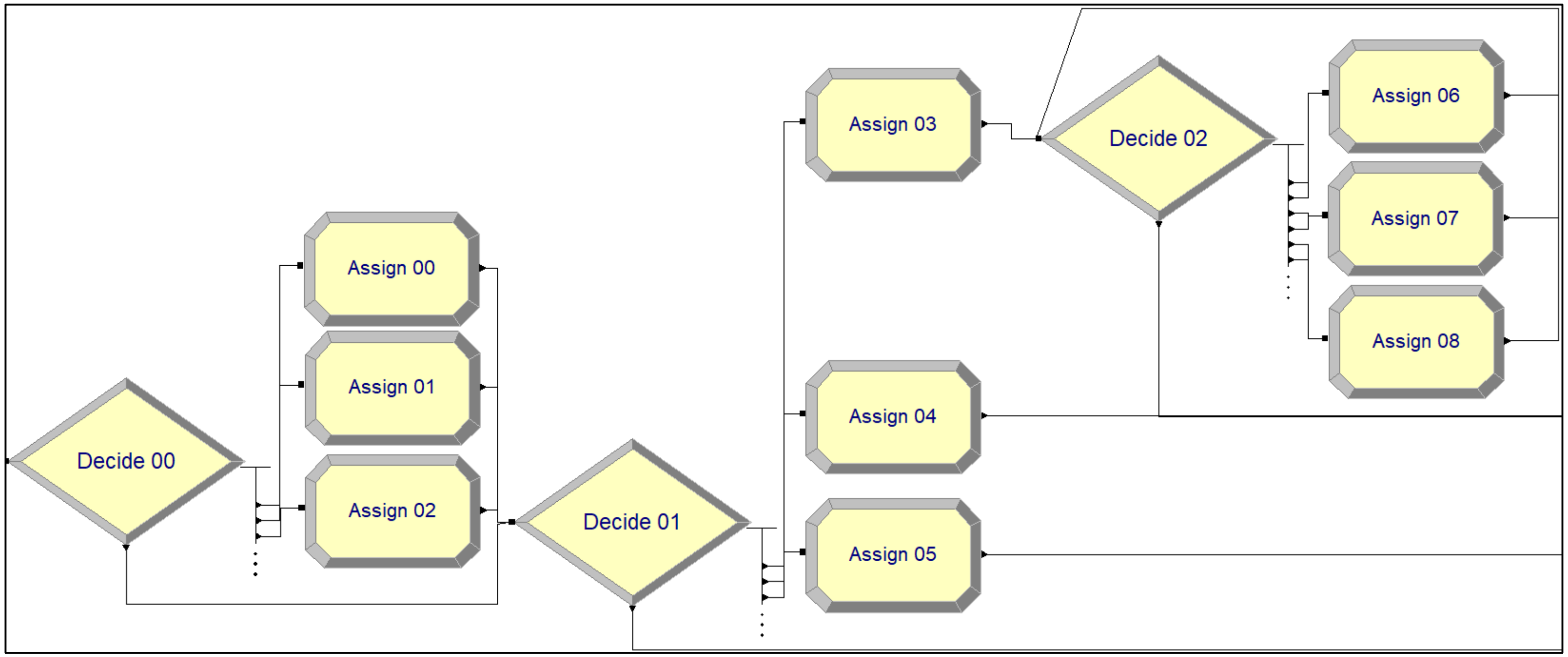

Figure C.16 Submodel for the shearer delays

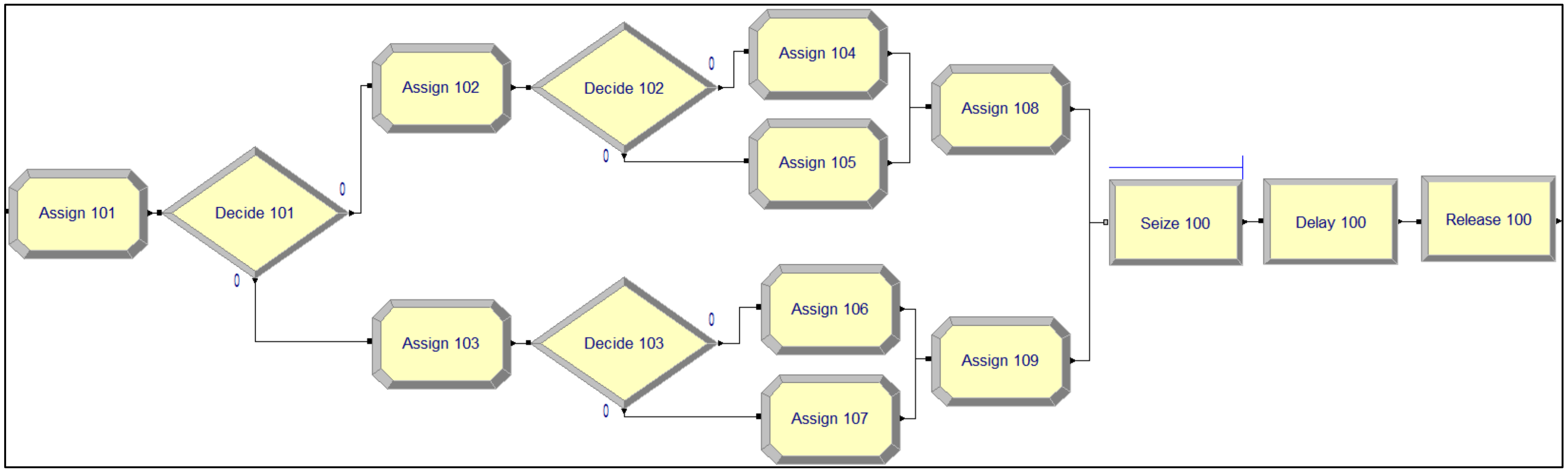

Figure C.17 Submodel for AFC

