DETERMINATION OF THE OPTIMAL EQUIPMENT FLEET FOR OVERBURDEN STRIPPING OPERATION IN A SURFACE COAL MINE WITH DISCRETE EVENT SIMULATION

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ŞAHABETTİN MERT AYTAÇ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
MINING ENGINEERING

AUGUST 2021

Approval of the thesis:

DETERMINATION OF THE OPTIMAL EQUIPMENT FLEET FOR OVERBURDEN STRIPPING OPERATION IN A SURFACE COAL MINE WITH DISCRETE EVENT SIMULATION

submitted by **ŞAHABETTİN MERT AYTAÇ** in partial fulfillment of the requirements for the degree of **Master of Science in Mining Engineering, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Naci Emre Altun
Head of the Department, **Mining Engineering Dept., METU**

Assist. Prof. Dr. Mustafa Erkayaoğlu
Supervisor, **Mining Engineering Dept., METU**

Examining Committee Members:

Assoc. Prof. Dr. İbrahim Ferid Öge
Mining Engineering Dept., Muğla Sıtkı Koçman University

Assist. Prof. Dr. Mustafa Erkayaoğlu
Mining Engineering Dept., METU

Assist. Prof. Dr. Onur Gölbaşı
Mining Engineering Dept., METU

Date:31.08.2021

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name Last name : Şahabettin Mert Aytaç

Signature :

ABSTRACT

DETERMINATION OF THE OPTIMAL EQUIPMENT FLEET FOR OVERBURDEN STRIPPING OPERATION IN A SURFACE COAL MINE WITH DISCRETE EVENT SIMULATION

Aytaç, Şahabettin Mert
Master of Science, Mining Engineering
Supervisor : Assist. Prof. Dr. Mustafa Erkayaoğlu

August 2021, 99 pages

Coal has a significant role in energy production, which is an essential factor in sustainable development. Overburden removal and coal production capacities have to be increased to provide sufficient amount and quality of coal continuously to thermal power plants to meet the increasing energy demand. In this study, discrete event simulation was implemented to determine the optimum equipment fleet for overburden removal operation in a surface coal mine. According to the long-term plan prepared by the company that provided data, the annual production rate was targeted to be increased significantly for ten consecutive years between 2021 and 2030. The foreseen amount of increase in overburden material led to the necessity of investigating whether this capacity can be met by utilizing conventional load-haul equipment. The fuel usage of haul trucks was investigated to determine the environmental impact of the production schedule by means of carbon dioxide emissions as well. Through this study, a preliminary model of the dispatch algorithm was developed, and the production of a surface coal mine was simulated for each year with the GPS data collected on-site. HAULSIM$^{®}$ 3D haulage simulation software was used to create the production models. The simulated dispatch model contains the road network, excavation site, dumpsite, and ancillary facilities of a surface coal mine in Turkey. Each production year was simplified to be represented by a shorter duration of operation days. After each model was run, simulation model results indicated that a traffic congestion might occur in some areas due to blockage of the trucks. A new mine plan and road network were designed to solve this issue, and the new models were re-evaluated to determine the required number of trucks to meet the planned production. Environmental impacts of the mining equipment were investigated through this study by comparing fuel consumption data of trucks utilized for previous and current mine plans. As a result of the study, it was proven that the new mine plan and new road network helped to solve the traffic issue by increasing the production rate by 26% for the year 2024, 6% for the year 2025, 33% for the year 2026, 23% for the year 2028 and 3% for the year 2030. It is suggested that a fleet management system is implemented to provide real-time data related to the production and the machine health of mobile equipment. By eliminating traffic congestions, the required number of trucks decreased 27% in traffic congestion areas by the aid of the new mine plan and road design. The collected data could be used to better represent the current operation by simulation and the development of business intelligence tools for continuous improvement.

Keywords: Overburden stripping, Discrete event simulation, Fleet management system, Truck-excavator allocation, Truck dispatch

ÖZ

AYRIK OLAY SİMÜLASYONU İLE BİR AÇIK OCAK KÖMÜR MADENİNDEKİ DEKAPAJ KAZISI İÇİN EN UYGUN FİLO EKİPMANLARININ BELİRLENMESİ

Aytaç, Şahabettin Mert
Yüksek Lisans, Maden Mühendisliği
Tez Yöneticisi: Dr. Öğretim Üyesi Mustafa Erkayaoğlu

Ağustos 2021, 99 sayfa

Kömür, sürdürülebilir kalkınmada önemli bir faktör olan enerji üretiminde önemli bir role sahiptir. Artan enerji talebini karşılamak için termik santrallere sürekli olarak yeterli miktarda ve kalitede kömür sağlamak için dekapaj kazılarının ve kömür üretim kapasitelerinin artırılması gerekmektedir. Bu çalışmada, bir açık ocak kömür madeninde dekapaj kazısı operasyonu için en uygun ekipmanları belirlemek için ayrık olay simülasyonu metotu uygulanmıştır. Şirketin uzun vadeli planına göre, 2021-2030 yılları arasında yıllık üretim miktarının önemli ölçüde artırılması hedeflenmiştir. Dekapaj kazılarındaki öngörülen artış miktarı, bu kapasitenin konvansiyonel yük taşıma ekipmanları ile karşılanıp karşılanamayacağının araştırılması gerekliliğini doğurmuştur. Üretim programının çevresel etkisini belirlemek için kamyonların yakıt tüketimi de karbon dioksit emisyonları hesaplanarak incelenmiştir. Bu çalışma ile yük taşıma algoritması için ön model geliştirilmiş ve sahadan elde edilen GPS verileri ile her yıl için madenin üretimi simüle edilmiştir. Üretim modellerini oluşturmak için HAULSIM® 3D nakliye simülasyon yazılımı kullanılmıştır. Simüle edilen yük taşıma modeli, madeninin yol ağını, kazı sahasını, döküm sahasını ve yardımcı tesisleri içermektedir. Üretim yılları, daha kısa çalışma günleriyle temsil edilecek şekilde basitleştirilmiştir. Yıllık bazda hazırlanan modellerin simülasyonu sonucu, maden sahasındaki bazı bölgelerde trafik sorunu oluşabileceği belirlenmiştir. Bu trafik sorunlarını çözmek için yeni bir maden planı ve yol ağı tasarlanmış ve planlanmış üretimi sağlayacak kamyon sayısının belirlenmesinde modeller yeniden değerlendirilmiştir. Bu çalışma ile önceki ve mevcut maden planlarında kullanılmaları öngörülen kamyonların yakıt tüketim verileri karşılaştırılarak madencilik ekipmanlarının çevresel etkileri araştırılmıştır. Çalışma sonucunda, yeni maden planının ve yeni yol ağının, üretim oranını 2024 yılı için %26, 2025 yılı için %6, 2026 yılı için %33, 2028 yılı için %23 ve 2030 yılı için %3 oranında artırarak trafik sorununun çözülmesine yardımcı olduğu gösterilmiştir. Mobil ekipmanların makine sağlığı ve üretim miktarları ile ilgili gerçek zamanlı verilerin sağlanması için bir filo yönetim sisteminin uygulanması önerilmektedir. Yeni bir maden ve yol planı tasarlanarak trafik sıkışıklığı olan bölgelerde trafik sorunu ortadan kaldırılmış ve bu doğrultuda gerekli kamyon sayısı %27 oranında azaltılmıştır. Toplanan veriler, simülasyon ve iş zekası araçlarının geliştirilmesi yoluyla mevcut operasyonu daha iyi temsil etmek için kullanılabilir.

Anahtar Kelimeler: Dekapaj kazısı, Ayrık olay simülasyonu, Filo yönetim sistemleri, Kamyon-kepçe tahsisi, Kamyon sevki

To My Family and Friends

ACKNOWLEDGMENTS

I would like to express my sincerest appreciation to my advisor Assist. Prof. Dr. Mustafa Erkayaoğlu for his valuable assistance, encouragement, and his supervision. He guided me through my journey anytime I needed his advice, and this study could not have been done without his precious guidance. I am also thankful to my committee members and Assoc. Prof. Dr. İbrahim Ferid Öge and Assist. Prof. Dr. Onur Gölbaşı for their precious comments on my thesis study.

I would like to thank Dr. Selin Yoncacı for her continuous support and for helping me broaden my perspective as an engineer.

My family, my mother Çiğdem Aytaç, my father Ahmet Aytaç and my sister Zeynep Aytaç, always supported me throughout my education, endlessly, and anytime I needed. Thanks to their support throughout my whole education life, I found my path.

My friends have a great impact on my study, as well. Every time I needed them; they were there for me. I am grateful to my friends Perin Çün, Işıkcan Yılmaz, Ozan Utku Rıdvanoğlu, Ozan Dernek, Mert Ozan Katipoğlu, Batu Aksu, Ahmet Berk Benlioğlu and Uğur Şahin, even though we are not able to physically see each other, they always supported me. Also, I want to thanks to my friends Faruk Küçüksubaşı, Kaan Onat, Anıl Yiğit, Ege Özgüven, Zafer Demirtaş, Gizem Aslan and my workmates who support me for being by my side anytime I needed. Also, I would like to give thanks to my research assistant friend Cengiz Kaydım for helping me during the thesis submission process. Finally, I owe great thanks to Hazal Melis Baydar for helping me through hard times unconditionally supporting me.

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CHAPTER 1

INTRODUCTION

1.1 Background Information

Coal has a significant role in energy production, which is an essential factor in sustainable development. Overburden removal and coal production capacities have to be increased to provide sufficient amount and quality of coal continuously to thermal power plants to meet the increasing energy demand. In this study, discrete event simulation was implemented to determine the optimum equipment fleet for overburden removal operation in a surface coal mine. Through this study, a preliminary mathematical model of the dispatch algorithm was developed, and the production of a surface coal mine was simulated for each year with the GPS data collected on-site. HAULSIM® 3D haulage simulation software was used to create the production models. The simulated dispatch model contains the road network, excavation site, dumpsite, and ancillary facilities of a surface coal mine in Turkey. Each production year was simplified to be represented by a shorter duration of operation days due. After each model was run, simulation model results indicated that a traffic congestion might occur in some areas due to blockage of the trucks. A new mine plan and road network were designed to solve this issue, and the new models were re-evaluated to determine the required number of trucks to meet the planned production. Environmental impacts of the mining equipment were investigated through this study by comparing fuel consumption data of trucks utilized for previous and current mine plans. Share in total electricity generation in the world is given in Figure 1.1 (International Energy Agency, 2019). Turkey is one of the countries that use fossil fuels as primary energy resources. Electricity in Turkey generated by coal is 37.3% of the total electricity generation by all sources. In Figure 1.1, energy generation by source in Turkey through the year 2018 is given. Capacities of thermal power plants must be increased to meet this increasing energy demand until renewable energy sources become the primary sources to generate electricity.

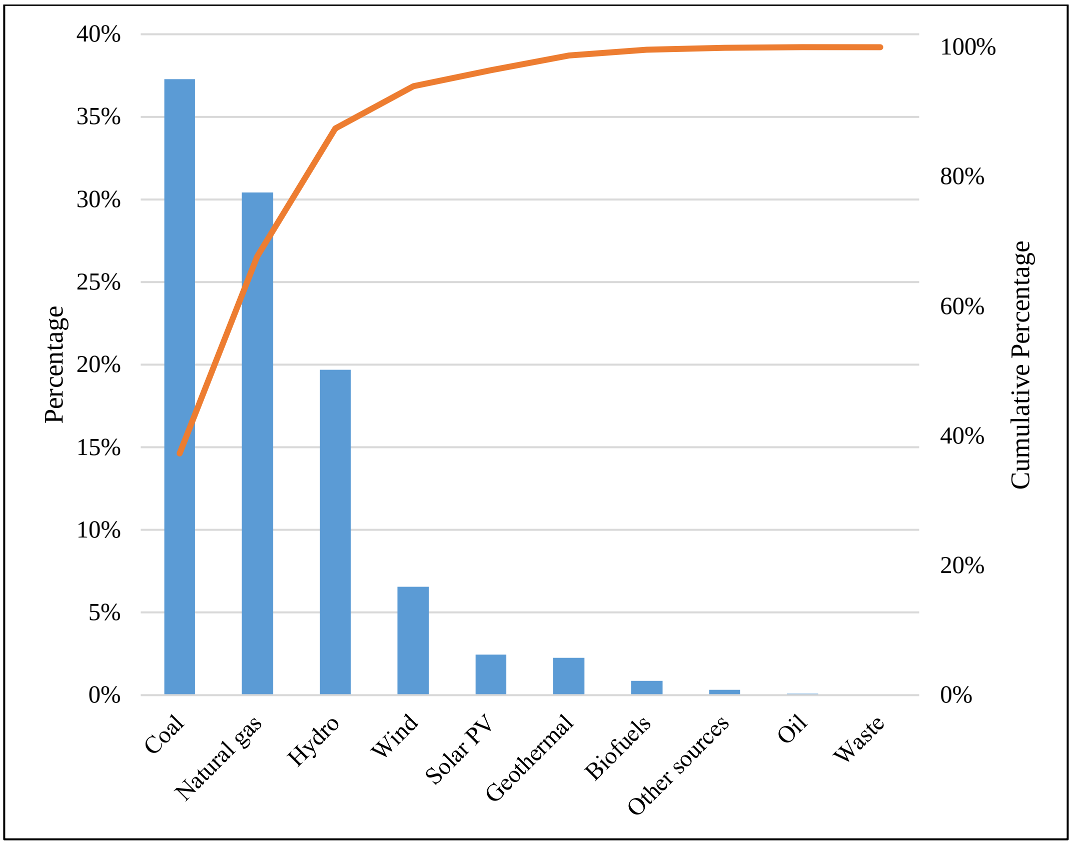


Figure 1.1 Electricity generation by source in Turkey (International Energy Agency, 2019)

1.2 Problem Statement

The dynamic operational conditions of surface mines require an optimum fleet configuration, especially for overburden stripping activities. The assessment of the fleet efficiency by conventional methods, such as calculation of cycle times is limited as the basis of the operational activities are assumed as being constant. Discrete event simulation is a commonly used methodology to investigate operational performance of mining equipment. This study aims to determine the optimum fleet configuration for a mine plan with increasing overburden removal.

The environmental burden of the conventional load and haul equipment is investigated by fuel usage to determine the environmental impact of the production schedule.

1.3 Objectives of the Study

This study aims to deliver an alternative approach to dispatch strategies while considering the environmental impact of the carbon dioxide emissions caused by mining equipment at a surface coal mine that will undergo capacity increase at the thermal plant for ten consecutive years. Since meeting this increasing demand depends on the rate of the overburden stripping operation, maximizing the operation rate with conventional mining equipment such as trucks and excavators is the focus of this thesis study. Therefore, both the optimum number and capacities of the trucks and excavators were determined to achieve the targeted production rate in a mining area. However, there is a risk of a considerably high number of trucks required to achieve the target production rate and traffic congestion problems could occurred at some parts on the road network. As a result, the main objective is finding the limits of the available equipment fleet to improve the efficiency of the overburden removal operation and minimize the environmental impact of the off-highway trucks by determining the optimum equipment fleet.

1.4 Methodology

The overburden stripping operation in a surface coal mine is simulated by implementing a discrete event simulation method for each year with the GPS data collected on-site. HAULSIM® 3D haulage simulation software is used to create the production models by designing road networks. Road designs are imported to the software as GPS data. Each point in GPS data represents nodes, and a road segment is created by joining the nodes. The software offers an equipment library that consists of various equipment to use in the simulation study. For this study, a new equipment is defined by importing properties of the truck and excavator available in the mining area. At the beginning of the study, a calibration model is created to simulate the mining operations realistically. Through these calibration studies, the cycle times of trucks, loading, spotting, maneuvering times of the excavators were calibrated in the simulation software. After the calibration studies were completed, the road networks and locations of excavation and dumping points of the selected simulation years were created in the software. Then, tasks that define equipment missions during the simulation run were assigned in the software. Moreover, fuel consumption data of existing equipment was imported, and the carbon dioxide emissions derived from the fuel consumption of the trucks were used to identify how carbon dioxide emission changed by optimizing overburden stripping operations. Workflow of the thesis study is given in Figure 1.2.

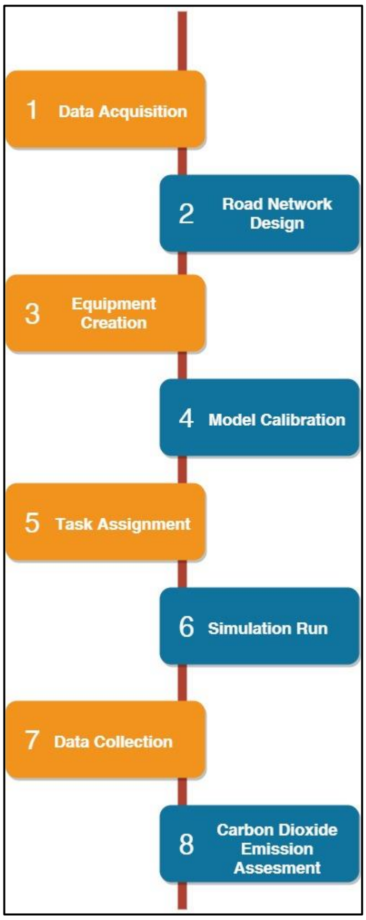


Figure 1.2 Workflow of the study

CHAPTER 2

LITERATURE REVIEW

Simulation techniques are widely used techniques to mimic real systems. Simulations could be divided into two groups which are continuous simulations and discrete event simulations (DES). In this thesis study, a discrete event simulation method is implemented to simulate an overburden stripping operation. Through this chapter, an introduction to simulation systems will be given. Then, research about fleet management systems (FMS) will be presented. FMS is a system that makes real-time decisions to optimize material handling operations. FMS is an essential system for haulage operations especially in case a vast amount of material handling is required. Finally, studies about the environmental impact of the haulage operations are presented. Due to the fossil fuel consumed by the mining equipment, a variety of airborne emissions, including carbon dioxide, is caused. Mining is one of the most energy-intensive industries and a considerable amount of fuel is consumed during production activities. Therefore, carbon dioxide emissions are investigated to determine potential ways to minimize the environmental impact of the operation.

2.1 Simulation Implementation

Simulation could be defined with different definitions. Basically, simulation could be defined as a technique that imitates real-world facilities and processes (Law, 2015). These facilities and processes are called systems (Kelton et al., 2010). Law (2015) states that a system can be examined by conducting experiments with the actual systems or the model of the system, and the model could be physical or mathematical, as seen in Figure 2.1. Moreover, if the mathematical model is simple enough, it could be examined analytically, but many systems are too complex to work, and simulation methods should be implemented to conduct experiment with the system (Law, 2015).

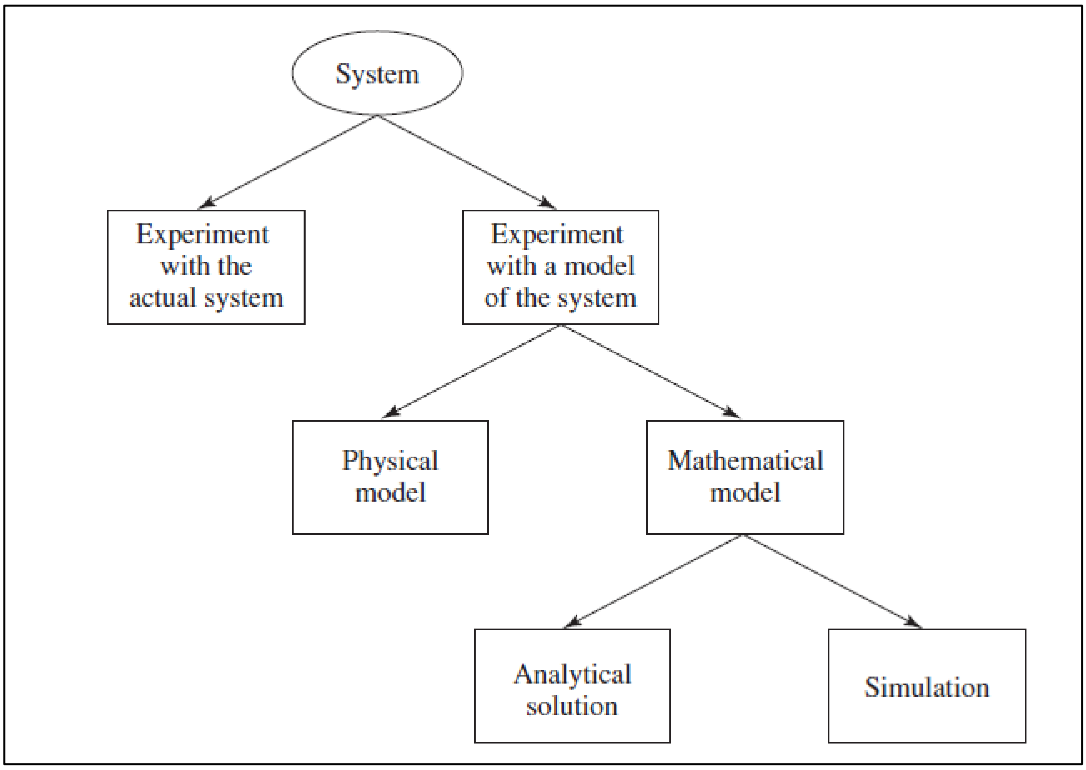


Figure 2.1 Ways to Study System (Law et al., 2015)

The real-world facilities and processes -or systems- have boundaries that involve internal entities of operation, configuration, and choice (Robinson et al., 2011). On the other hand, external entities are not modeled unless they affect the system. Simulation studies date back to the 18th century. Georges Louis Leclerc conducted one of the famous simulation studies to estimate the value π by using needles in 1773 (Kelton et al., 2010). With the rise of digital computers in the 1950s and 1960s, people created simulation models in computers using programming languages like FORTRAN (Kelton et al., 2010). However, simulation studies required a considerable budget to create the complex model and run the model in these years. Today, personal computers are used to make complex models since the computational power of personal computers today is much higher than the computers used in the 1950s.