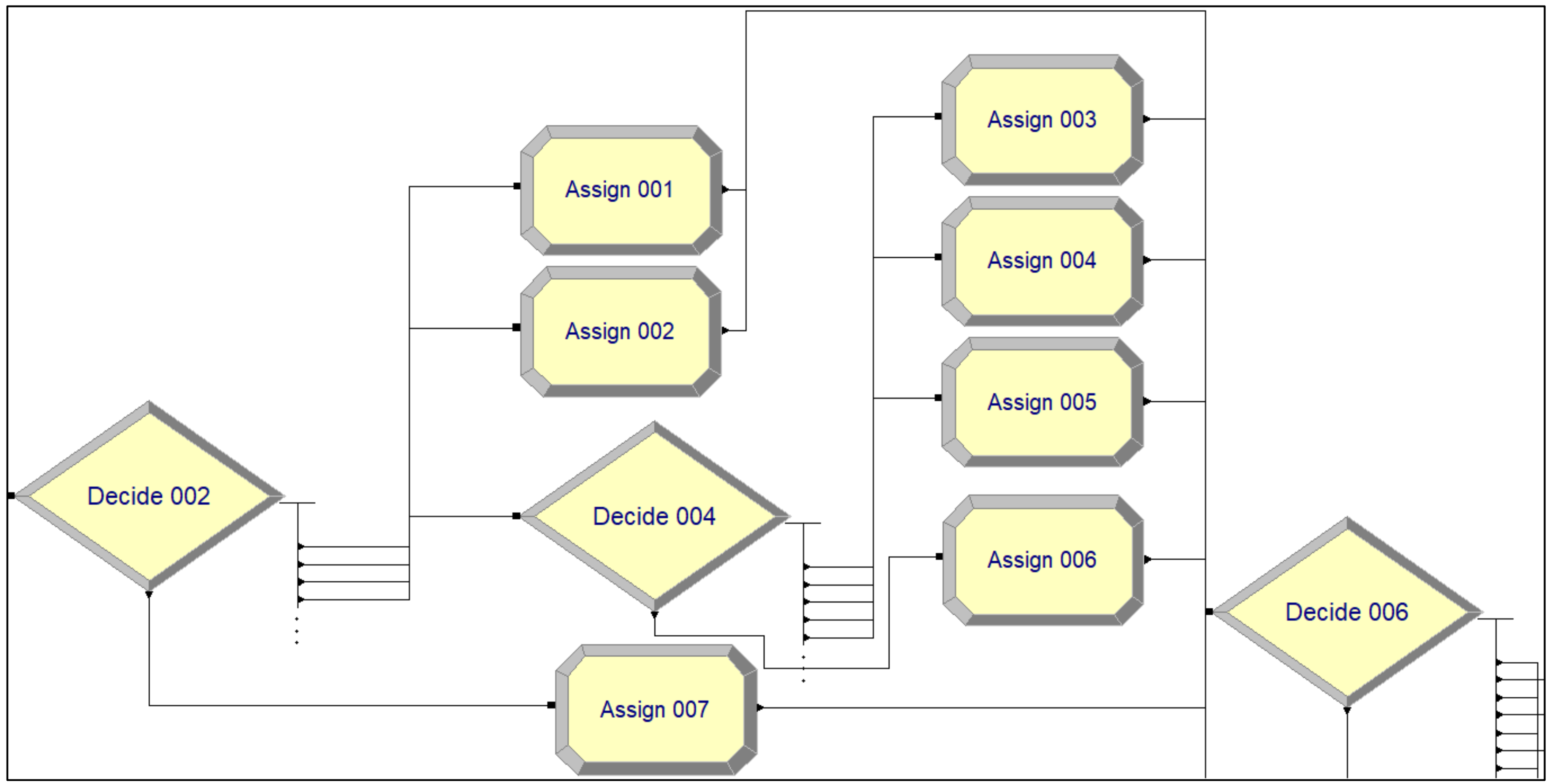

Figure C.18 Submodel for identifying top coal entities produced from the related shield for one direction of the shearer

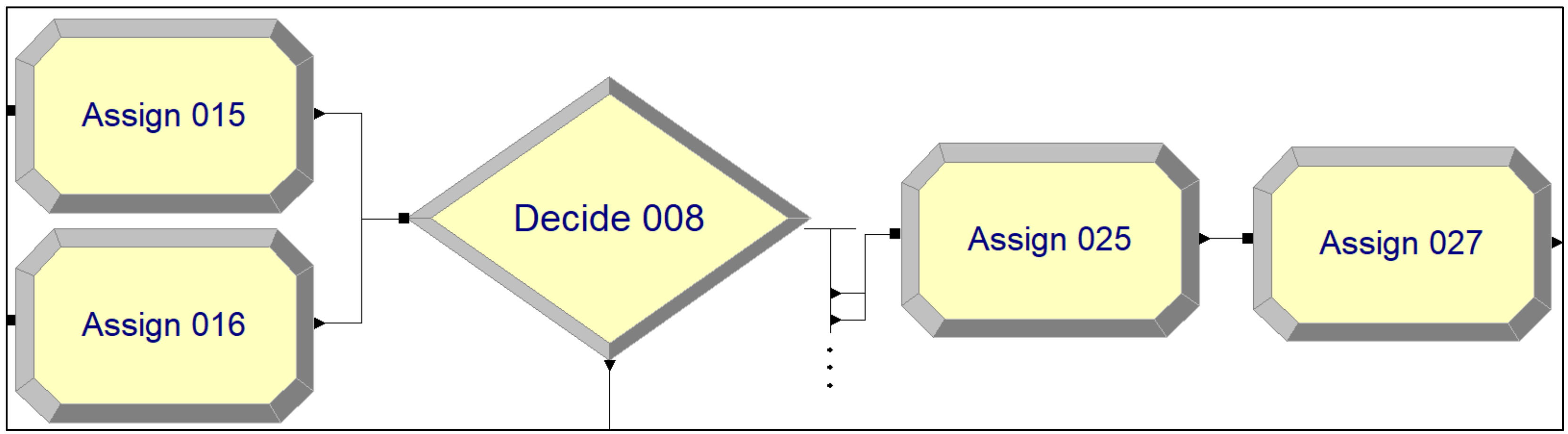

Figure C.19 Submodel for checking the last advancing shield number at the end of the related shearer movement