Simulation models could be divided into subgroups according to different categorizations. A simulation model could be deterministic or stochastic. According to the Law (2015), simulation models that do not contain any random variables are called deterministic mode, and models that contain some random input components are called stochastic. Another categorization divides simulations into two subgroups as discrete and continuous. Law (2015) defines continuous simulation models as containing variables that change continuously with respect to time. On the other hand, discrete simulation models consist of variables that change instantaneously in discrete time intervals (Law, 2015). Discrete event simulation is a widely used technique that is used to forecast production outcomes. One of the first simulation studies in mining application is done in the 1960s, aiming to determine the optimum number of trains to have on a haulage level in an underground molybdenum mine (Rist, 1961). This study is followed by other studies that concern mining applications, as well. More complex simulation models of mining operations are simulated since the 1990s due to the increasing computational power (Almgren, 1990; Hoare & Willis, 1992). Ozdemir & Kumral (2019) used a simulation-based optimization method to consider uncertainties in a mining operation in their studies. In this study, linear programming was utilized. Researchers create a model for multi pit operations. In details, the equipment fleet was divided into sub fleets and this approach was tested in a real mine site. According to the results, significant increase in production obtained with 9.4% increase (Ozdemir & Kumral, 2019). Similarly, Ta et al. (2013) develop a model by utilizing linear programming to minimize number of trucks required to meet the desired production. Moradi Afrapoli et al. (2019) use discrete event simulation to create dynamic dispatch model for their study. They used a powerful discrete event simulation software ARENA® to simulate dispatch operation in mining area. Main goal of the study is to minimize shovel idle times, truck wait times and deviations from the path production requirements. According to study, 15% reduction in calculated desired fleet by utilizing multiple objective model (Moradi Afrapoli et al., 2019). Another study that presents a simulation optimization tool to account uncertainties in mining area as a proactive decision-making approach carried out by Upadhyay & Askari-Nasab (2018). Main objective of this study is the develop robust short-term plans by regarding minor details in mining area. Yilmaz & Erkayaoglu (2021) utilized DES method to evaluate performance of the shearers that work in longwall coal mines. According to the study, most influential parameter on shearer performance is determined as shearer stoppages. Another DES study carried out by Golbasi & Turan (2020) aims to optimize multi scenario maintenance policies by minimizing maintenance cost and maximizing system availability.

2.2 Fleet Management System (FMS)

FMS is a monitoring system that continuously monitors and manages production. The main aim of using FMS could be described as optimizing mine production and efficiency by utilizing real-time data. Moradi Afrapoli & Askari-Nasab (2019) mentioned the study of Bogert (1964) that referred to radio communication between mining equipment for the first time. Also, the first implementation of fleet management applied in the late 1970s was mentioned in the study of Mueller (1977). Chaowasakoo et al.'s (2017) study aims to improve fleet management in mines by investigating the match factor, which is defined as the ratio of the truck arrival rate and the shovel service time. Early studies were conducted on match factor in the early 1960s (Douglas, 1964; Morgan & Peterson, 1964).

In the study of Moradi Afrapoli & Askari-Nasab (2019), it was stated that FMS plays a significant role since the main objective is maximizing production. Dynamic FMSs also have a role in reducing risks, increasing quality, and improving the operation's efficiency (Billhardt et al., 2014). An example of a dynamic FMS is given in Figure 2.2.

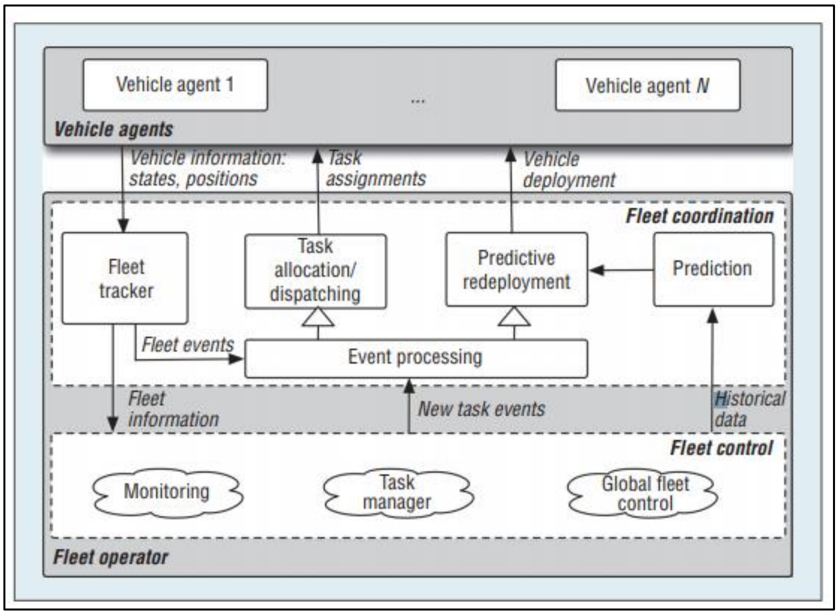


Figure 2.2 Architecture for Dynamic Fleet Management (Billhardt et al., 2014)

Moradi Afrapoli & Askari-Nasab (2019) divide mining FMSs into two categories. These are:

- Fixed Truck Allocation
- Flexible Truck Allocation

In fixed truck allocation systems, a group of hauling equipment -trucks- is locked to each transportation route. Trucks follow the same path in every cycle. Trucks do not leave the paths unless a critical event happens. On the other hand, in flexible truck allocation systems, the path is locked same as fixed truck allocation systems at the beginning of the shift. However, this time, trucks get a new task from the dispatch system for every cycle (Moradi Afrapoli & Askari-Nasab, 2019).

Dispatch systems in a mining operation could be investigated by implementing the discrete event simulation method as well. Some researchers investigated dispatch systems in mining operations using different methodologies (Moradi Afrapoli & Askari-Nasab, 2019b; Ozdemir & Kumral, 2019). Moradi Afrapoli et al. (2019) used Modular Mining DISPATCH, a widely used FMS in the mining industry, to create a dynamic truck dispatching model for their study. According to their study, 30% less truck is required to operate process plants with full capacity by utilizing FMS and discrete event simulation. Ozdemir & Kumral (2019) studied simulation-based optimization in their study, and they refer to the FMS as a solution to the truck dispatch problems. The strategy in the study was developed for multi-pit surface mines by dividing the truck fleet into sub fleets, and the proposed strategy was tested in a real open-pit surface mine. According to the study results, production was increased by 9.4% by utilizing a developed approach. These complex strategies cannot be operated without using any FMS.

2.3 Studies on Diesel Consumption in Mining Area

Studies related to diesel engines started at the end of the 19th century by Dr. Rudolf Diesel. He designed stationary air blast injected engines in the beginning. The development rate of diesel engines increased during World War I and World War II (Baranescu & Challen, 1999). The main working principle of diesel engines is compression ignition, as seen in Figure 2.3. Unlike gasoline engines, a heterogeneous charge of previously compressed air and a finely split liquid fuel spray are used in the compression ignition engine, as seen in Figure 2.3 (Baranescu & Challen, 1999).

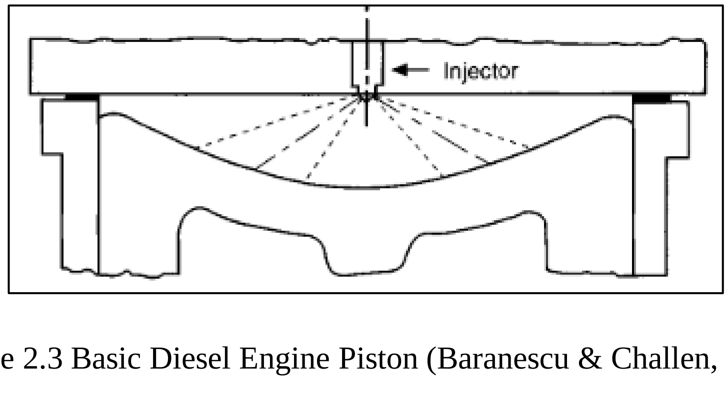


Figure 2.3 Basic Diesel Engine Piston (Baranescu & Challen, 1999)

Fuel economy is the key determinant to choose a diesel engine instead of a gasoline engine. Even though small size gasoline engines have made significant improvements, diesel engines are still more economical than gasoline engines since diesel motors have developed in several areas such as fuel injection, lean-burn operation, and combustion (Baranescu & Challen, 1999).

Overburden material is removed and hauled with different strategies to dumping areas by using equipment that is commonly diesel-powered. For example, shovel, dragline, or bucket wheel excavators are used to load material on belt conveyors, railroad cars, or -in most cases- trucks (Brannon et al., 1992). Either an electric engine or diesel engine could operate these equipment. Moreover, hybrid systems in mining are studied, and according to the results, natural gas-based hybrid engines show 18.7% better performance than diesel fuel consumption (Zhang et al., 2021). However, diesel engines are still the primary engine type for off-highway trucks.

Mining is one of the most energy-intensive industries since considerable energy is required for mining operations. According to EIA (2019), mining activities are responsible for 12% of the industrial energy consumption, as seen in Figure 2.4.

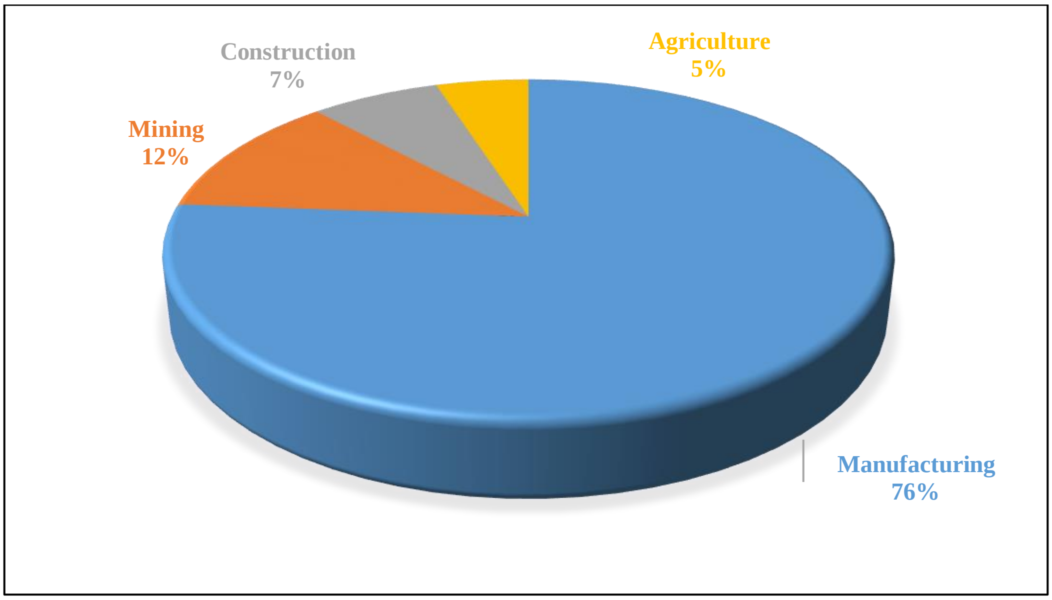


Figure 2.4 Percentages of Industrial Energy Consumption (EIA, 2019)

Moreover, the fuel consumption of open-pit mine trucks holds a 22% share of the total cost in mining operations (Wang et al., 2021). Conventional mining equipment uses diesel fuel to be operated. Since a considerable amount of diesel is consumed during the mining operations, Rodovalho et al. (2016) studied different haulage configurations to reduce diesel consumption. 10% reduction in diesel consumption is achieved by finding the optimum configuration. The queue is another problem in terms of fuel consumption. Empty, idle trucks are the primary sources of unnecessary fuel consumption in mining areas (Dindarloo & Siami-irdemoosa, 2016). Fuel consumption of trucks in the queue is also regarded in the study of Wang et al. (2021). According to the study of Wang et al. (2021), while the impact weight of the major hauling operations on fuel consumption is 0.959, the weight of the queuing time is 0.014, which count cannot be disregarded.

2.4 Studies about Off-Highway Trucks' Carbon Dioxide Emissions

Carbon dioxide is emitted when fossil fuels are burned since carbon-based lifeforms are the primary origin of fossil fuels. Fossil fuels used in industry, power generation, and transport are the primary carbon dioxide sources (IPCC, 2005). Carbon dioxide is one of the Green House Gases (GHG), and emission of these gases should be avoided to minimize the environmental impact of the mining operations. European Commission initiated a European Green Deal policy that will transform European Union into a carbon-natural region regarding economic growth by 2050 with modern and resource-efficient policies (European Commision, 2019). According to the International Energy Agency (2020) data given in Figure 2.5, industrial energy consumption rates have increased dramatically between the years 1990 and 2018. 804,964 metric tons of oil equivalent (ktoe) electricity were consumed in 2018, almost 210% of the electricity consumed in 1990.

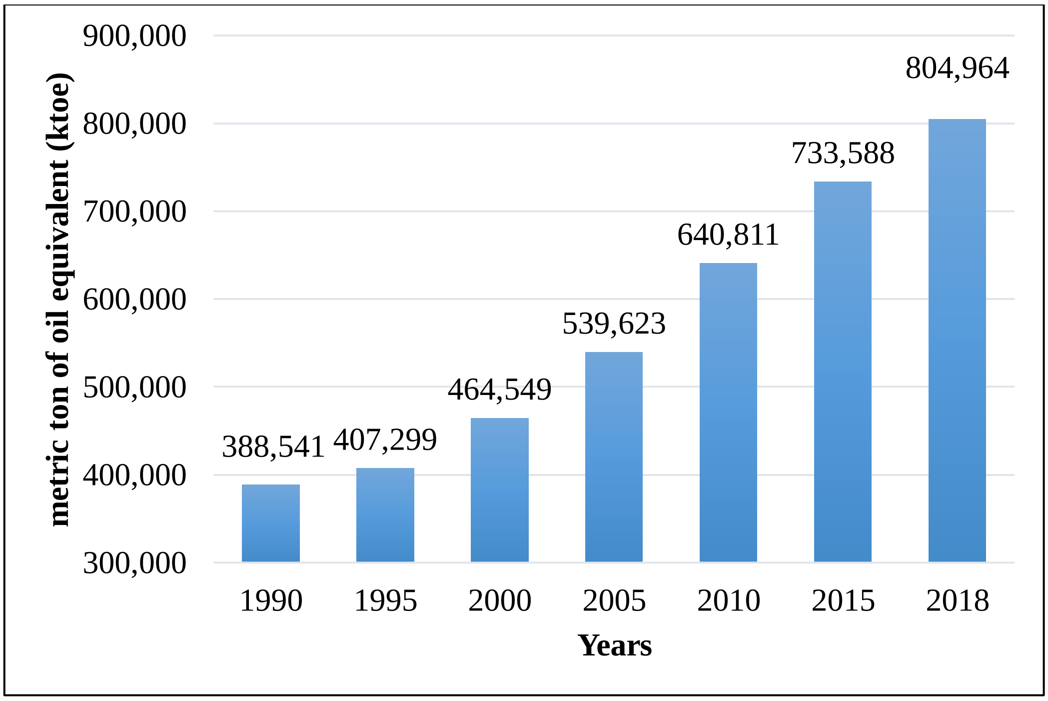


Figure 2.5 Electricity Final Consumption by Industry (International Energy Agency, 2020)

Projections show that the industrial energy consumption of OECD countries will not dramatically increase by 2050; however, both overall and industrial energy consumption of the non-OECD countries increase significantly, according to Figure 2.6 (EIA, 2019).

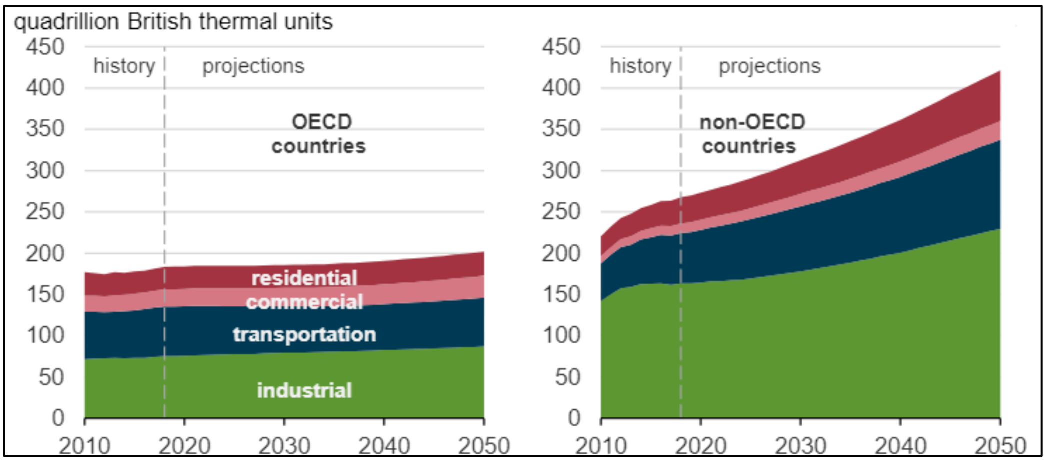


Figure 2.6 Energy Consumption by Sector (EIA, 2019)

Since energy generation highly depends on fossil fuels, as mentioned earlier, carbon dioxide emissions increase with fossil fuels usage. According to the European Commission (2016), transportation represents a quarter of the greenhouse gas emissions. Road transport accounted for 72.8% of greenhouse gas emissions in greenhouse gas emissions from transportation in 2004, as seen in Figure 2.7. Increasing the efficiency of the transportation systems, developing low-emission alternative energy, and deploying zero-emission vehicles are the strategies to decrease greenhouse gas emissions caused by transportation (European Commission, 2016).

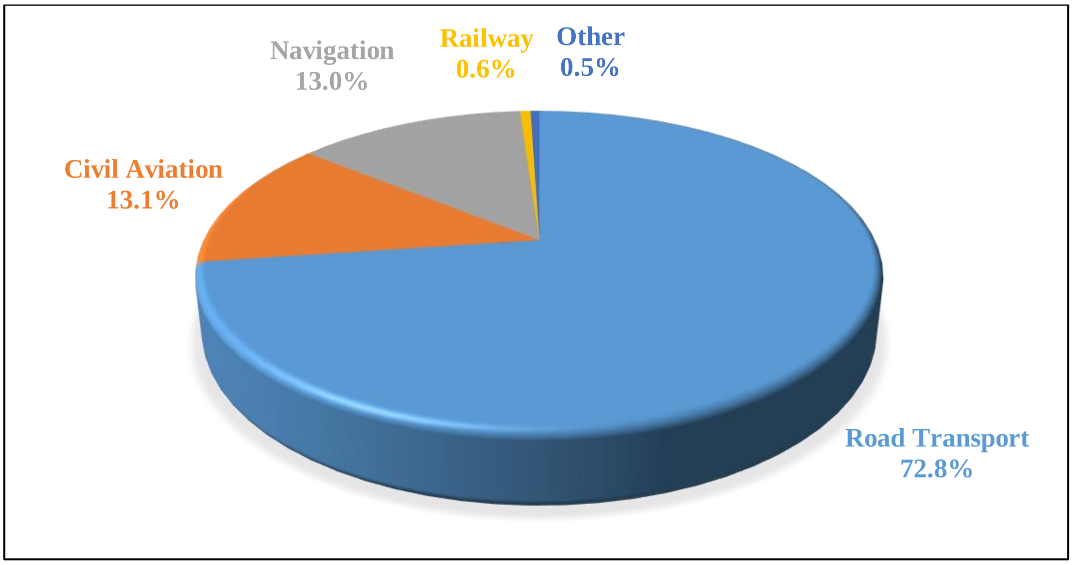


Figure 2.7 Green House Gas Emissions from Transport in 2004 (European Commission, 2016)

Carbon dioxide emissions could be investigated by utilizing discrete event simulation as well. For example, the environmental impact of off-highway trucks was studied in several studies (Bharathan et al., 2017; Jassim et al., 2018). In the study of Bharathan et al. (2017) different power sources such as diesel fuel, compressed natural gas, and electricity for mine trucks are examined to compare carbon dioxide emitted by mentioned power sources. According to the study, if diesel engines change with the electric engines and compressed natural gas engines, carbon dioxide emissions decrease by 30% and 80%, respectively

(Bharathan et al., 2017). Jassim et al. (2018) studied energy consumption and carbon dioxide emissions by utilizing an artificial neural network and discrete event simulation as well. First, data exported from discrete event simulation results database to assess fuel consumption and carbon dioxide emission to analyze different site conditions. Then these data are utilized by importing them to the artificial neural network model. Artificial neural network model is used to estimate energy usage and carbon dioxide emissions. According to the results of this study, grade, horsepower, and haul distance have a significant effect on fuel consumption and carbon dioxide emissions (Jassim et al., 2018).

Moreover, Peralta et al. (2016) aimed to keep GHG emissions minimum while maximizing equipment availability. The effect of truck maintenance on fuel consumption and carbon dioxide emission is examined in the study. Results of the study show that truck reliability is equally important with weight and haul distance in terms of fuel consumption (Jassim et al., 2018). These studies showed that optimizing equipment availability to maximize production output help to reduce carbon dioxide emissions as well.

CHAPTER 3

DETERMINATION OF OPTIMAL EQUIPMENT FLEET AND ASSESSMENT OF CARBON DIOXIDE GAS EMISSIONS

Different types of equipment could be utilized to perform overburden stripping operations. For this case, excavators and trucks are preferred to perform overburden stripping operations by the company. As a conventional approach, capacities and the number of trucks were decided according to the production rate. However, a different dispatch approach was implemented by fixing truck capacity and increasing the number of trucks since the production rate will significantly increase for the next ten years. The number of trucks required to meet the targeted capacity could be calculated by estimating the truck's average speed. Estimation is done by utilizing historical cycle time data of the previous production years. Average cycle time and the capacity of trucks are used to calculate the required number of trucks for the cases that do not require a vast amount of production. However, for the cases that a vast number of trucks are required, this way is disadvantageous since this way does not consider the traffic congestion on main roads, excavation areas, and dumping areas. The discrete event simulation method is advantageous since it could represent traffic congestion on the road network for each truck in a realistic manner. This study shows that the number of trucks required for production years with low targeted production rates is almost the same when determined by hand calculation and discrete event simulation method. On the other hand, it is also shown that the required number of trucks for the production years with high targeted production rates should be determined by implementing discrete event simulation since there is a difference in the number of trucks between hand calculation and discrete event simulation method. The discrete event simulation method is implemented using HAULSIM® 3D simulation software to understand the outcomes of this strategy in this thesis study. Field, road, and equipment properties are imported to the software by collecting data such as GPS, cycle time, spotting time etc. The company provided data such as equipment properties, road properties, and road network designs, which are used to create a calibration model to represent overburden operations more realistic. Since a significant number of trucks are required to handle the increased production rate, carbon dioxide emissions have to be monitored to figure out the operation’s environmental impact. In the scope of this thesis study, the environmental impact of the overburden stripping operation is simulated by monitoring fuel consumption with HAULSIM® 3D simulation software. After that, the amount of carbon dioxide emitted during the overburden removal operation is derived from fuel consumed by the trucks.

3.1 Simulation Model in HAULSIM®

The material haulage operations of a surface coal mine were modeled in HAULSIM® 3D simulation software. As a first step, the road network was created by utilizing GPS coordinates to represent the gradient of road segments realistically. In Figure 3.1, a representative road network created for the production year 2024 can be seen. Excavation areas are separated, and each excavation area is connected to the dumping area with an independent road network. In other words, road networks that connect excavation areas to dumping areas do not cross each other for the simulation studies. During this thesis study, excavation and dumping areas are named after according to their targeted production rates. Figure 3.1 shows the area that holds the maximum target production rate named excavation area 1, and the other area is named excavation area 2. Sub excavation areas are named according to their targeted production rates, as well. Excavation area 1-1 and excavation area 2-1 are the first sub excavation areas since they hold the maximum target production rates among their excavation areas. Target production rates of the excavation area 1-2 and excavation area 2-2 are lower than the first excavation areas.

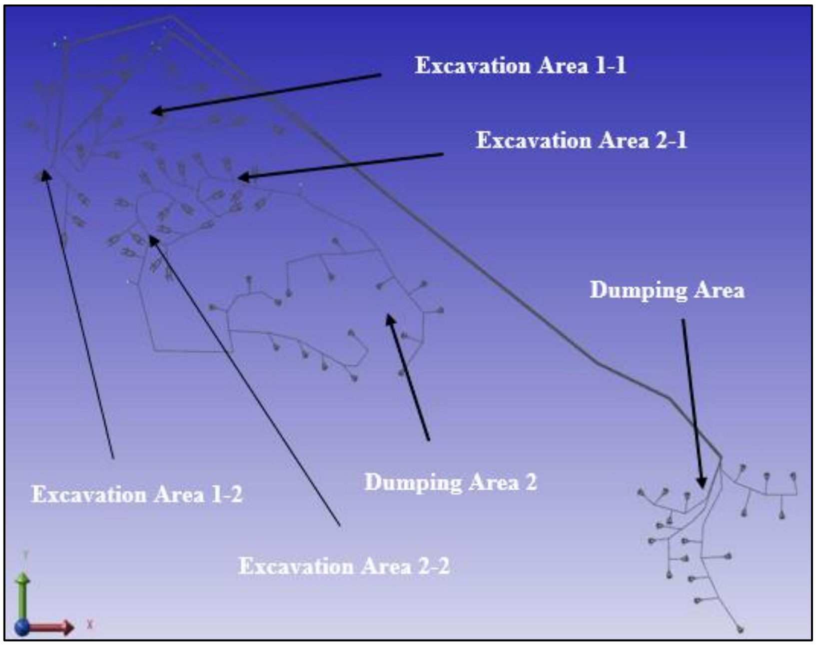
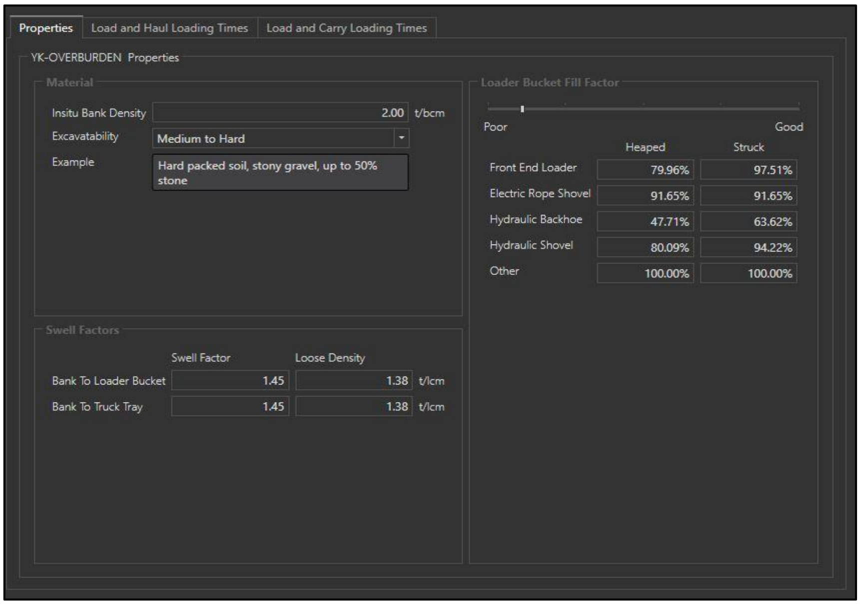


Figure 3.1 Representative Road Network

In-situ density and swell factor are two crucial parameters that significantly affect the production rate in the excavation area by affecting the amount of material that can be hauled per truck. These material properties are introduced to the software using the interface seen in Figure 3.2 to model material in the excavation area.



YK-OVERBURDEN Properties

Material

Insitu Bank Density: 2.00 t/bcm
Excavatability: Medium to Hard
Example: Hard packed soil, stony gravel, up to 50% stone

Swell Factors

	Swell Factor	Loose Density	
Bank To Loader Bucket	1.45	1.38	t/lcm
Bank To Truck Tray	1.45	1.38	t/lcm

Loader Bucket Fill Factor

	Heaped	Struck
Front End Loader	79.96%	97.51%
Electric Rope Shovel	91.65%	91.65%
Hydraulic Backhoe	47.71%	63.62%
Hydraulic Shovel	80.09%	94.22%
Other	100.00%	100.00%

Figure 3.2 Material Properties

The simulation software has an extensive database that covers a wide variety of mining equipment. Both used and existing equipment is available in this library. User could either choose a used equipment or new equipment for simulation run. New equipment can also be created, as well. However, the truck used in the mine introduced in the case study is not available in the database represented in Figure 3.3.

A new piece of equipment was created in the database as conventional trucks and excavators, commonly used in the construction industry, were utilized for overburden removal operations. The capacity of the trucks is 40 tons, and the bucket capacity of the excavators is 6.5 m^3. Through a preliminary study conducted on-site, the truck cycle, maneuvering, spotting, and dumping times were recorded. These data were used the create the calibration model.

Class:	Status	Description	Rated Payload	Modified	Net Power	Library
LHD	Current	Standard	-19,300.00	4/11/2016 1:04:00 PM	144.00	Standard
Backhoe	Current	1650mm Arm	0.00	11/12/2014 6:07:00 PM	51.00	Standard
Backhoe	Old	6.45 m boom, 3.1 m arm (Narrow long crawler machine with 6.45 m boom, 3.1 m arm,	0.00	8/30/2005 11:49:45 AM	198.00	Standard
Rope Shovel	Current	Standard	0.00	3/31/2017 7:39:00 PM	0.00	Standard
FEL	Old	Super High Lift	0.00	9/25/2012 2:24:14 PM	1,176.00	Standard
FEL	Old	HL (3.2m2 Grapple with 800/65 R29 Tire)	6,857.00	2/16/2015 1:24:12 AM	206.00	Standard
FEL	Old	Standard (STEP BOE 4.0m3/5.2yd3 bucket)	6,223.31	8/22/2005 11:47:11 AM	200.00	Standard
Backhoe	Current	Cummins	0.00	9/19/2012 6:01:35 PM	2,984.00	Standard
FEL	Current	Standard Boom	0.00	11/19/2014 1:39:00 PM	120.00	Standard
FEL	Old	HL (STD. TIRES, ROPS & CANOPY, OPERATOR, FULL CAP.OF COOLANT, LUBRICANT, FL	0.00	10/12/2009 2:01:42 PM	641.00	Standard
FEL	Old	Standard	6,764.00	1/21/2010 1:37:33 PM	235.00	Standard
Shovel	Current	Cat (Standard rock bucket: ESCO S 95 6.2m boom 4.4m stick)	0.00	9/5/2012 3:08:05 PM	1,140.00	Standard
Backhoe	Old	T3 Cat (Standard rock bucket: ESCO V 61)	0.00	9/6/2012 12:17:28 PM	522.00	Standard
Shovel	Old	Standard	0.00	8/29/2012 5:18:43 PM	960.00	Standard
FEL	Old	Standard (25.23cu.m BUCKET)	0.00	4/1/2005 12:59:12 PM	1,343.00	Standard
LHD	Old	3Yard bucket (Electric 11600lb, 3yard bucket)	0.00	4/1/2005 11:49:25 AM	75.00	Standard
Backhoe	Current	Mass Boom (6.59m Mass Boom, R2.57WB Stick)	0.00	9/27/2012 4:06:42 PM	302.00	Standard
FEL	Old	Standard (STD. TIRES, ROPS & CANOPY, OPERATOR, FULL CAP.OF COOLANT, LUBRICA	0.00	4/28/1994 1:18:00 PM	689.00	Standard
LHD	Current	Electric (Motor, transfer case, axles, tyres.)	6,577.00	6/19/2008 1:54:40 PM	94.00	Standard
Shovel	Old	Cat 3512C	0.00	9/6/2012 12:16:12 PM	2,240.00	Standard
Shovel	Old	Standard (600mm wide tracks.)	0.00	1/5/1993 1:26:00 PM	302.00	Standard
Backhoe	Old	Standard (Standard rock bucket: ESCO size 110)	0.00	9/6/2012 12:14:34 PM	1,880.00	Standard
Backhoe	Current	Standard (LFR/SP 11003232-1-03.10)	0.00	9/3/2012 6:08:09 PM	1,600.00	Standard
LHD	Old	XTRA LHD - Tier 2 emissions (Bucket size 8.2-11.6 cu-m ,Fuel Capacity 900litres Height	17,200.00	2/16/2015 1:35:41 AM	306.00	Standard
Rope Shovel	Current	DC (Electric control, dipper&dipper trip, cable, lighting)	0.00	9/20/2012 4:27:00 PM	0.00	Standard
FEL	Old	Standard (STEP BOE 5.4m3/7.1yd3 bucket)	8,581.90	8/22/2005 11:56:54 AM	262.00	Standard
FEL	Old	Standard (STD. TIRES, ROPS & CANOPY, OPERATOR, FULL CAPACITYOF COOLANT, LUE	0.00	1/6/1993 11:58:00 AM	309.00	Standard
Backhoe	Old	Standard (Standard Backhoe, 800 mm wide tracks.Boom 8.15m, Stick 4.25m)	0.00	7/21/1997 8:00:00 PM	840.00	Standard
LHD	Current	9851 2308 01 (15 tonne tramming capacity, density 2.0 t/ m3)	15,000.00	5/25/2009 6:03:32 PM	0.00	Standard
FEL	Old	High Lift	0.00	9/3/2012 6:56:52 PM	708.00	Standard
FEL	Current	Standard	0.00	5/5/2016 3:00:00 PM	215.00	Standard
FEL	Old	Standard (STD. TIRES, ROPS & CANOPY, OPERATOR, FULL CAP.OF COOLANT, LUBRICA	0.00	4/14/1994 5:34:00 PM	689.00	Standard

Figure 3.3 Equipment Library

3.2 System Description

Data were acquired from all available data sources during several site visits. Node locations representing the loading spots and dumpsites, spotting, maneuvering, and loading times of trucks and excavators were recorded for a specific period by considering the effect of different operators and road conditions. Mobile GPS devices were used to collect location data. These location data were used as nodes. By connecting two nodes, one rode segment is created. Spotting, maneuvering, and loading times were collected by observing the spotting, maneuvering, and loading operations. These data were used to create distributions. Bucket capacity and tray capacity data were obtained from manufacturer catalogs and speed limits were determined according to the safety regulations in the mining area.

The mining field used in the case study is located in the southwest part of Turkey. The overburden material's in-situ density (D) is 2.00 t/m^3, and the swell factor (S) is 1.45. Therefore, the loose density (L) of the material was calculated with the formula given below:

$$L=D/S \tag{1}$$

$$L=2.00/1.45 \tag{2}$$

$$L=1.38\ t/m^3 \tag{3}$$

Excavatability of the material is assumed as medium to hard, and the rolling resistance of the road network is determined as 3% based on the information provided by the company.

The developed dispatch system consists of both deterministic and stochastic variables. The required set of deterministic data can be listed as follows.

- *Location of Nodes*
- *Speed Limits*
- *Rolling Resistance of the Road*
- *Truck Capacity*

- *Excavator Capacity*
- *Excavability of Overburden Material*
- *The density of Overburden Material*
- *Swell Factor*

In case an FMS is available, the following data could be represented in a stochastic manner:

- *Speed of Trucks*
- *The payload of Excavators and Trucks*
- *Spotting, Maneuvering, and Loading Time of Trucks*

The variables that are assigned values are the following:

- S_t: *Simulation Time*
- Rt_n: *Route (n=1, 2)*
- MHT_i: *Material Hauled by Truck i (i=1, 2 …….)*
- MLE_j: *Material Loaded by Excavator j (j = 1, 2, 3, 4…)*
- Ct_j: *Cycle Time for Truck j (j=1,2 …….)*
- BPB_kT_m: *Bucket Pass for Bucket k Truck m (k=1, 2 ……), (m=1,2 …….)*
- V_{ln}: *Speed Limit of Segment l Route n (l=1,2 …….)*

3.2.1 Dispatch Algorithm

The surface coal mine investigated in this study has an equipment fleet of haul trucks and excavators with different capacities that are operated on networks of roads connecting excavation sites and dumpsites. Motor power and distributions for speed are assumed identical for all trucks and excavators. Any other variable that affects the operation is excluded and left out of the system boundary. The main objective is to represent the system by utilizing variables that describe real data. As an example, the trucks can be overloaded or underloaded by the operators of excavators. Because of that, the payload of the trucks could be represented by probability distributions based on historical data provided by the mining company.

Similarly, the number of buckets loads and spotting, maneuvering, and loading times could be represented by probability distributions, as well. However, since distribution data was not available, an availability factor is used instead of using distributions. Data used in the study was collected manually on-site as an FMS was not available.

The dispatch algorithm developed by HAULSIM® for the overburden removal activities has a flexible structure to incorporate different scenarios according to available data on-site. As seen in Figure 3.4, the algorithm starts with the definition of the number of trucks based on data collected on-site. Then, the location of dumping points and excavation points are determined according to the annual mining plan. The model is run for a predetermined period to represent the annual production without compromising the computational capacity of the hardware used. Based on the assumption that the mine operates on three shifts continuously, the simulation duration can be adjusted accordingly.

The maintenance activities and equipment breakdown are defined as an option where it can be assumed that no breakdown will occur during the simulation run since an availability factor is defined to represent breakdowns, maintenance, and shift changes.

After the run is completed, the results are recorded and can generate reports and other business intelligence tools. If the annual targeted production is satisfied, the results are recorded and reported automatically to stop the algorithm. If results are not met the production requirements, either road network design or number of trucks is changed to meet the production requirement. This process continues until the production requirements met. After requirements are met, data such as production amount of each truck production amount of each excavator, fuel consumed by each truck and the states of truck in each discrete interval is recorded.

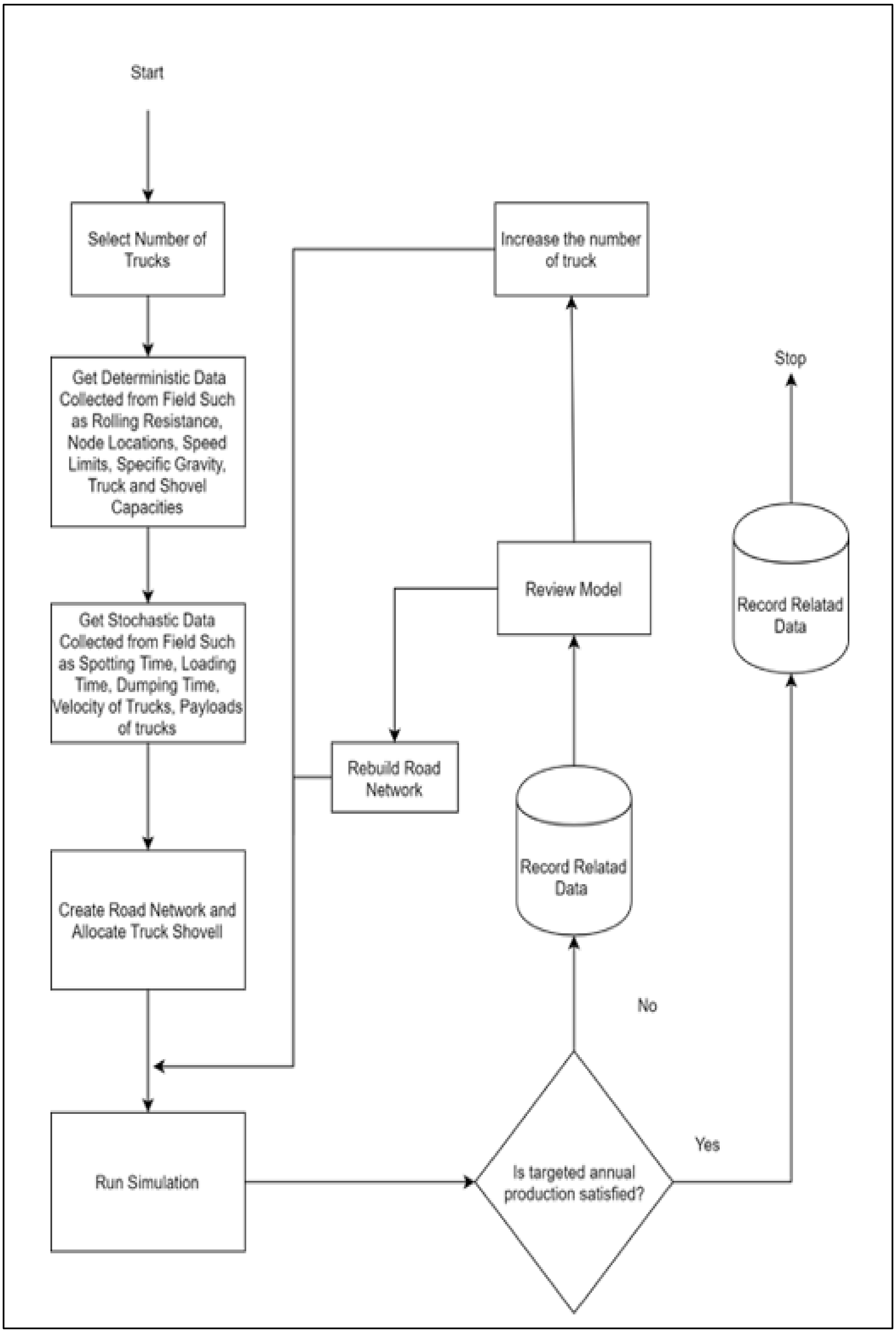


Figure 3.4 Dispatch Algorithm

3.2.2 Carbon Dioxide Emissions of the Haulage Activities Modeled

In the scope of this study, carbon dioxide emissions of the year 2024 are derived from the total fuel consumed. According to the fuel consumption data, 43% less amount of diesel fuel was consumed during the revised simulation study. Therefore, 2019 Refinement to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories is used to assess carbon dioxide emission. According to the IPCC (2019), steps that should be followed to estimate carbon dioxide emissions are given in Figure 3.4. In this study, methane and nitrous oxide calculations are not performed; only carbon dioxide emissions are calculated.

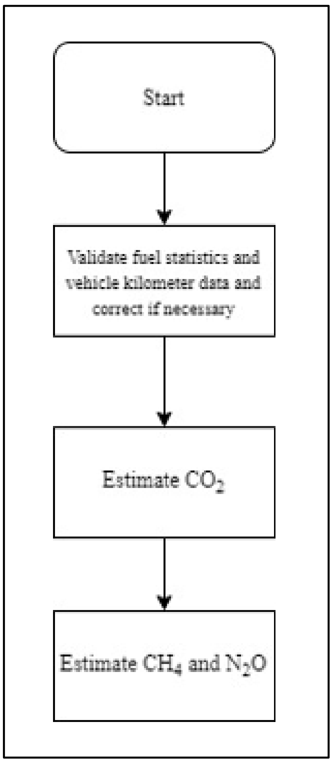


Figure 3.4 Steps in estimating emissions from road transport (IPCC, 2019)

Carbon dioxide calculations are completed according to the Tier-1 method, which assumes all diesel fuels have default carbon dioxide emission factors. After fuel consumption data was obtained from the software, data is entered to A section in the worksheet in Table 3.1 in metric tons unit. Conversion factor B, Carbon Emission D, and the fraction of carbon oxidized F are obtained from IPCC guidelines. Other parameters have calculated the formulas given in the Table 3.1.

Table 3.1 IPCC Tier-1 Worksheet (IPCC, 2019)

Step 1	**Step 2**		**Step 3**		
A Consumption (10^3 metric tons)	**B Conversion Factor (TJ/10^3 metric tons)**	**C Consumption (TJ)**	**D Carbon Emission Factor (t C/TJ)**	**E Carbon Content (t C)**	**F Carbon Content (Gg C)**
	43.3	C=(AxB)	20.2	E=(CxD)	F= (Ex10^{-3})
Step 4			**Step 5**		**Step 6**
G Fraction of Carbon Stored	**H Carbon Stored (Gg C)**	**I Net Carbon Emissions (Gg C)**	**J Fraction of Carbon Oxidized**	**K Actual Carbon Emissions (Gg C)**	**L Actual CO2 Emissions (Gg CO2)**
-	H=(FxG)	I=(F-H)	1.00	K=(IxJ)	L=(Kx[44/12])

3.3 Calibration Model

One of the road networks that given in Figure 3.5 used recently for production on site was recreated in the simulation software to calibrate the modeled equipment. It was investigated whether the modeled equipment met the actual production rate. 9 excavators are located into Excavation Area 1 and Area 3 excavators are located into Excavation Area 2. 60 trucks are assigned for this task. Maneuvering and spotting times were obtained from the field trip and data are given in Table 3.2.

Table 3.2 Time data obtained from field

Excavation Point Queuing and Maneuvering Time (min)	Average Excavator Loading Time (min)	Dumping Point Queuing and Maneuvering Time (min)	Average Dumping Time (min)
2.18	2.12	0.64	0.93

Production month of September 2018 is selected for the calibration process and available production for the September 2018 is 1,992,422 m^3. Speed limits were assigned to road segments for cycle time calculations. Limits determined for the road network of September 2018 is used for the simulation model, as well. Speed limits are assigned as 33 km/h and 37 km/h for loaded and empty trucks on main roads, respectively. In excavation and dumping area, limit was reduced to 14 km/h for both loaded and empty trucks.

According to the data provided by the company, equipment is worked on the field for 576 hours in one month. After excavators and dumping points are located, simulation model run for 576 hours. According to the results, 1,876,046 m^3 production is obtained and it is seen that simulation model represent the overburden stripping operation realistically.