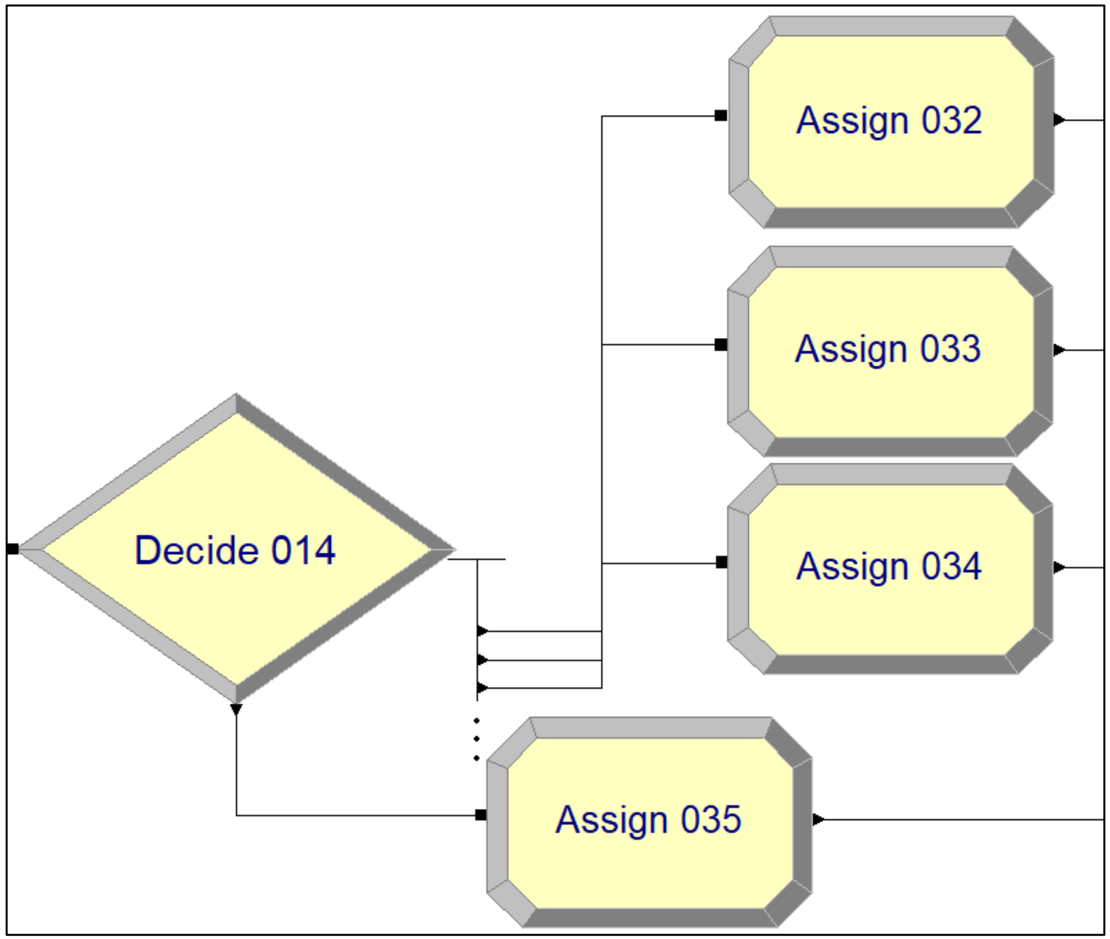

Figure C.20 Submodel for arrangement of advancing shields in the related shearer movement