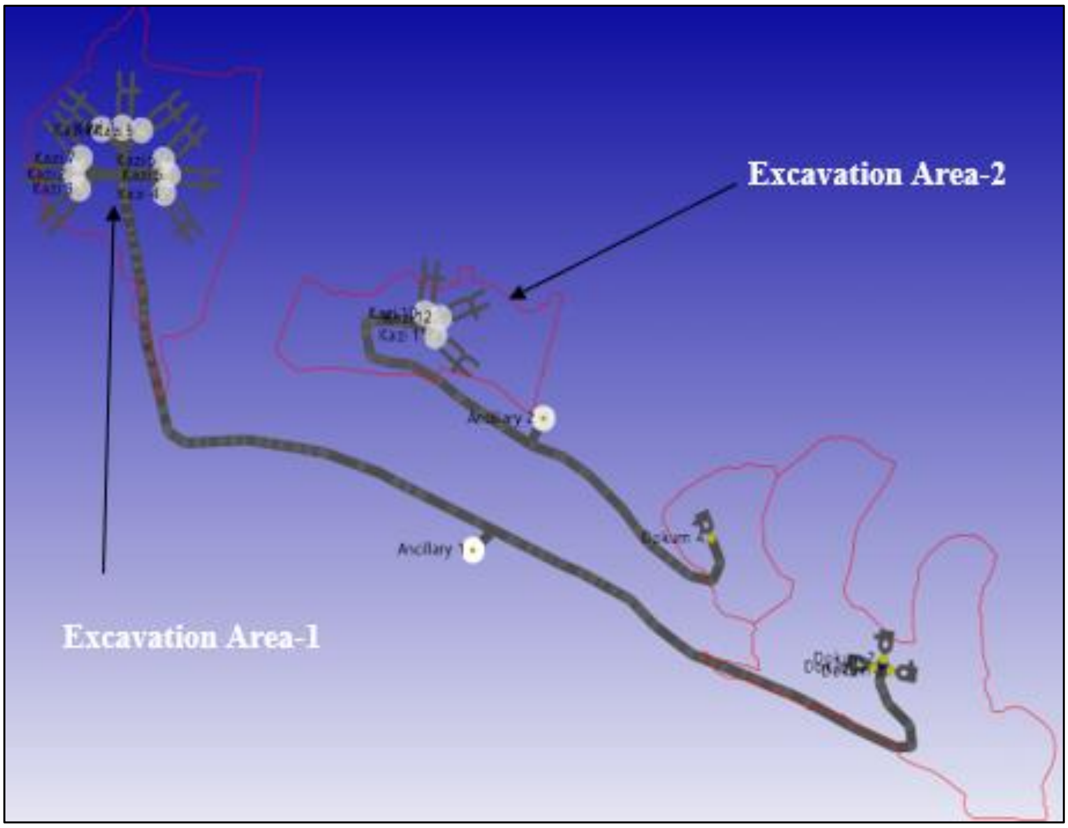


Figure 3.5 Road design used for calibration

Since, the equipment library does not involve the type of truck that used in the study, a new equipment is created by importing equipment characteristics given in Table 3.3. For instance, in the mining area, 6.5 m³ of excavators are used, and suitable equipment is existing in the library.

Table 3.3 Technical specifications of the truck used in the study

Motor Power (kW)	**Capacity (m^3)**	**Maximum Load (tonnes)**	**1,2 Shaft Capacity (kg)**	**3,4 Shaft Capacity (kg)**
330	20.5	41	8,000	13,000
Empty Weight (kg)	**Height (mm)**	**Length (mm)**	**Tire Size**	
10,781	3,585	9,305	13R22.5	

HAULSIM® software records fuel consumption data during the simulation run. The engine load factor is used to assess the fuel consumption of the trucks. For instance, 100% engine load factor represents maximum power, and idle state is represented by -100%. Fuel consumption data for each engine load factor level is obtained and assigned to the truck used during the simulation study. Since fuel consumption increases with the increasing road gradient, different engine load factors were assigned to each different gradient level. Fuel consumption of the trucks were recorded with a unit of liters. However, the volume of fuel must be converted into the mass to evaluate carbon dioxide emission. Therefore, the density of diesel is multiplied by the volume of fuel consumed during the study to convert the fuel volume to mass. HAULSIM® allows users to examine consumption data for each state of trucks since it records the consumption data in discrete time intervals. These states are travel loaded, travel loaded blocked, travel empty, and travel empty blocked. Blocked states represent the time durations when the selected equipment is prevented to travel empty or loaded by another equipment. For instance, a truck could be blocked by another truck at the conjunction point of two road segments. One of them must wait for the other truck in this case. State of the waiting truck is called blocked. By evaluating fuel consumption state by state, it is tried to understand in which states trucks' fuel consumption is comparably higher.

CHAPTER 4

RESULTS OF SIMULATION MODELLING IN HAULSIM®

This chapter introduces the study results from a different point of view, such as production rate, number of trucks, fuel consumption rate, and carbon dioxide emission rate. The case study is investigated in two parts to compare the different strategies. The results of these studies are compared to understand whether changes in mine plan and road design aided the operation to achieve target production rate and solve the traffic congestion that occurs on the road network. Production in each year was represented with ten days due to the limited processing capacities of personal computers and the simulation software. Then results are extended to the annual production amounts for each year in both studies. In the first study, the years 2024, 2025, 2026, 2028, and 2030 are studied since the production rate of these years is relatively higher than the other years. The difference in the required fleet size for different years could create an overcapacity; however, the company providing data for this study cooperates with a subcontractor. Therefore, it is considered that the variance in the required number of equipment would not cause any inefficiency as the subcontractor can assign the fleet partially to other mining sites.

All years are studied in the second study because total production for ten years is distributed homogenously for each year. However, for the second study, only excavation levels that possibly have traffic congestion were studied. Fuel consumption and carbon dioxide emission rate are compared only for 2024 since there is a significant traffic congestion in the road network for that period. A subcontractor company provides trucks, and the subcontractor company declares that they could provide the required number of trucks for all years.

4.1 Initial Mine Plan and Road Design Simulation

In the scope of this study, the company provided long-term mining plans and road networks for the years between 2021 and 2030. However, the years mentioned in the previous chapter selected for simulation study and targeted annual productions for all years are given in Table 4.1. While designing a road network, two-lane roads are preferred for the first study as a conventional approach.

Table 4.1 Targeted annual productions of first simulation study

	Targeted Annual Production (m^3)
2021	35,300,000
2022	46,800,000
2023	79,000,000
2024	77,000,000
2025	76,000,000
2026	79,000,000
2027	80,000,000
2028	76,600,000
2029	80,000,000
2030	80,500,000

4.1.1 Production Output of Simulation Model of the Year 2024

Two different excavation areas are designed for the year 2024. Targeted annual production amount, ten days production amount, and the number of excavators of the excavation area 1 and excavation area 2 are given in Table 4.2. There are 22 and 20 excavators in excavation area 1 and excavation area 2, respectively. It was planned to have 430 trucks for year 2024 for both excavation areas, however, number of trucks could not meet the production requirements for this year according to the simulation results.

Table 4.2 Production rate and number of excavators of the year 2024 of first simulation study

Excavation Areas	**Annual Production Amount (m³)**	**10 Days Production Amount (m³)**	**Number of Excavators**
Excavation-1	20,000,000	666,667	11
	20,000,000	666,667	11
Excavation-2	17,000,000	566,667	9
	20,000,000	666,667	11

Each excavation area works independently from the other, as seen in Figure 4.1. Each excavation area consists of two sub-excavation areas. For example, in excavation area 2, each sub-area is connected to the dumping site with different roads. However, on the contrary, sub-areas of excavation area 1 are connected to dumping sites with the same road.

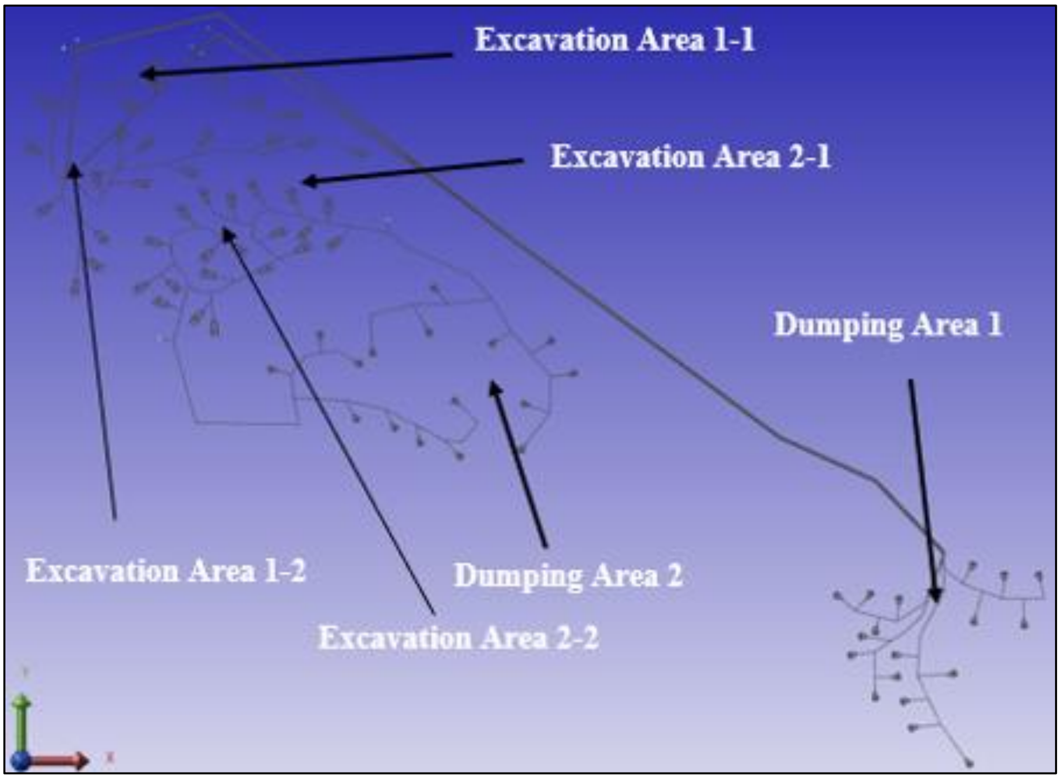


Figure 4.1 Road network design of the year 2024

Since sub-areas in excavation area 1 are connected to a dumping site with the same road, the traffic congestion occurs as seen in Figure 4.2 in the junction of the two roads connected to sub excavation areas in excavation area 1.

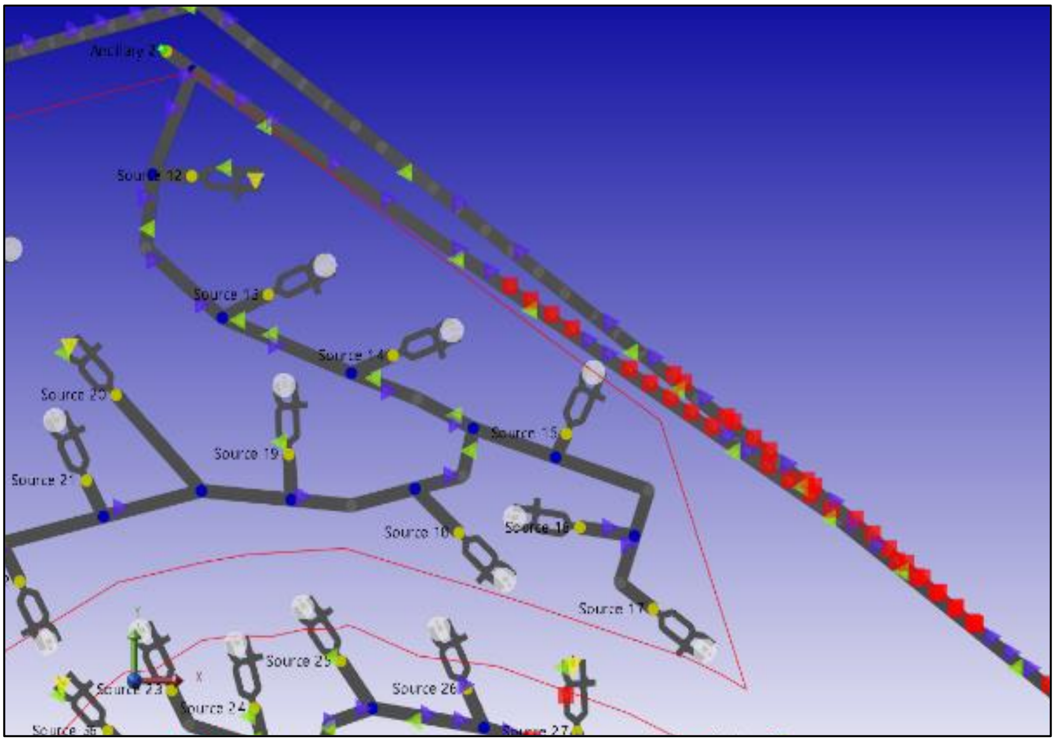


Figure 4.2 Traffic congestion at the junction of the two roads

The production rate of each excavator in excavation area 1 is examined, and according to the results given in Figure 4.3, the maximum production rate is achieved by excavator 12. Production rates of excavator 9, excavator 10, excavator 11, excavator 20, and excavator 22 are below 40,000 m^3 due to their locations. However, there is no significant difference between the production rate of the excavators located in excavation area 1. Since the algorithm prefers the closest, most available excavator for trucks and excavator 12 is located at the exit of excavation area 1, excavator 12 holds maximum production rate, as expected.

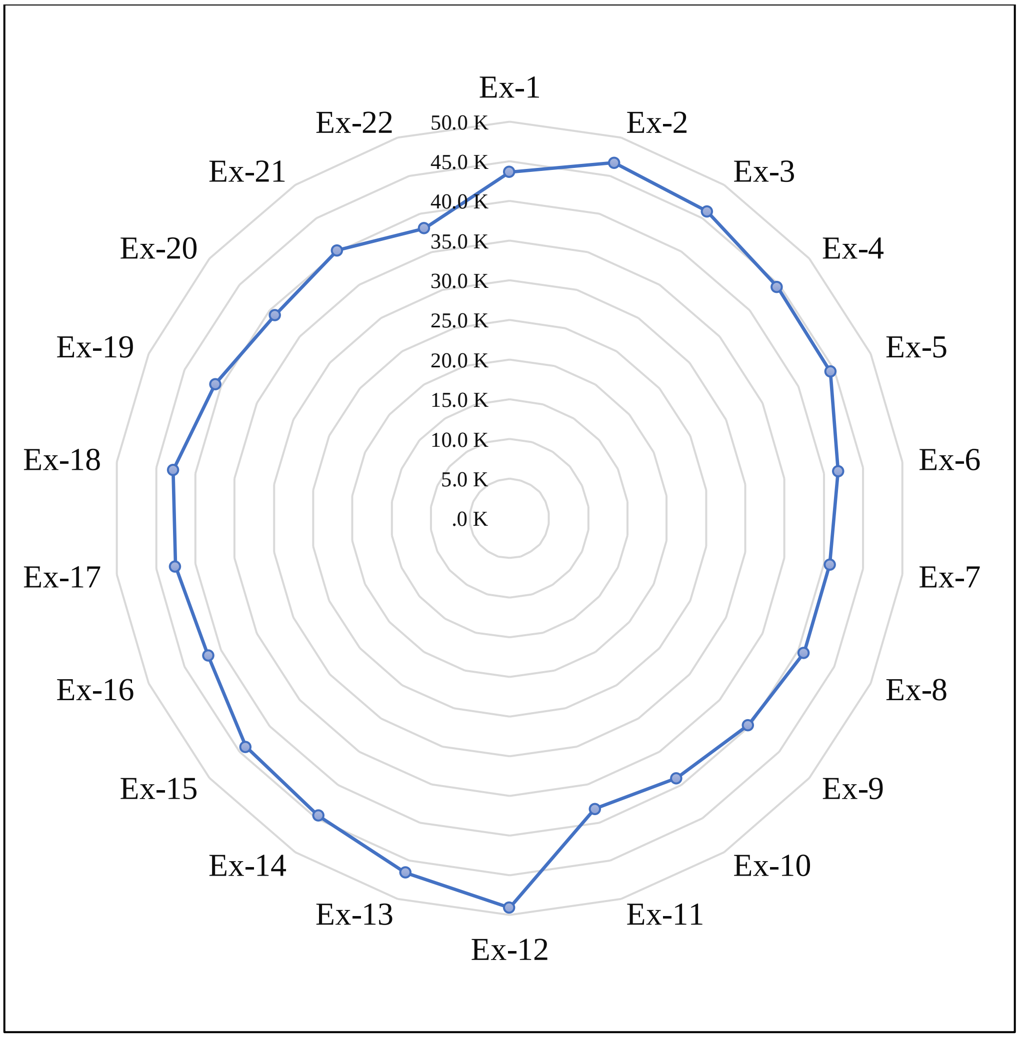


Figure 4.3 Production rate of excavators in excavation area 1 in the first study of the year 2024

The production rate in excavation area 1 is distributed homogenously among excavators. On the other hand, in excavation area 2, excavator 27 and excavator 28 showed outstanding performance, as seen in Figure 4.4. These performances result from the algorithm's working principle; however, since there is a considerable gap (37,030 m³) between the excavators that hold maximum and minimum production rates, locations of excavators in excavation area 2 could be rearranged to increase production excavation area.

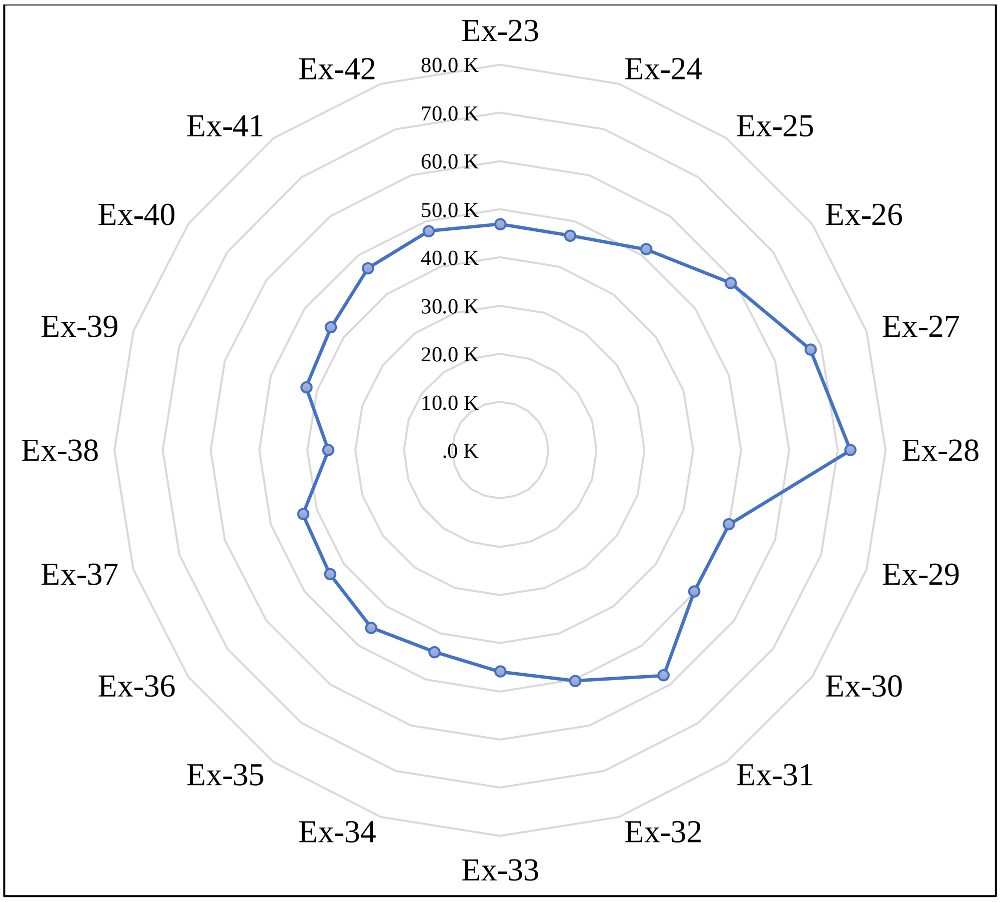


Figure 4.4 Production rate of excavators in excavation area 2 in the first study of the year 2024

4.1.2 Production Output of Simulation Model of the Year 2025

Two different excavation areas are designed for the year 2025. Targeted annual production amount, ten days production amount, and the number of excavators of the excavation area 1 and excavation area 2 are given in Table 4.3. There are 22 and 19 excavators in excavation area 1 and excavation area 2, respectively. It was planned to have 463 trucks for the year 2025 for both excavation areas; however, the number of trucks could not meet the production requirements for this year, according to the simulation results.

Table 4.3 Production rate and number of excavators of the year 2025 of first simulation study

Excavation Areas	Annual Production Amount (m³)	10 Days Production Amount (m³)	Number of Excavators
Excavation-1	20,000,000	666,667	11
	23,000,000	766,667	13
Excavation-2	21,000,000	700,000	12
	12,000,000	400,000	7

Excavation area 1 consists of two sub excavation areas: excavation area 1-1 and excavation area 1-2. Excavation area 2 is divided into two sub excavation areas; however, these areas are smaller than the sub excavation areas of excavation area 1, as given in Figure 4.5. Excavation area 1-1 and excavation area 1-2 connected to one dump area with different roads do not cross. Excavation area 2-1 and excavation area 2-2 connected to two different dumping areas with the same road.

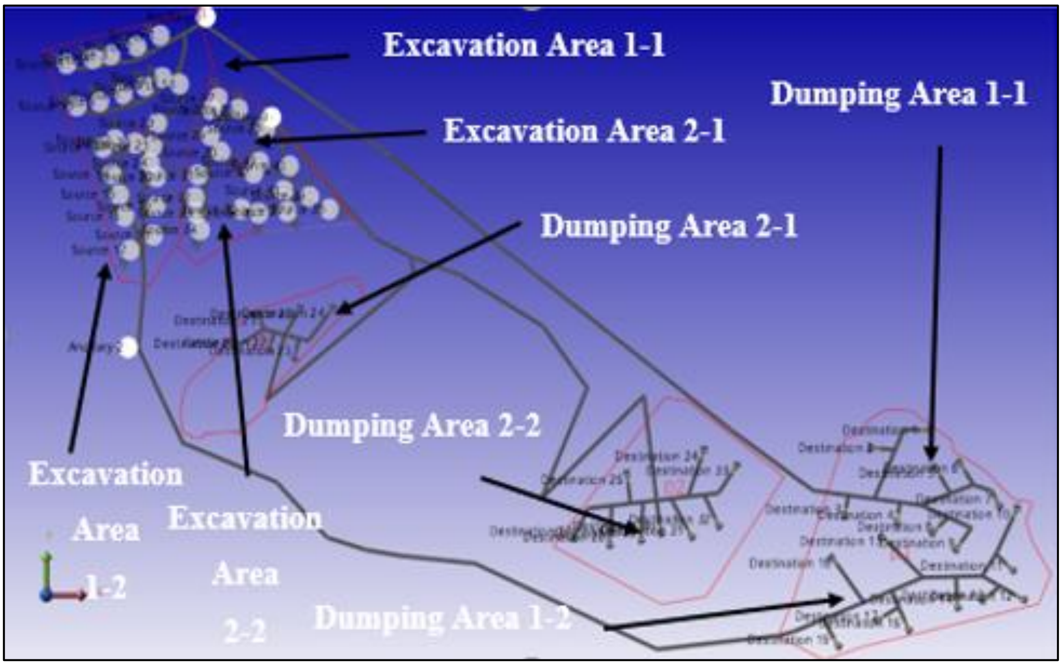


Figure 4.5 Road network design of the year 2025

Traffic congestions occurred in the year 2025 as well. For example, in Figure 4.6, it could be seen that trucks are stuck in the excavation area 2-1. This traffic congestion occurred since the targeted production rate is too high for excavation area 2-1. Therefore, the targeted rate and the number of trucks should be decreased to solve the traffic congestion in excavation area 2-1. Moreover, sub excavation areas connect to dumping areas with the same road, making traffic congestion worse.

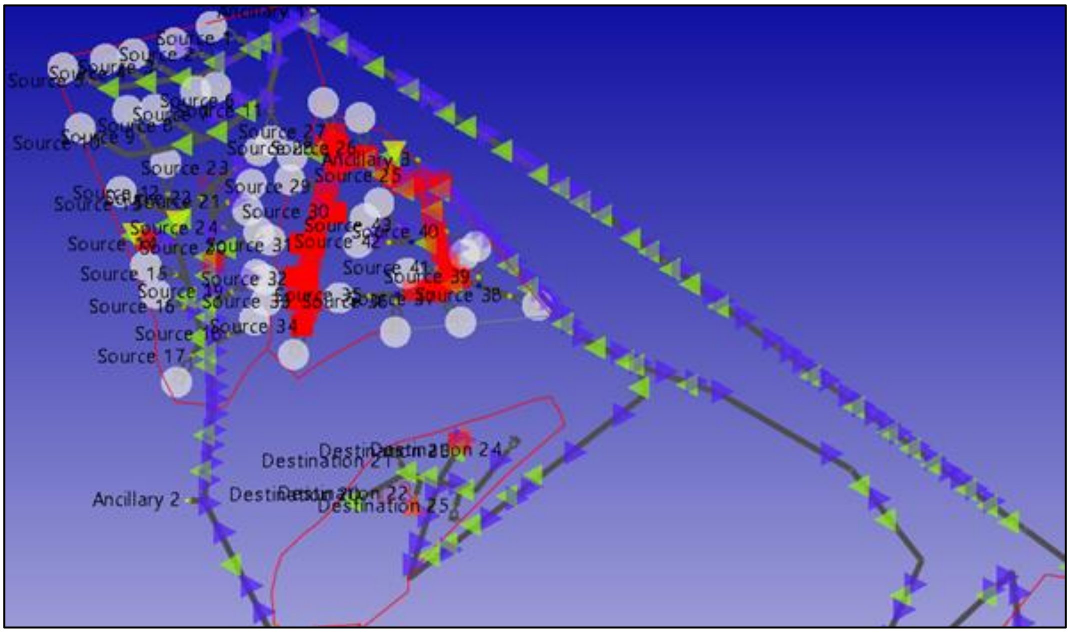


Figure 4.6 Traffic congestion at the excavation area 2 of the year 2025

Production rates of excavators in excavation area 1 are homogenously distributed, as seen in Figure 4.7. Maximum and minimum production rates are achieved by excavator 1 and excavator 23, respectively. The production rate of excavator 1 is 67,975 m³, and the production rate of excavator 23 is 50,612 m³. Difference in production rates is not significant between excavators. Since there are no traffic congestions, the targeted production rate for excavation area 1 is achieved.

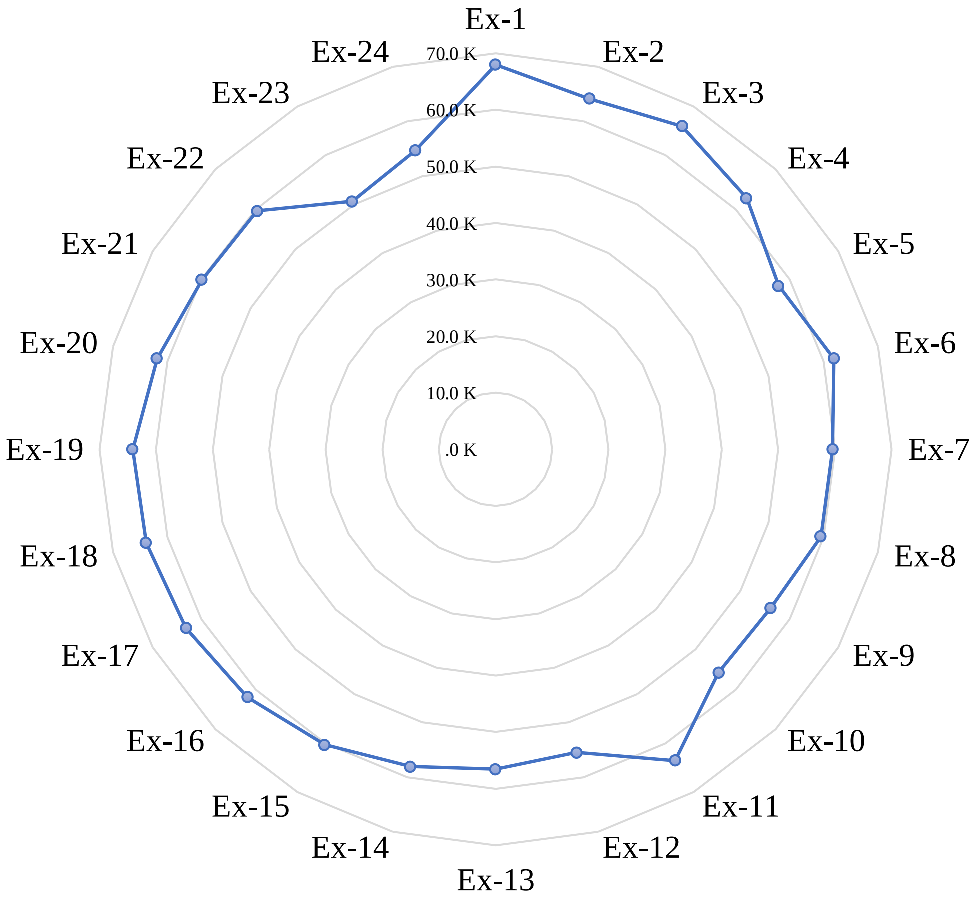


Figure 4.7 Production rate of excavators in excavation area 1 in the first study of the year 2025

Due to the traffic congestion that occurred in the excavation are 2, the production rate of the excavators is not distributed homogenously for excavation area 2. Therefore, as seen in Figure 4.8, excavator 33 and excavator 34 hold the lowest production rates, while the production rate of excavator 25 is almost ten times higher than these two excavators.

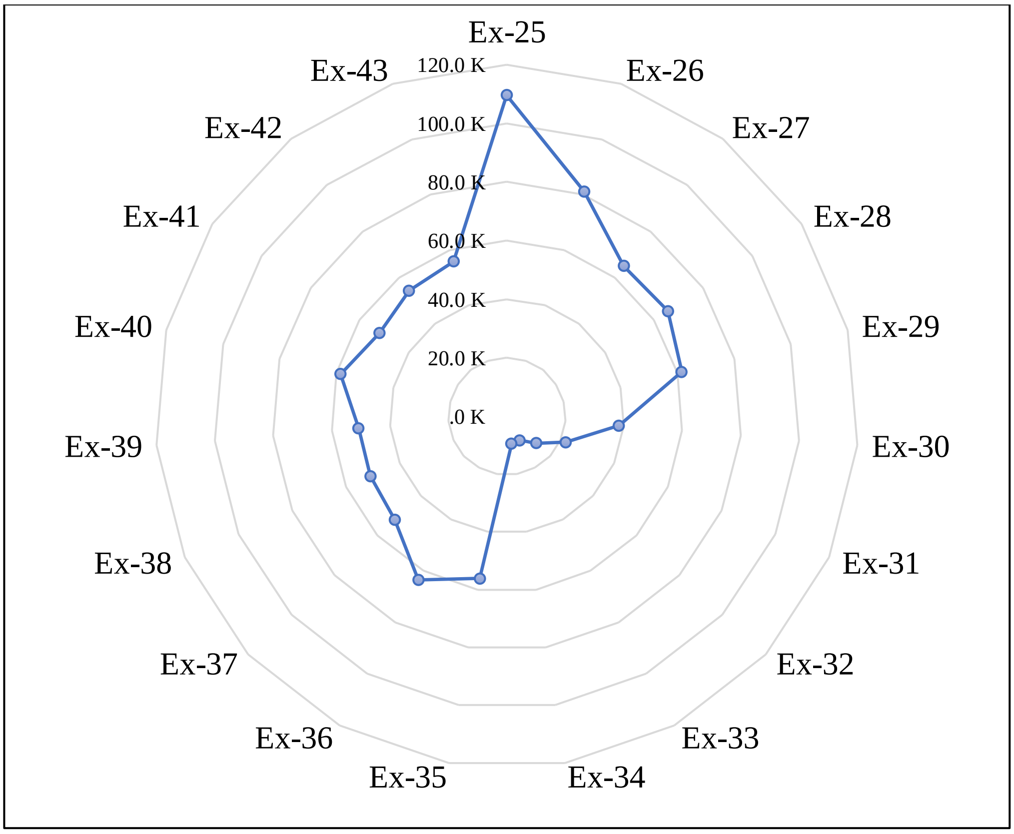


Figure 4.8 Production rate of excavators in excavation area 2 in the first study of the year 2025

4.1.3 Production Output of Simulation Model of the Year 2026

Two different excavation areas are designed for the year 2026. Target annual production amount, ten days production amount, and the number of excavators of the excavation area 1 and excavation area 2 are given in Table 4.4. There are 21 and 23 excavators in excavation area 1 and excavation area 2, respectively. It was planned to have 362 trucks for the year 2026 for both excavation areas; however, the number of trucks could not meet the production requirements, according to the simulation results.

Table 4.4 Production rate and number of excavators of the year 2026 of first simulation study

Excavation Areas	Annual Production Amount (m³)	10 Days Production Amount (m³)	Number of Excavators
Excavation-1	18,000,000	600,000	10
	19,000,000	633,333	11
Excavation-2	33,000,000	1,100,000	18
	9,000,000	300,000	5

The year 2026 consists of two excavation areas, and each excavation area consists of two sub excavation areas. This year has a complex road network design because road networks of excavation areas 1 and 2 cross each other at one point. Therefore, sub excavation areas of excavation area 1 are connected to the dumping area with two independent roads that do not cross each other. On the other hand, sub-areas of excavation area 2 are connected to dumping areas via the same road. This road cross with the road that connects one of the roads connects one of the sub excavation areas of excavation area 1 to the dumping area given in Figure 4.9.

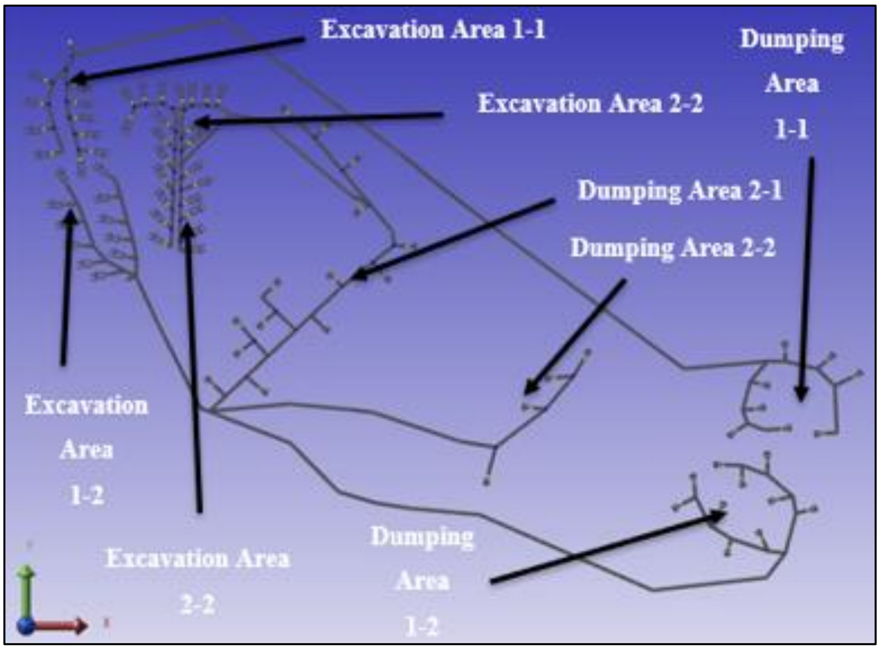


Figure 4.9 road network design of the year 2026

Considerable traffic congestion occurred due to several reasons. Similarly, in 2025, the targeted production rate is too high for the excavation area 2. Since roads with high traffic density cross each other, as seen in Figure 4.10, almost all trucks are stuck in traffic during this production year. Therefore, the problem is not only about excavation area 2 but also about excavation area 1. The number of trucks is too high, which causes traffic congestion in the road network of excavation area 1.

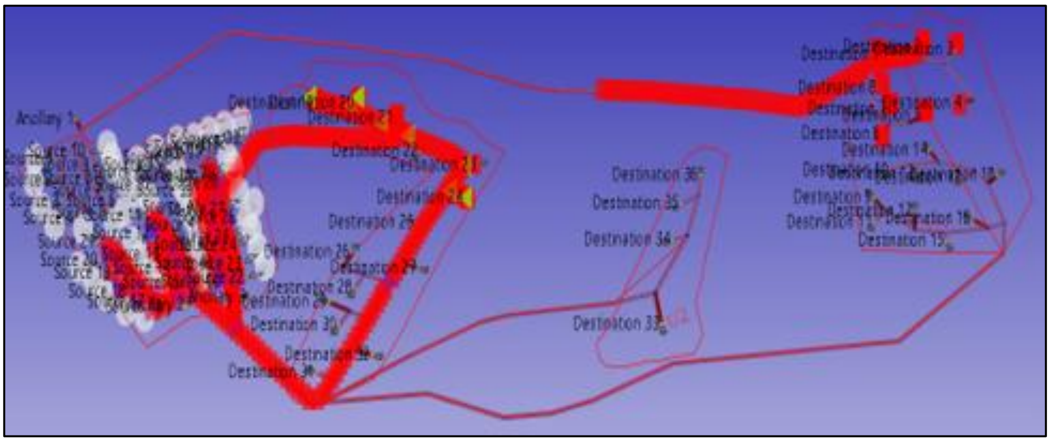


Figure 4.10 Traffic congestion in excavation area 2 and dumping site

The first ten excavators work in excavation area 1-1, and this sub excavation area is connected to the dumping area with an independent road network. Since there is traffic congestion in this road network, production rates of these two sub excavation areas are almost similar, as seen in Figure 4.11. However, the average production rates of the excavators located in excavation area 1-1 are slightly higher than those located in excavation area 1-2. The maximum production rate is held by excavator 1 with over 50,000 m^3 of production, and the minimum production rate is held by excavator 21 with 39,098 m^3. Targeted production was not met for excavation area 1 due to the traffic congestion on the road network, especially in the excavation area.

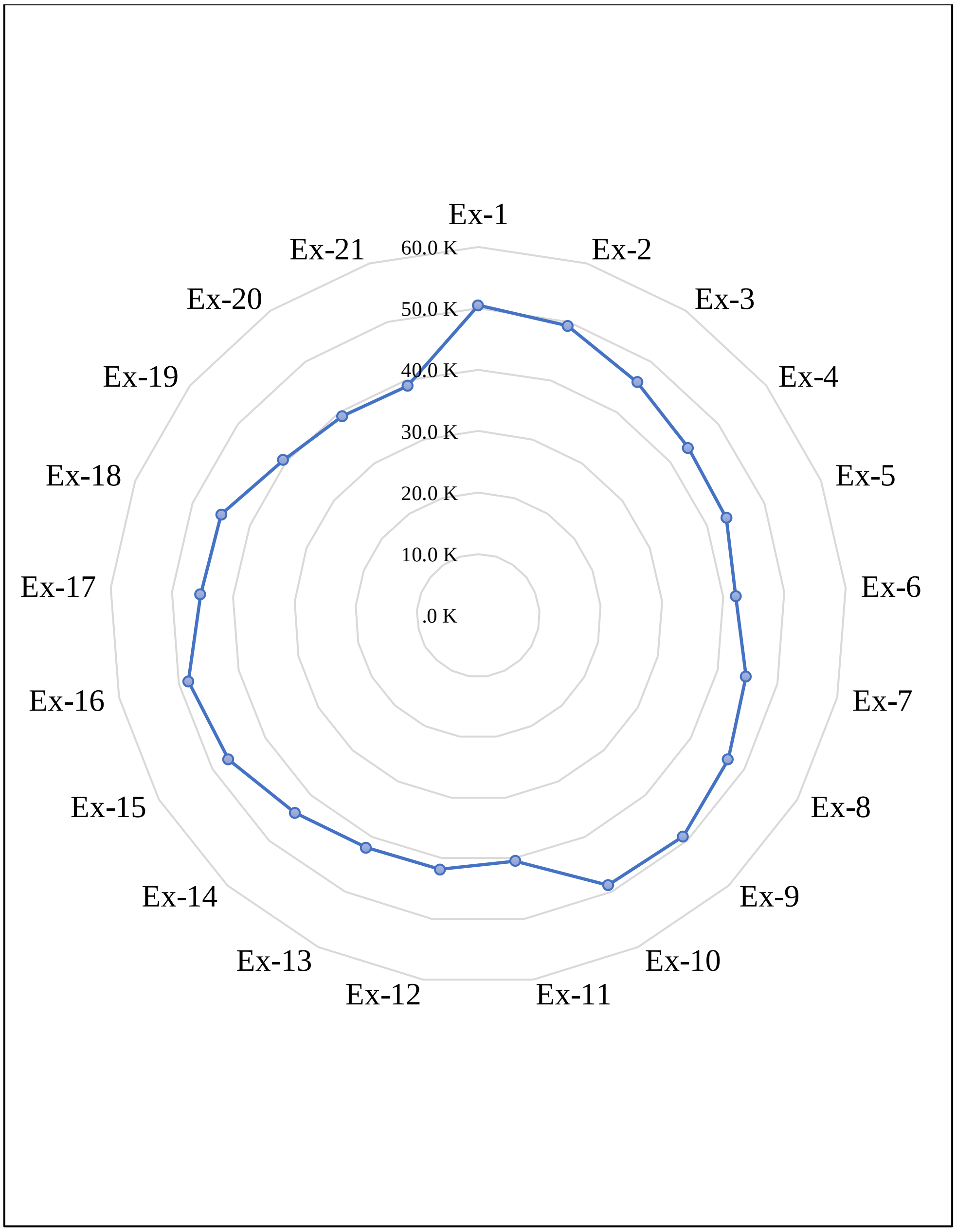


Figure 4.11 Production rate of excavators in excavation area 1 in the first study of the year 2026

Since there is significant traffic congestion in excavation area 2, production rates of the excavators are not homogenously distributed among excavators, as seen in Figure 4.12, similar to previous years.

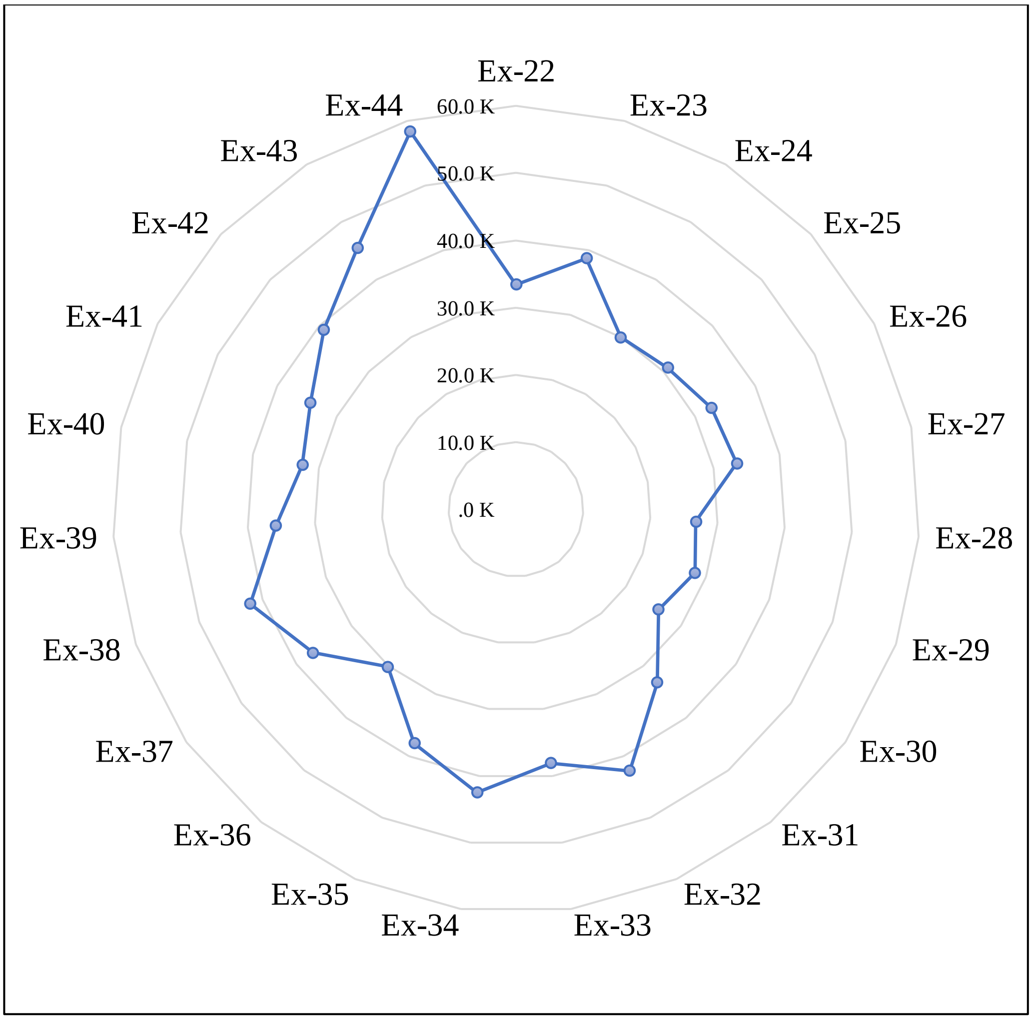


Figure 4.12 Production rate of excavators in excavation area 2 in the first study of the year 2026

4.1.4 Production Output of Simulation Model of the Year 2028

Two different excavation areas are designed for the year 2028. Targeted annual production amount, ten days production amount, and the number of excavators of the excavation area 1 and excavation area 2 are given in Table 4.5. There are 23 and 19 excavators in excavation area 1 and excavation area 2, respectively. It was planned to have 314 trucks for the year 2028 for both excavation areas; however, according to the simulation results, the number of trucks could not meet the production requirements for this year.

Table 4.5 Production rate and number of excavators of the year 2028 of first simulation study

Excavation Areas	**Annual Production Amount (m³)**	**10 Days Production Amount (m³)**	**Number of Excavators**
Excavation-1	21,600,000	720,000	12
	20,000,000	666,667	11
Excavation-2	35,000,000	1,166,667	19

In the year 2028, there are two excavation areas. Excavation area 2 has no sub excavation areas; however, excavation area 1 is divided into sub excavation areas. Each sub excavation areas of excavation area 1 have an independent road network that connects sub excavation areas to the dumping area. Likewise, excavation area 2 is connected to the dumping area with an independent road network, as seen in Figure 4.13.