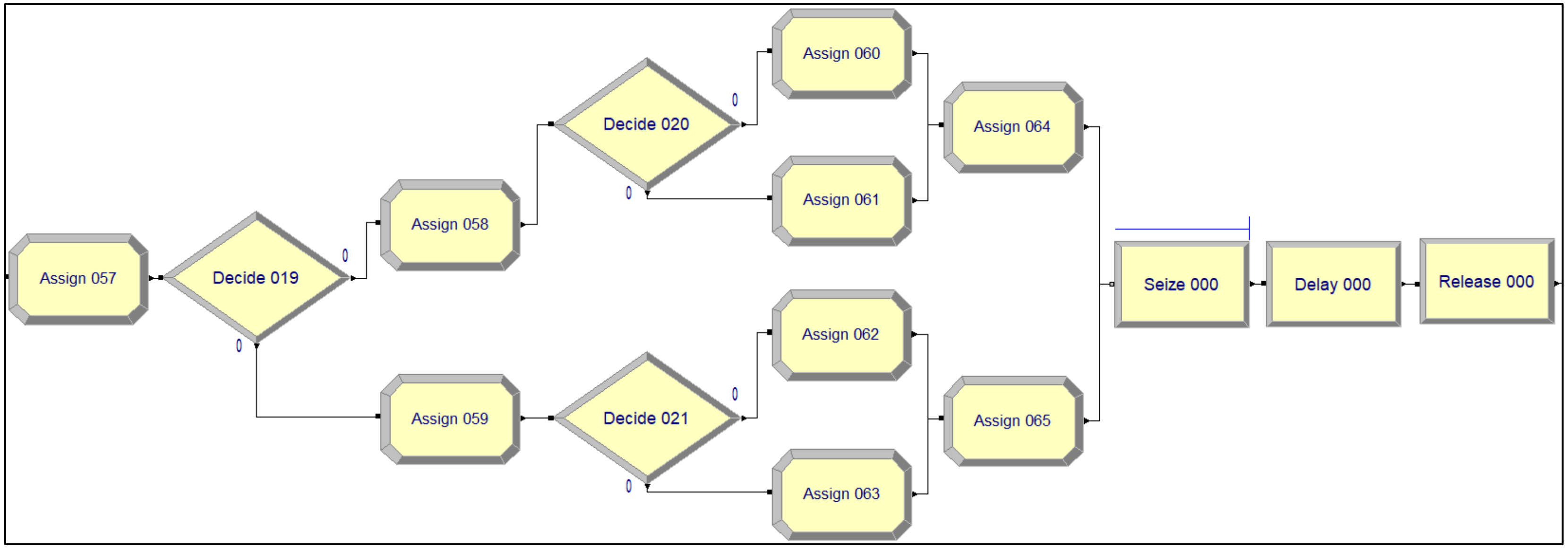

Figure C.21 Submodel for RC

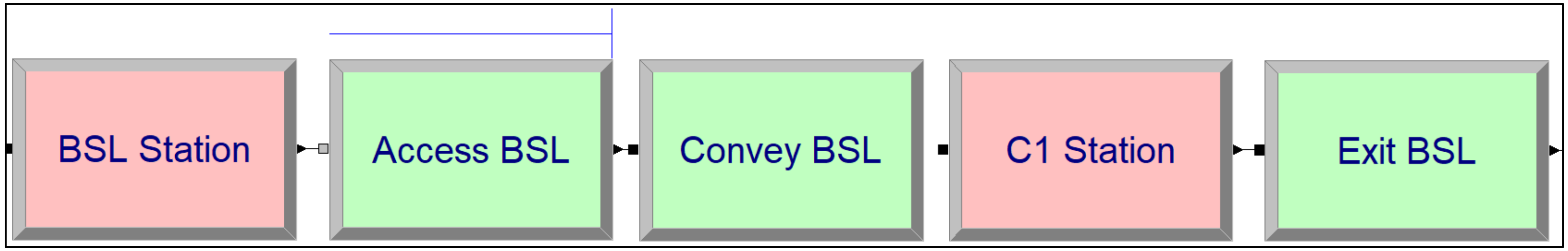

Figure C.22 Submodel for BSL

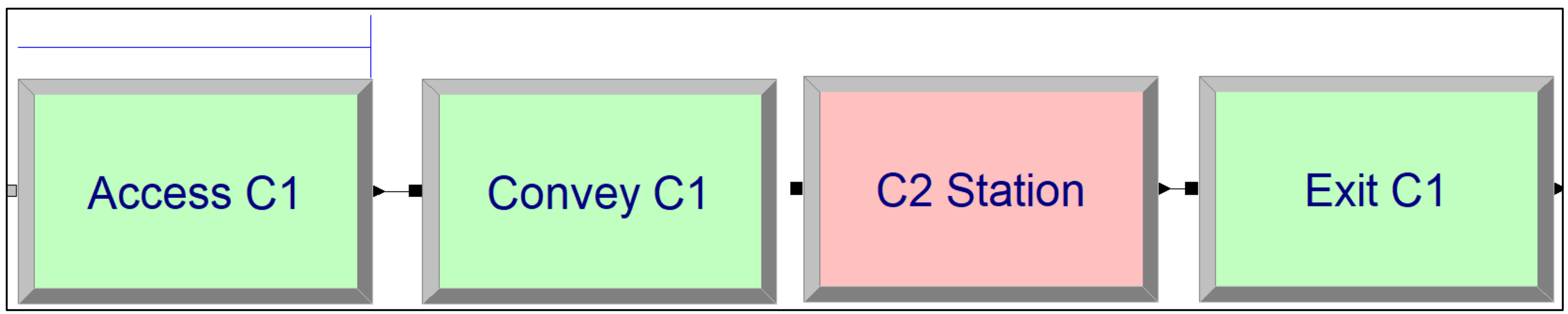

Figure C.23 Submodel for belt conveyor 1

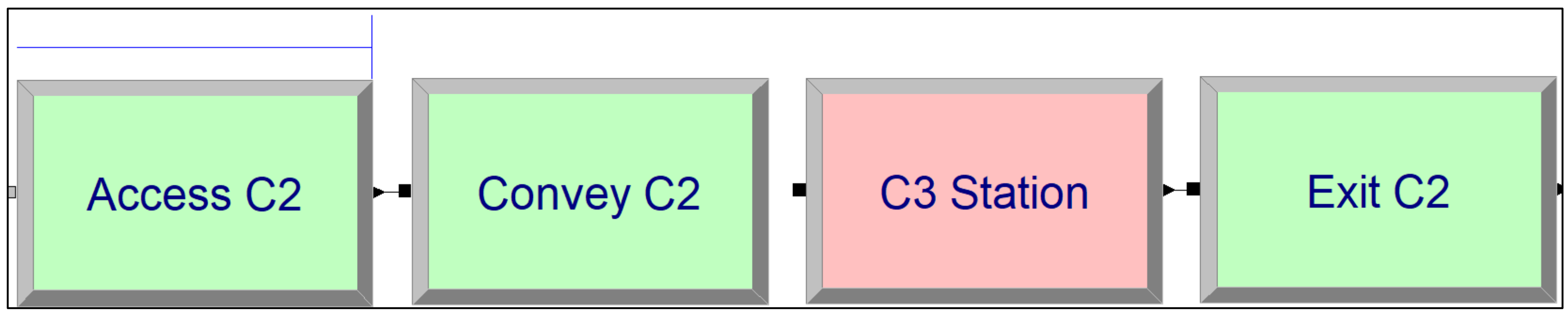

Figure C.24 Submodel for belt conveyor 2

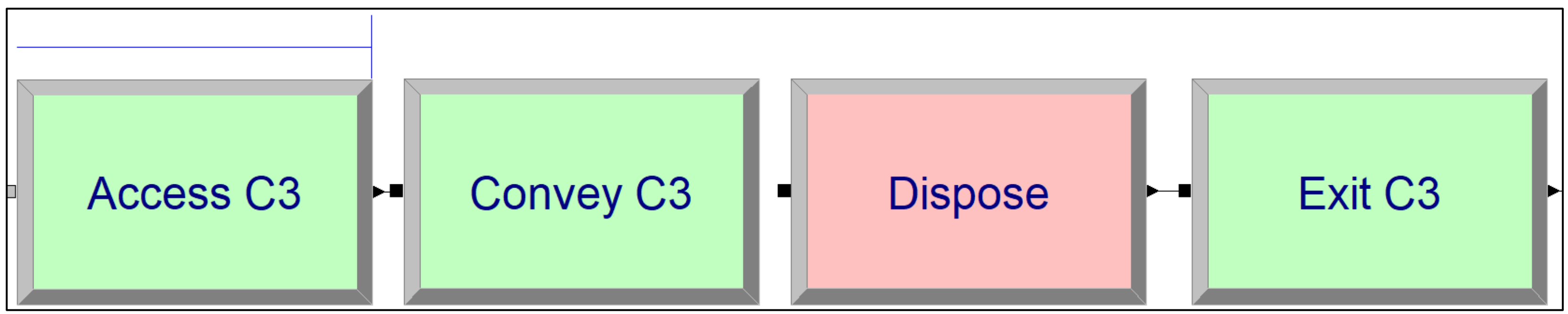

Figure C.25 Submodel for belt conveyor 3