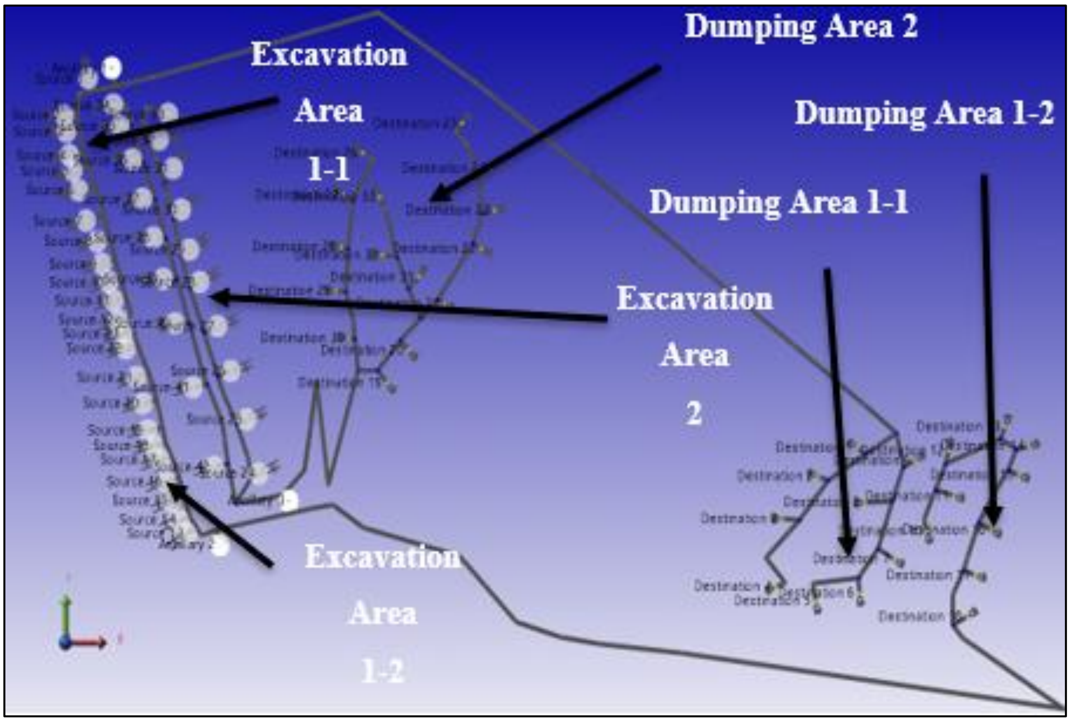


Figure 4.13 Road network design of the year 2028

In the year 2028, traffic congestion occurs at the entrance of excavation area 2, as seen in Figure 4.14. There is a sharp corner at the entrance of the excavation area 2. Trucks have to slow down at the entrance of excavation area 2 because of the sharp corner. Moreover, the road is divided into two separate roads at the entrance of excavation area 2, and because of that, traffic density at the entrance node becomes too high, and trucks are blocked at that point.

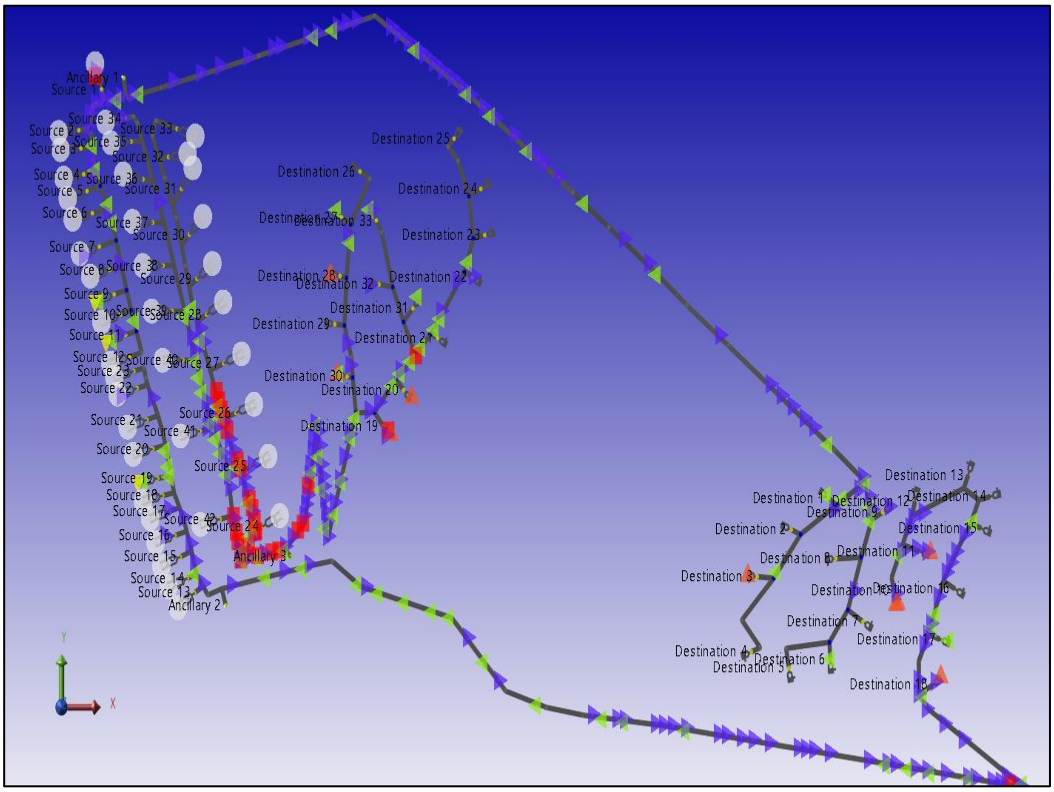


Figure 4.14 Traffic congestion in excavation area 2

In excavation area 1, some excavators show outstanding performance since these excavators are located at the entrance of sub excavation areas of excavation area 1. Since the algorithm forces trucks to get allocated to the most available and closest excavators, trucks' first option is to allocate the excavators located at the entrance of the excavation area, if possible, because of the reason that excavator 1 and excavator 14 hold the highest production rates of the excavation area 1 as seen in Figure 4.15.

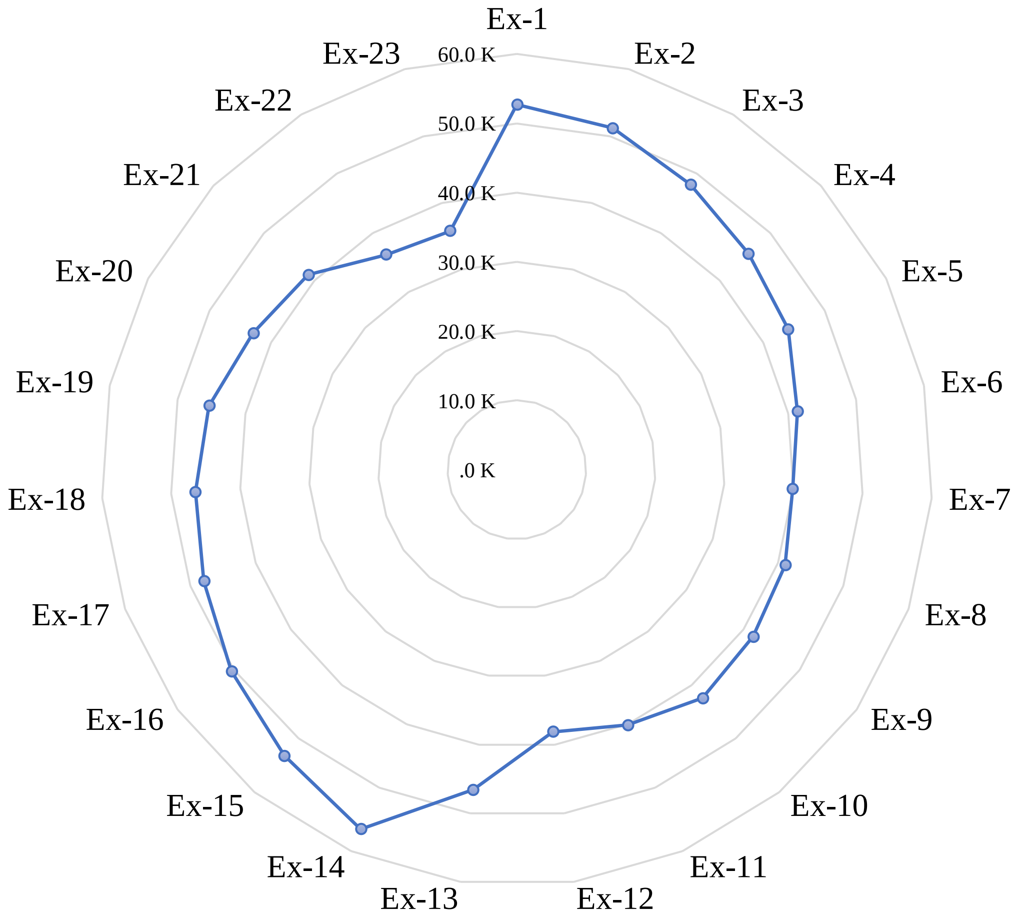


Figure 4.15 Production rate of excavators in excavation area 1 in the first study of the year 2028

Since there is traffic congestion at the entrance of excavation area 2, the excavators' production rates in excavation area 2 are lower than the excavators' work in excavation area 1, as seen in Figure 4.16. On the other hand, the production rate of excavator 24 is higher than the other excavators work in excavation area 2 since excavator 24 is located at the entrance of excavation area 2.

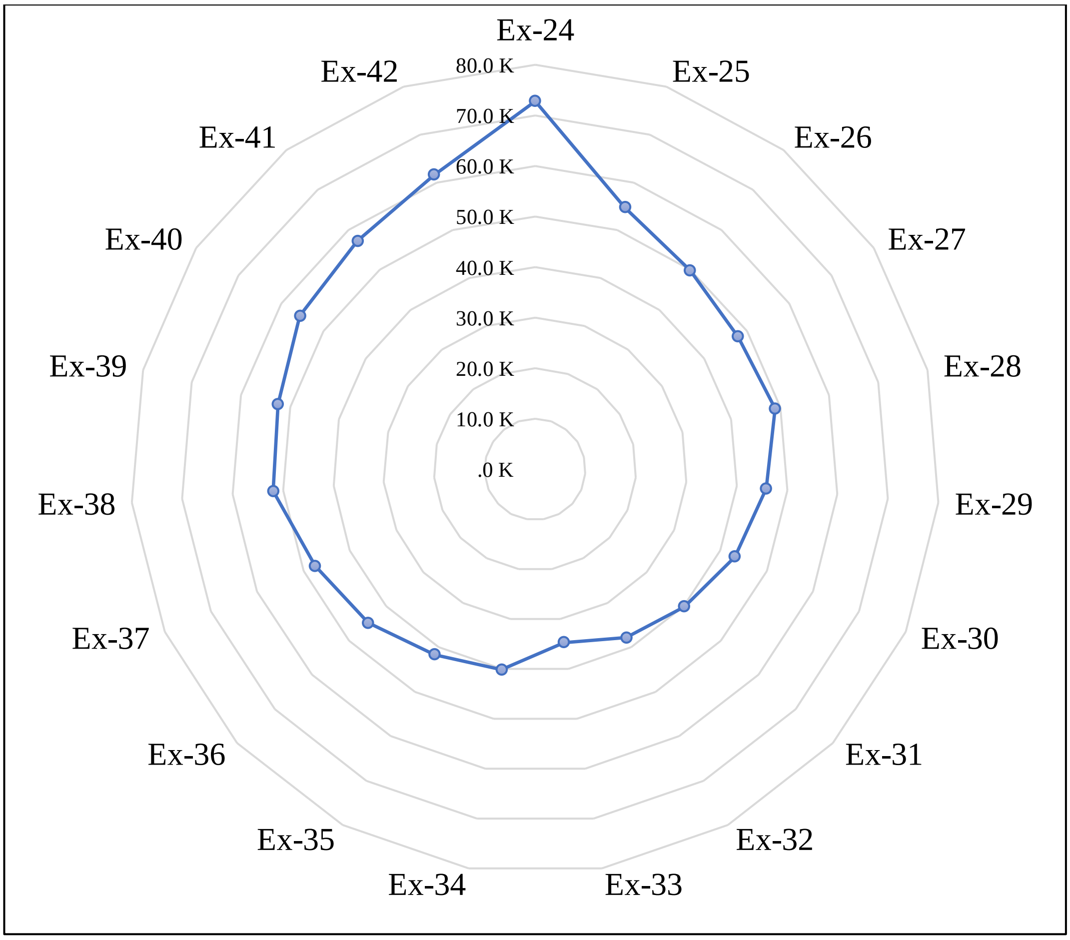


Figure 4.16 Production rate of excavators in excavation area 2 in the first study of the year 2028

4.1.5 Production Output of Simulation Model of the Year 2030

Two different excavation areas are designed for the year 2030. Targeted annual production amount, ten days production amount, and the number of excavators of the excavation area 1 and excavation area 2 are given in Table 4.6. There are 29 and 16 excavators in excavation area 1 and excavation area 2, respectively.

It was planned to have 395 trucks for the year 2030 for both excavation areas. The number of trucks could meet the production requirements for this year according to the simulation results.

Table 4.6 Production rate and number of excavators of the year 2030 of first simulation study

Excavation Areas	Annual Production Amount (m^3)	10 Days Production Amount (m^3)	Number of Excavators
Excavation-1	26,500,000	883,333	15
	26,000,000	866,667	14
Excavation-2	28,000,000	933,333	16

The road network design of the year 2030 is similar to the road network design of the year 2028, as seen in Figure 4.17. It is planned to have two sub excavation areas at the excavation area 1 for the year 2030. Two independent road networks do not cross each other connect sub excavation areas to dumping areas. Excavation area 2 is connected to its dumping area with an independent road network as well.

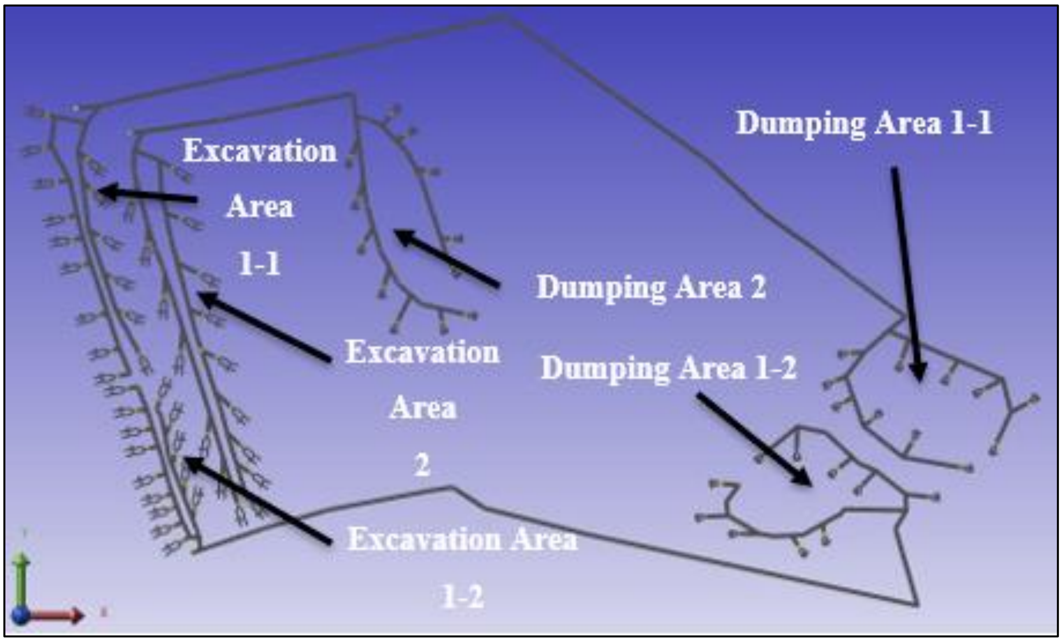


Figure 4.17 Road network design of the year 2030

Traffic congestion that occurred in this year occurs with similar reasons of traffic congestion in the year 2028. As seen in Figure 4.18, traffic congestion occurs at the excavation area 2. High traffic density is observed at the crossing point of the two road segments belongs to excavation area 2.

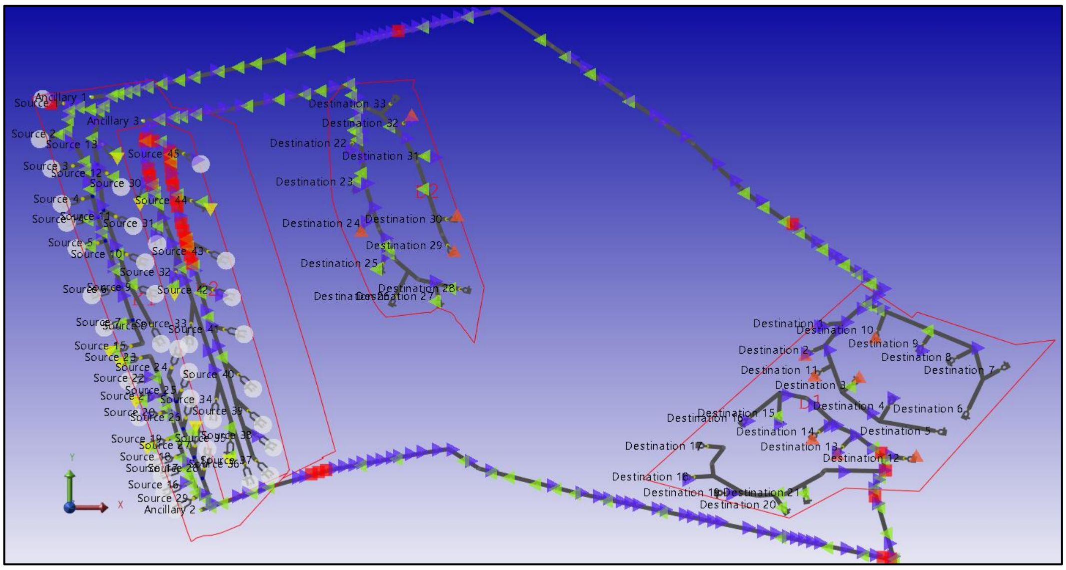


Figure 4.18 Traffic congestion in excavation area 2

Production rates of the excavators work in excavation area 1 given in Figure 4.19 shows that excavators that work at the entrance of the excavation area hold the maximum production rate among excavators located at the excavation area 1. For example, excavator 1 and excavator 16 are located at the entrance of the excavation area. Thus, these excavators hold the maximum production rates. Similarly, the production rates of excavator 14 and excavator 15 are the minimum production rates among excavators work in sub excavation area 1-1 and sub excavation area 1-2, respectively.

The production rate of excavator 15 is significantly lower than the other excavator since it is located at the end of the excavation area 1-1. This situation can be considered a result of the working principle of the simulation algorithm since excavation points were distributed homogenously in the excavation area 1-1. Significant traffic congestion does not occur. Thus, a targeted production rate for the excavation area 1-1 is achieved.

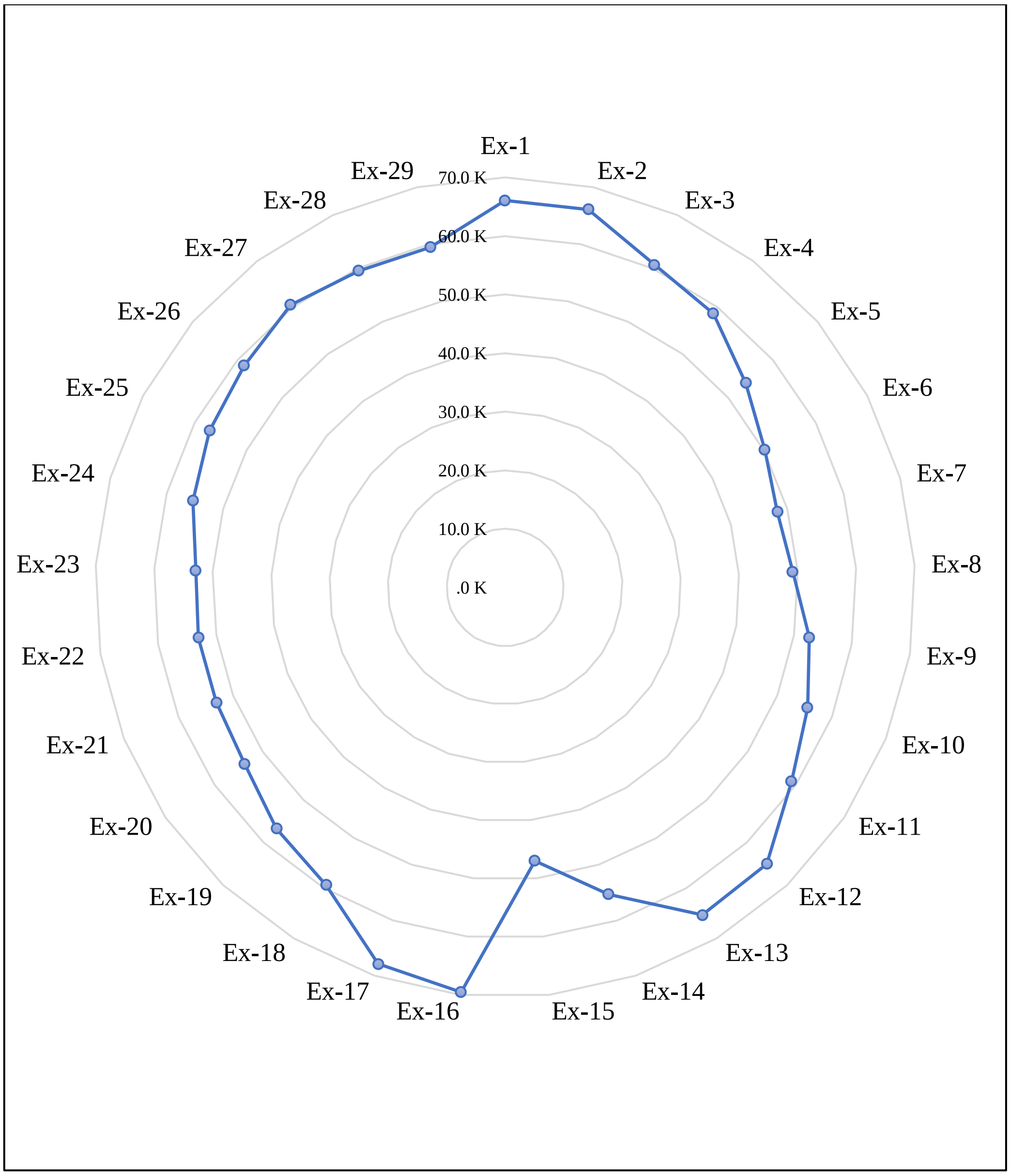


Figure 4.19 Production rate of excavators in excavation area 1 in the first study of the year 2030

Even though traffic congestion is observed in excavation area 2, there is no considerable decrease in production rates observed among excavators, as seen in Figure 4.20. Excavator 30 and excavator 37 hold maximum and minimum production rates respectively among excavators who work in excavation area 2 due to the same reasons valid for excavation area 1.

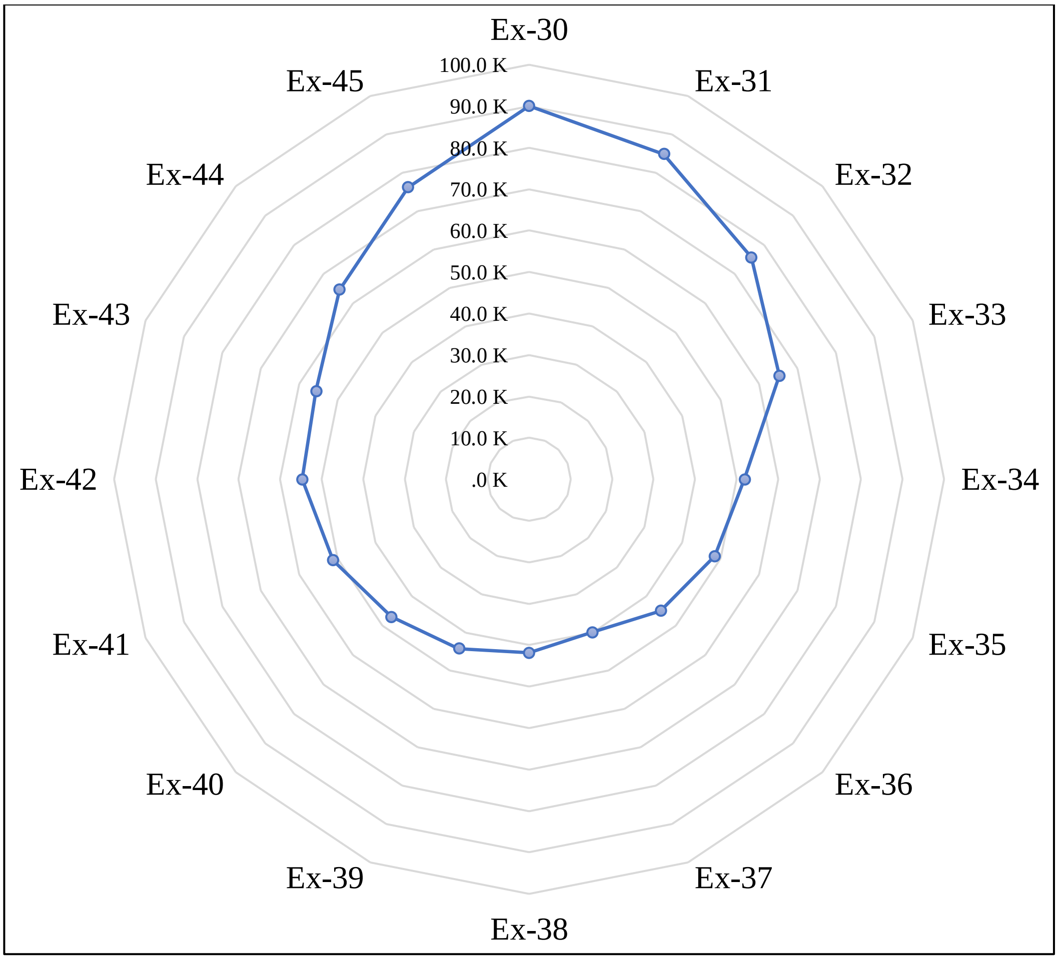


Figure 4.20 Production rate of excavators in excavation area 2 in the first study of the year 2030

4.2 Revised Mine Plan and Road Design Simulation Study

In this section, the results of the revised simulation study are given. In the first simulation study, target production amounts could not be met entirely due to the traffic issues that occurred in certain areas. New mine and road plans were prepared since production amounts in the simulation study cannot meet the targeted production amounts.

All excavation areas that are planned in relevant years are studied in the first study. However, in the second study, only the excavation areas with the possibility of high traffic density are studied. Target production amounts are summarized in Table 4.7.

Table 4.7 Targeted annual productions of revised simulation study for only selected years

	Targeted Annual Production (m³)
2021	20,700,000
2022	20,600,000
2023	55,500,000
2024	44,700,000
2025	48,700,000
2026	56,700,000
2027	77,400,000
2028	28,300,000
2029	46,000,000
2030	48,000,000

Each production level has its own road network that connects the excavation level to the dumping level in the revised study. This represents the multi-bench operation of the site as the excavators will be loading material from different elevations synchronously.

The main objective of this strategy is to decrease the traffic load on the main roads. This way, the trucks that are assigned to different excavators will not share a single road for entering or leaving the excavation areas. Trucks are assigned to different production levels. Each road network does not cross each other to ensure that trucks do not pass to other road networks, as seen in Figure 4.21. By implementing this strategy, decreasing traffic congestion on main roads is aimed since all trucks that work on different benches use the same single lane road previous strategy. The simulation model is revised to include separate roads in the haulage network, although this could be challenging to construct on-site. However, since the company declare that they could construct separate road network for each production level, this strategy is implemented.

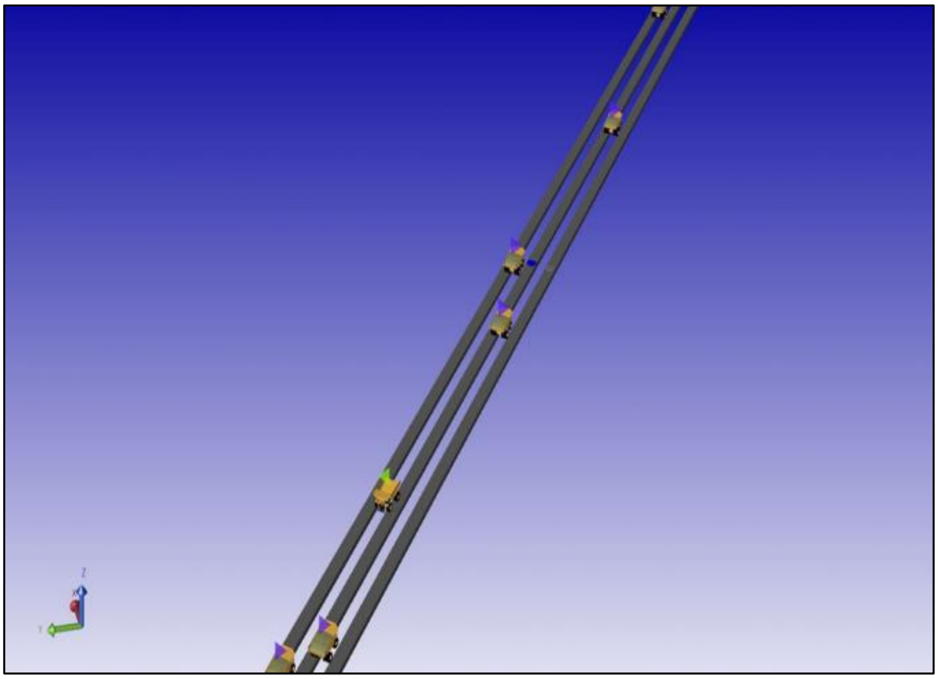


Figure 4.21 Revised Road Networks

4.2.1 Production Output of Simulation Model of the Year 2021 and 2022

One excavation area is designed for the years 2021 and 2022. Targeted annual production amount, ten days production amount, and the number of excavators of the excavation area 1 are given in Table 4.8 for the year 2021 and Table A.1 for the year 2022. 12 excavators were located in excavation area 1 for the year 2021 and 11 excavators for the year 2022.

It was planned to have 180 trucks for the year 2021 and 106 trucks for the year 2022 for both excavation areas. The number of trucks could meet the production requirements for these years, according to the simulation results.

Table 4.8 Production rate and number of excavators of the year 2021 of revised simulation study

Excavation Area	**Annual Production Amount (m^3)**	**10 Days Production Amount (m^3)**	**Number of Excavators**
Excavation-1	20,700,000	690,000	12

Excavation area 1 is connected to the dumping area with three different road networks. Excavators and trucks are distributed to each production level homogenously. In each production level, four excavators are operated, as seen in Figure 4.22 and Figure B.1.

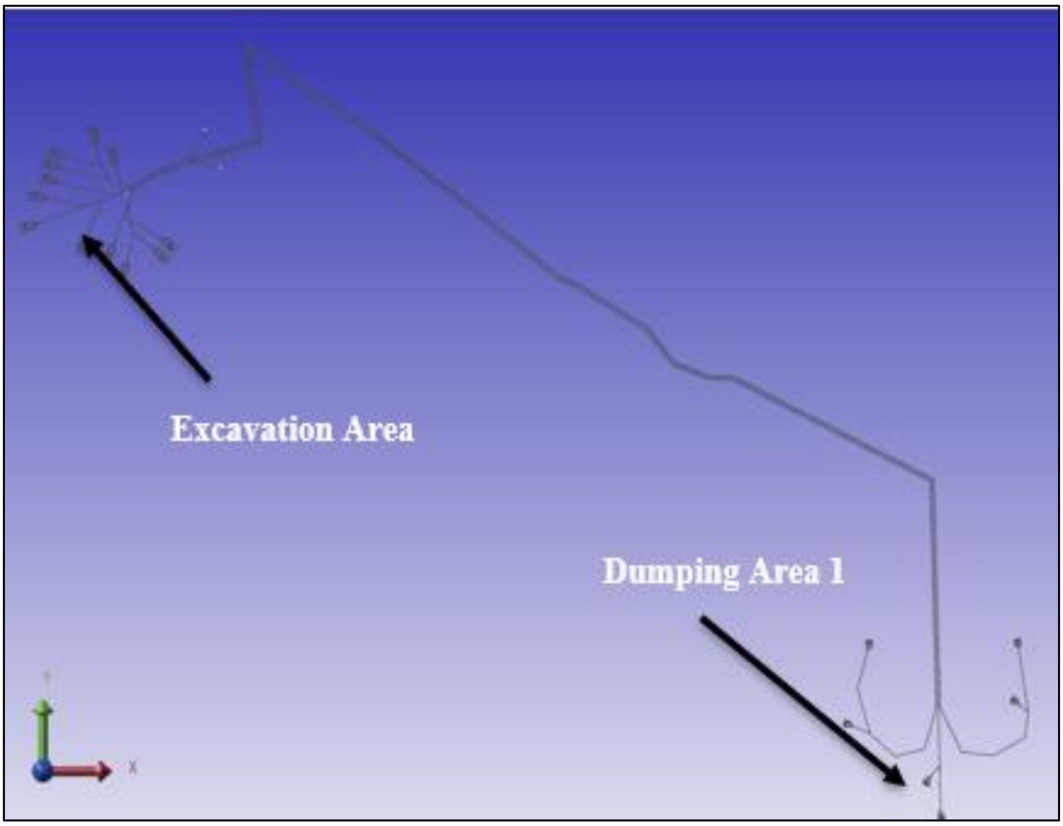


Figure 4.22 Revised road network design of the year 2021

For the years 2021 and 2022, traffic congestion does not occur. According to the potential traffic spots given in Figure 4.23 and Figure B.1, there might be the possibility of the traffic struck at the dumping area; however, according to the simulation study, there are no traffic issues at the dumping area, and the target production amount is met. For both years, few blocked trucks were observed on the road network.

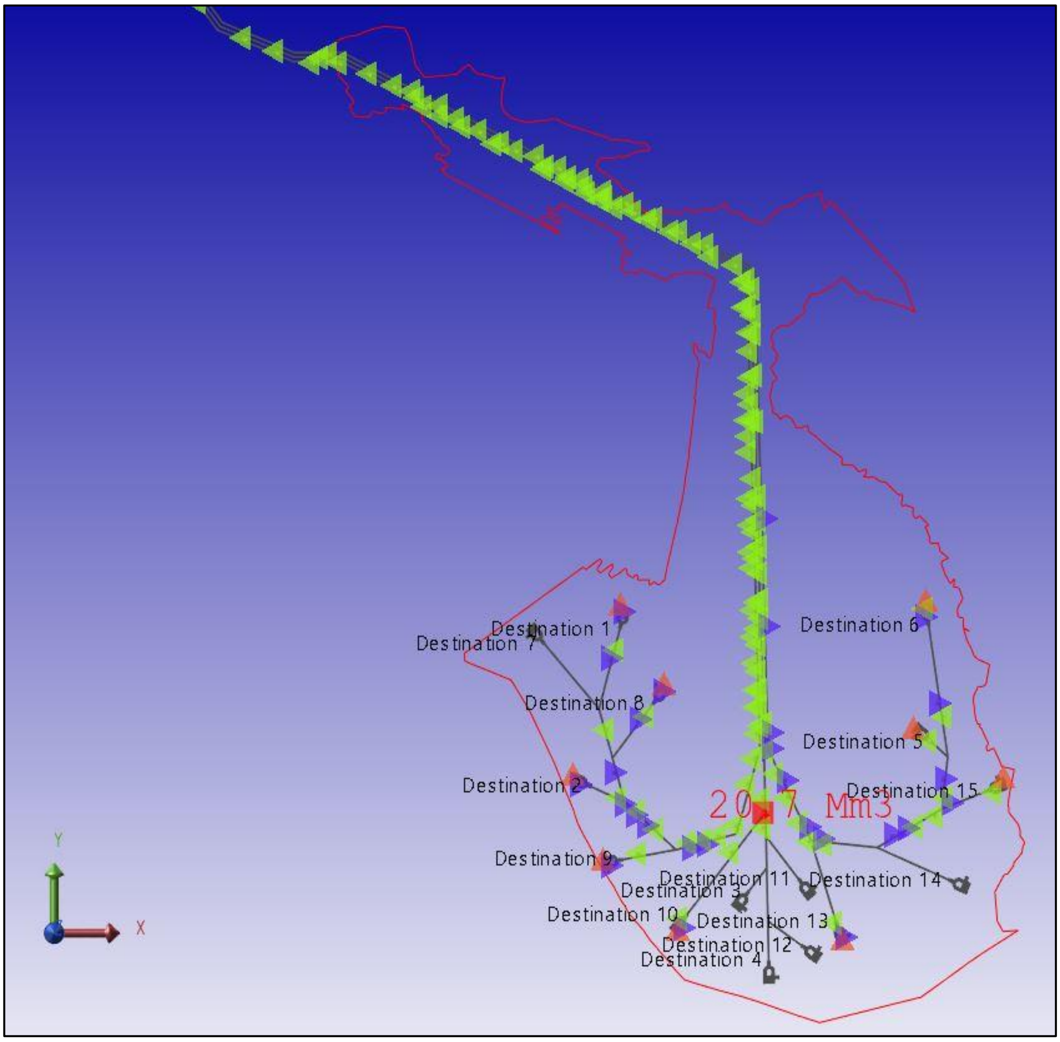


Figure 4.23 Traffic density in dumping area

Production rates of the excavators that work in excavation area 1 are almost identical according to Figure 4.24 and Figure C.1. This could be considered as the result of the optimum locations of the excavators. Excavator 5 and excavator 3 holds maximum and minimum production rates among excavators in excavation area 1. The production rate of excavator 1 and excavator 3 are 60,404 m^3 55,299 m^3, respectively. Production rates of the excavators are distributed homogenously, which indicates the excellent placement of the excavators.

Figure 4.24 Production rate of excavators in excavation area 1 in the revised study of the year 2021

4.2.2 Production Output of Simulation Model of the Year 2023

Two excavation areas are designed for the year 2023. Target annual production amount, ten days production amount, and the number of excavators of the excavation area 1 and excavation area 2 are given in Table 4.9. There are 17 and 14 excavators in excavation area 1 and excavation area 2, respectively. It was planned to have 270 trucks for the year 2023 for both excavation areas. The number of trucks could meet the production requirements for this year according to the simulation results.

Table 4.9 Production rate and number of excavators of the year 2023 of revised simulation study

Excavation Areas	Annual Production Amount (m³)	10 Days Production Amount (m³)	Number of Excavators
Excavation-1	30,800,000	1,030,000	17
Excavation-2	24,700,000	820,000	14

Both excavation area has independent road network each other as seen in Figure 4.25. The main road that connects excavation area 1 to the dumping area is longer than the road that connects excavation area 2 to the dumping area. Each road network has three separate roads that connect production levels to dumping levels.

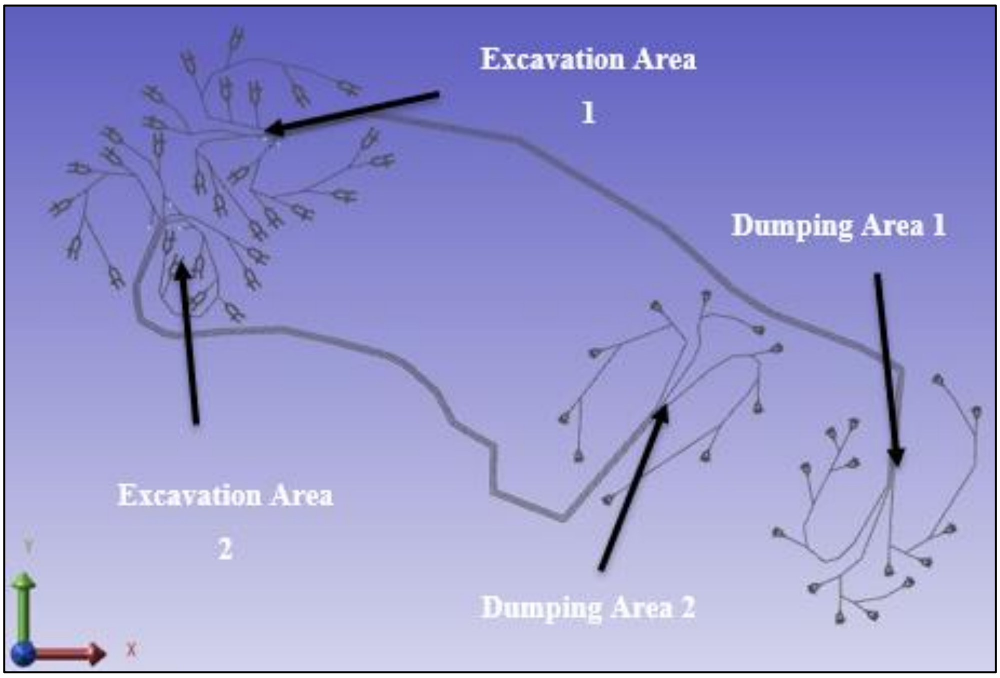


Figure 4.25 Revised road network design of the year 2023

Similar to previous years of revised study, traffic congestion does not occur in the year 2023 as well. In Figure 4.26, potential dense traffic spots are shown; however, during the simulation study, trucks are not stuck in the traffic due to the areas with high-density traffic. Thus, targeted production is met for the year 2023 as well.

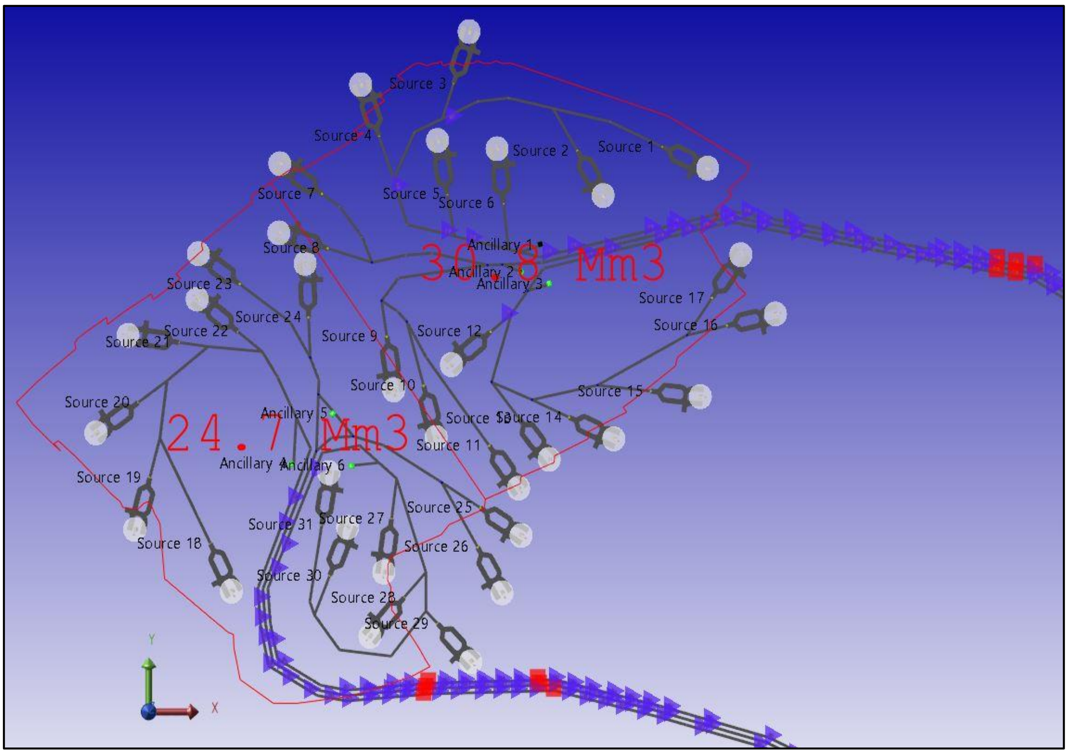


Figure 4.26 Traffic density in excavation area 1 and 2

Performances of excavators are similar as seen in Figure 4.27; however, excavator 6, excavator 7, and excavator 12 hold the maximum production rate among other excavators that work at the same level since these excavators are located at the entrance of their production level. The production rate of excavator 6, excavator 7, and excavator 12 are 65,623 m^3, 65,623 m^3, and 68,330 m^3, respectively. The minimum production rate is held by the excavator 17 with 48,820 m^3. Since there is no significant traffic congestion on the road network, production rates of the excavators are distributed homogenously among excavators located in the excavation area 1.

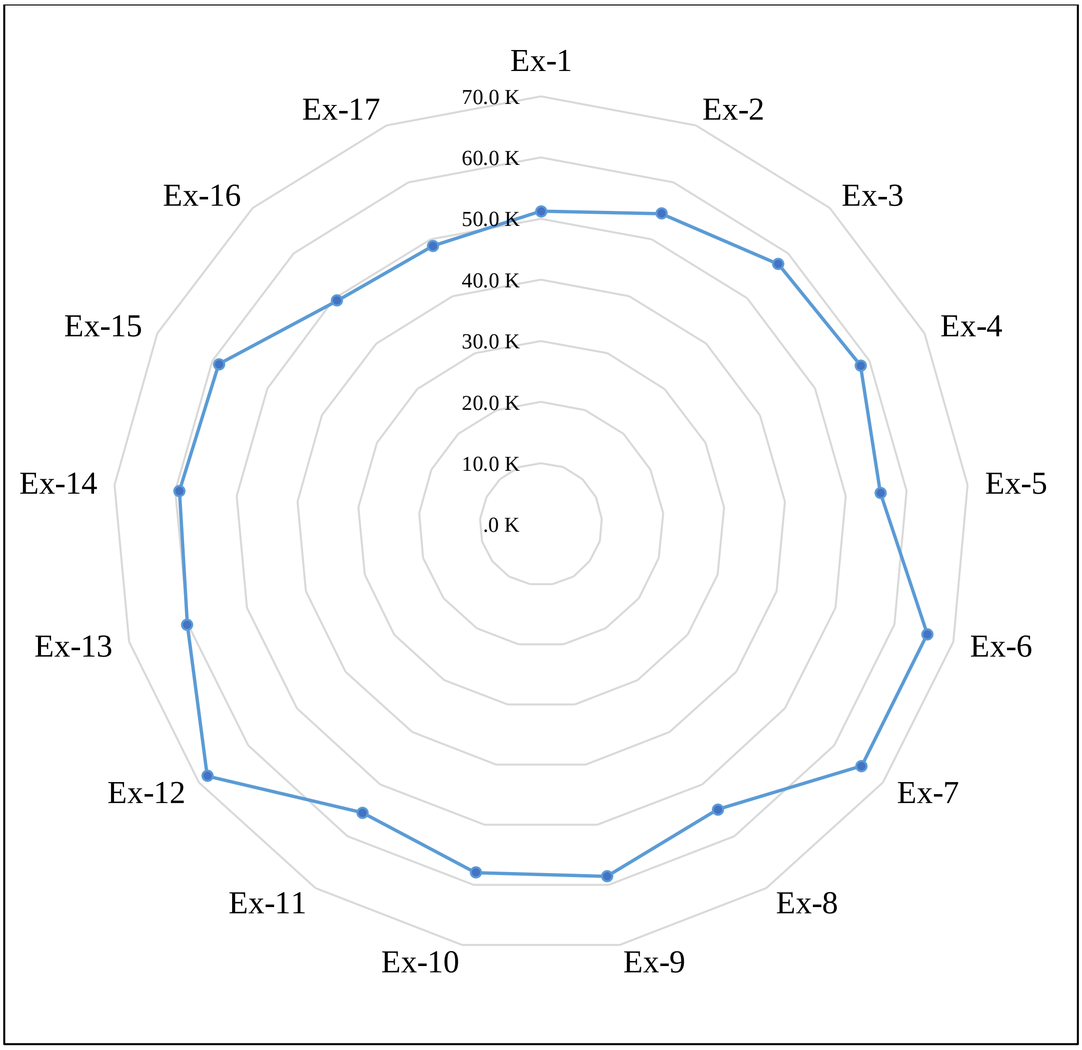


Figure 4.27 Production rate of excavators in excavation area 1 in the revised study of the year 2023

In excavation area 2, the excavator shows similar performances, as seen in Figure 4.28. Significant differences between the production rates of the excavators are not observed. However, the production rates of excavator 23, excavator 24, excavator 25, and excavator 25 are higher than the other excavators that work at the same production level because the distance between the excavators is longer than the other excavators that work at the same production level.

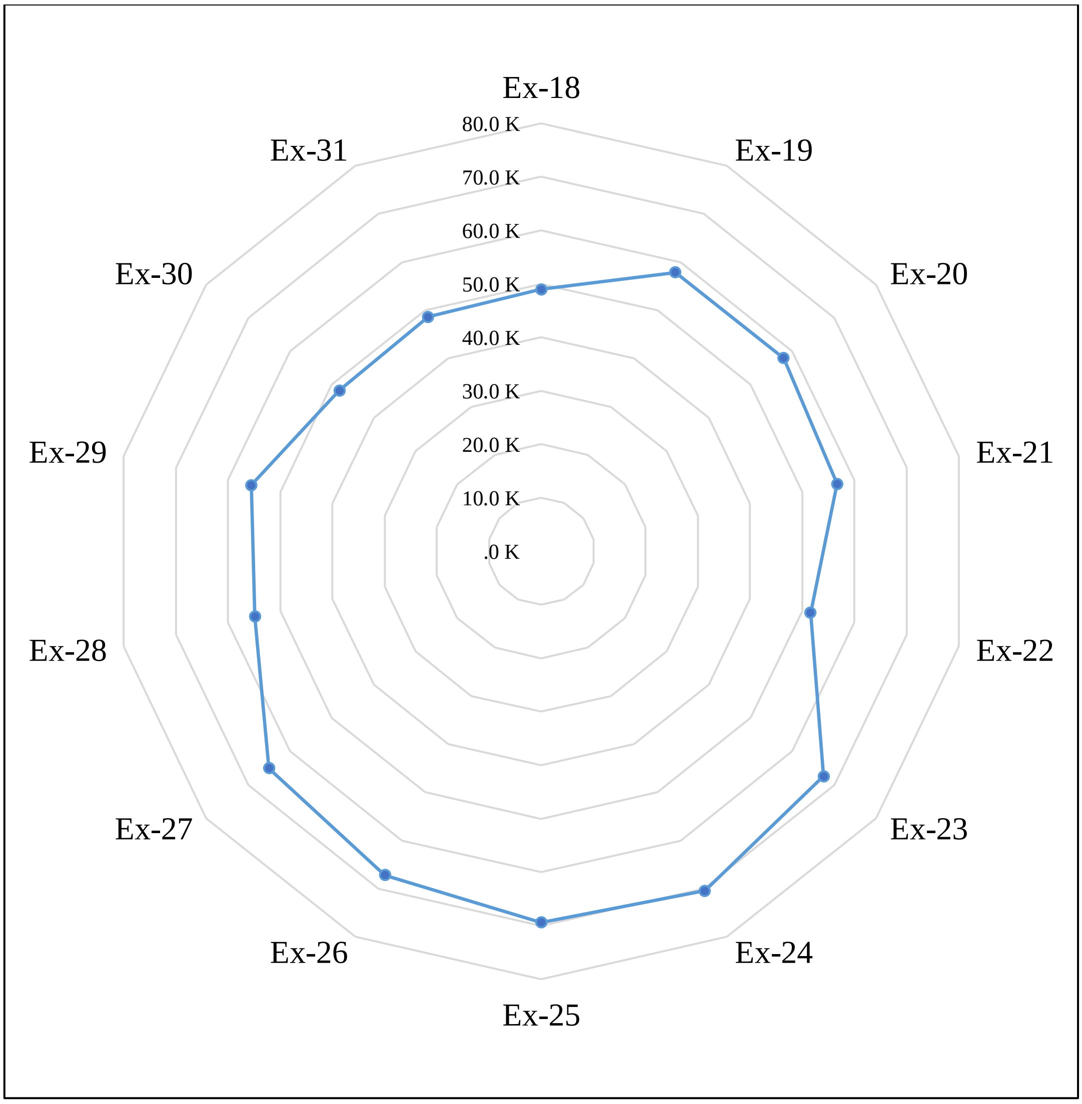


Figure 4.28 Production rate of excavators in excavation area 2 in the revised study of the year 2023

4.2.3 Production Output of Simulation Model of the Year 2024

Two excavation areas are designed for the year 2024. Targeted annual production amount, ten days production amount, and the number of excavators of the excavation area 1 and excavation area 2 are given in Table 4.10. There are 13 and 12 excavators in excavation area 1 and excavation area 2, respectively. It was planned to have 316 trucks for the year 2024 for both excavation areas. The number of trucks could meet the production requirements for this year according to the simulation results.

Table 4.10 Production rate and number of excavators of the year 2024 of revised simulation study

Excavation Areas	**Annual Production Amount (m³)**	**10 Days Production Amount (m³)**	**Number of Excavators**
Excavation-1	22,700,000	760,000	13
Excavation-2	22,000,000	730,000	12

In the year 2024, a different design approach was used to create a road network. There are two different production levels at each excavation area instead of three excavation areas. Both excavation areas are connected to one dump area, as seen in Figure 4.29.

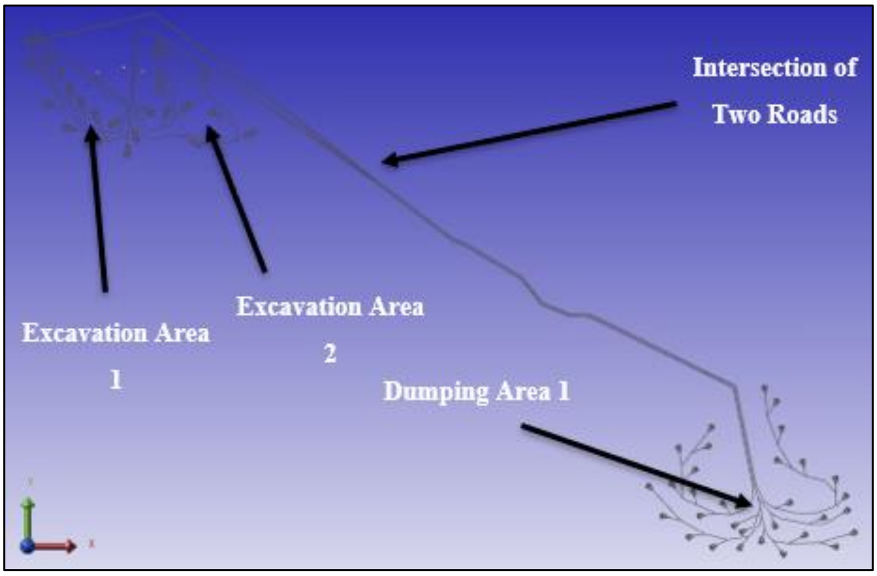


Figure 4.29 Revised road network design of the year 2024

However, roads from each production level join on the main road, as seen in Figure 4.30. By using this approach, trucks that work in excavation area 1 and excavation area 2 use the same main road. In other words, trucks that work on two different production levels used the same road network to dump material.

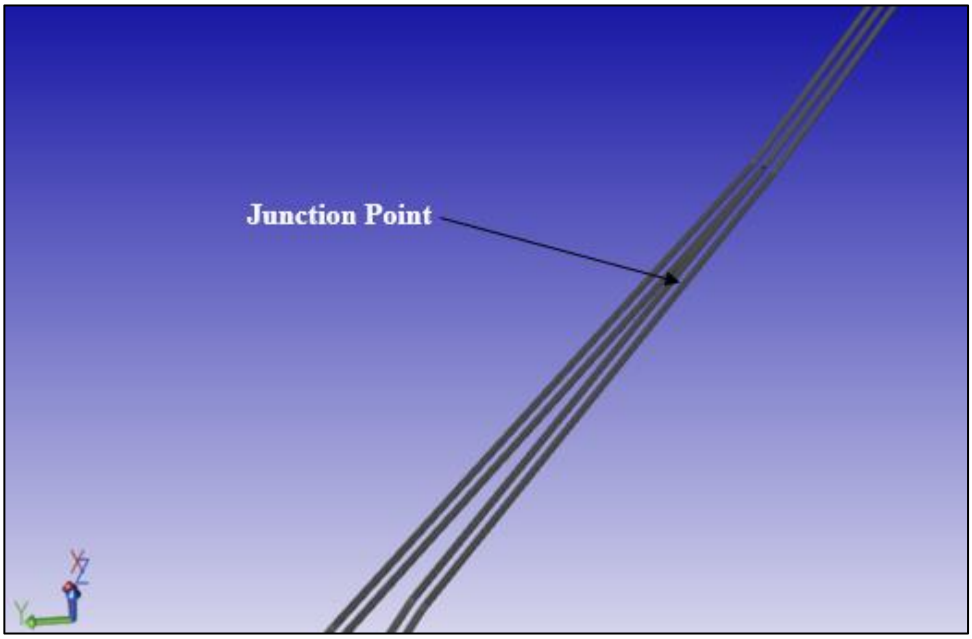


Figure 4.30 Junction point of the roads

This approach causes traffic congestions at the junction point of two ancillary roads. Red squares that can be seen in Figure 4.31 show the blocked trucks at that point. However, by using this approach, the targeted production amount is met according to the simulation results.

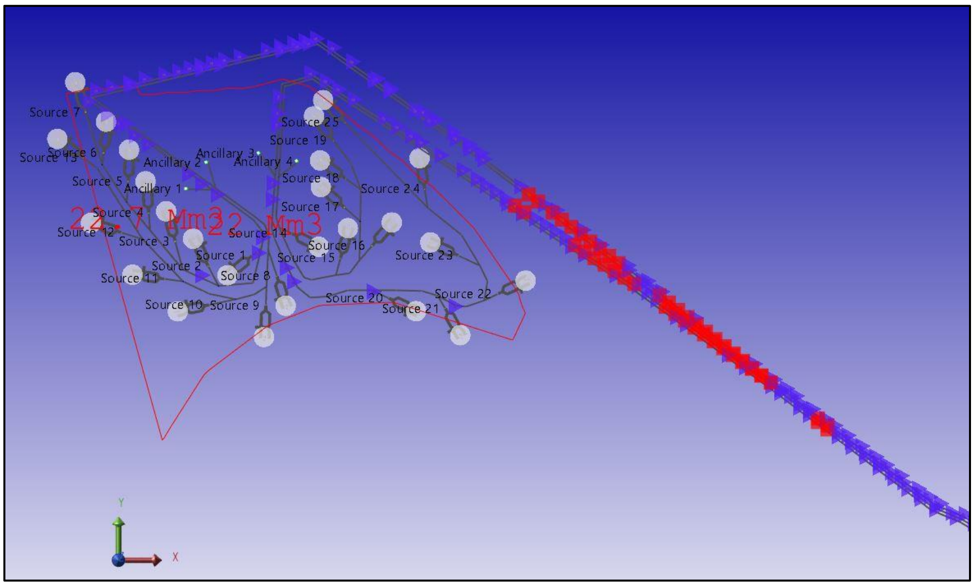


Figure 4.31 Traffic density in the junction of two road

Even though trucks from different production levels use the same road, each truck is allocated to only one production level. There are differences in production rates of the excavators that work in excavation area 1. However, there are no significant differences observed as seen in Figure 4.32 despite using different strategies rather than other years.

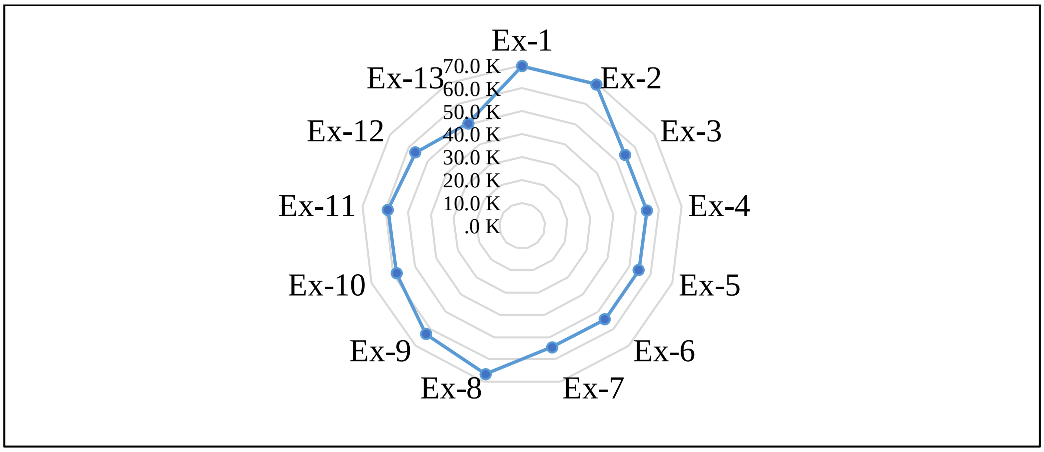


Figure 4.32 Production rate of excavators in excavation area 1 in the revised study of the year 2024

Excavators that work in excavation area 2 shows respectively similar performances among each other. Excavator 20 holds the minimum production rate, as seen in Figure 4.33, since excavator 20 is located at the end of the production level.

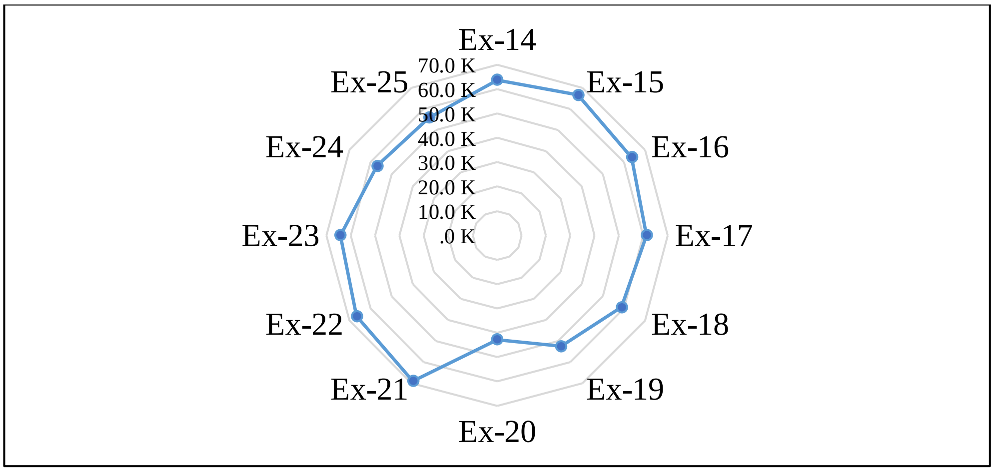


Figure 4.33 Production rate of excavators in excavation area 2 in the revised study of the year 2024

4.2.4 Production Output of Simulation Model of the Year 2025 and 2026

Two excavation areas are designed for the years 2025 and 2026. Targeted annual production amount, ten days production amount, and the number of excavators of the excavation area 1 and excavation area 2 are given in Table 4.11 and Table A.2. There are 14 and 13 excavators in excavation area 1 and excavation area 2, respectively. For the year 2026, there are 18 and 13 excavators in excavation area 1 and excavation area 2, respectively. It was planned to have 298 trucks for the year 2025 and 362 trucks for the year 2026 for both excavation areas. The number of trucks could meet the production requirements for these years according to the simulation results.

Table 4.11 Production rate and number of excavators of the year 2025 of revised simulation study

Excavation Areas	Annual Production Amount (m^3)	10 Days Production Amount (m^3)	Number of Excavators
Excavation-1	25,400,000	850,000	14
Excavation-2	23,300,000	780,000	13

Road network designs of the year 2025 and 2026 consist of two excavation areas. Each excavation area consists of three different production levels connected to the dumping level with an independent road network given in Figure 4.34 and Figure B.1.

Two different excavation areas were studied for years 2025 and 2026 since there is a possibility of traffic congestion for both excavation areas. The same design approach is utilized with the previous years of the revised study, as well. Dumping and excavation points are homogeneously distributed in the excavation and dumping areas.

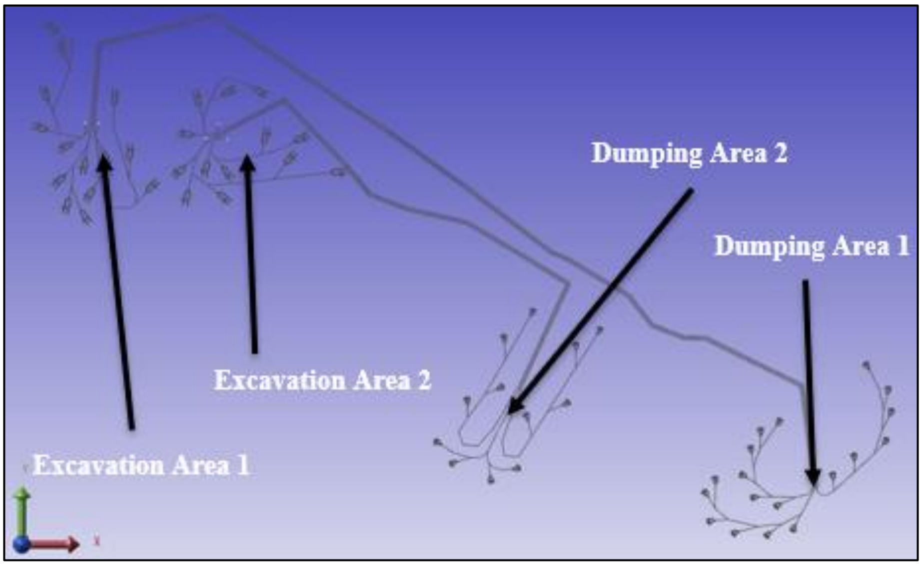


Figure 4.34 Revised road network design of the year 2025

There is no traffic congestion observed on the road network designed for the years 2025 and 2026, as seen in Figure 4.35 and Figure C.2. Some trucks are instantly blocked on the main road due to the heavy traffic conditions. However, traffic flows continuously during the simulation run, and the targeted production rate for years 2025 and 2026 are met.

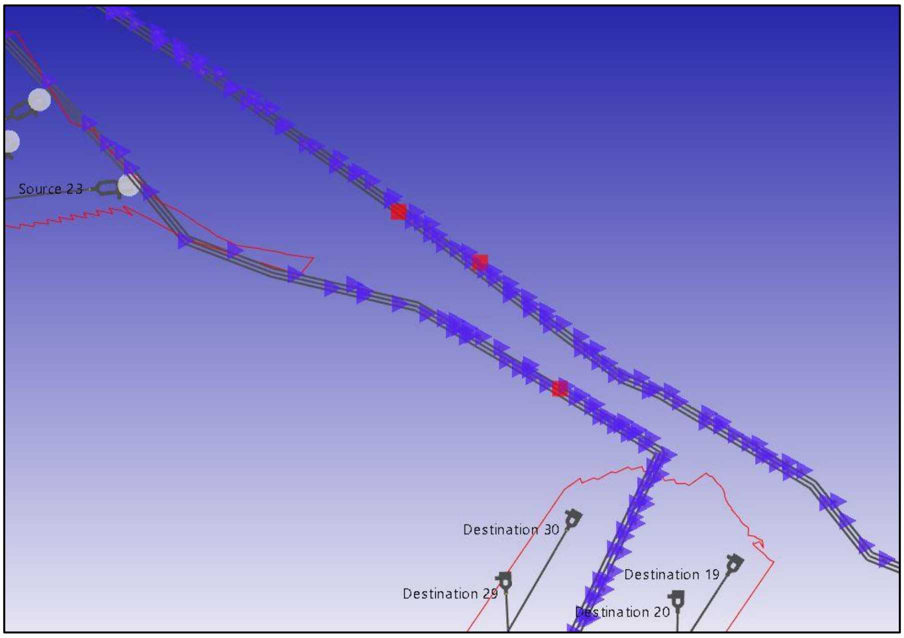


Figure 4.35 Traffic density in road network

Excavators that work at excavation area 1 show similar performances in the year 2026. Excavator 6 holds the maximum production rate among excavators works in excavation area 1, as seen in Figure 4.36, due to the location of the excavator. Also, for the year 2026, since excavation area 1 is larger than the excavation areas of previous years, and the gap between excavators is larger, production rates of the excavators are close to each other, as seen in Figure D.2.

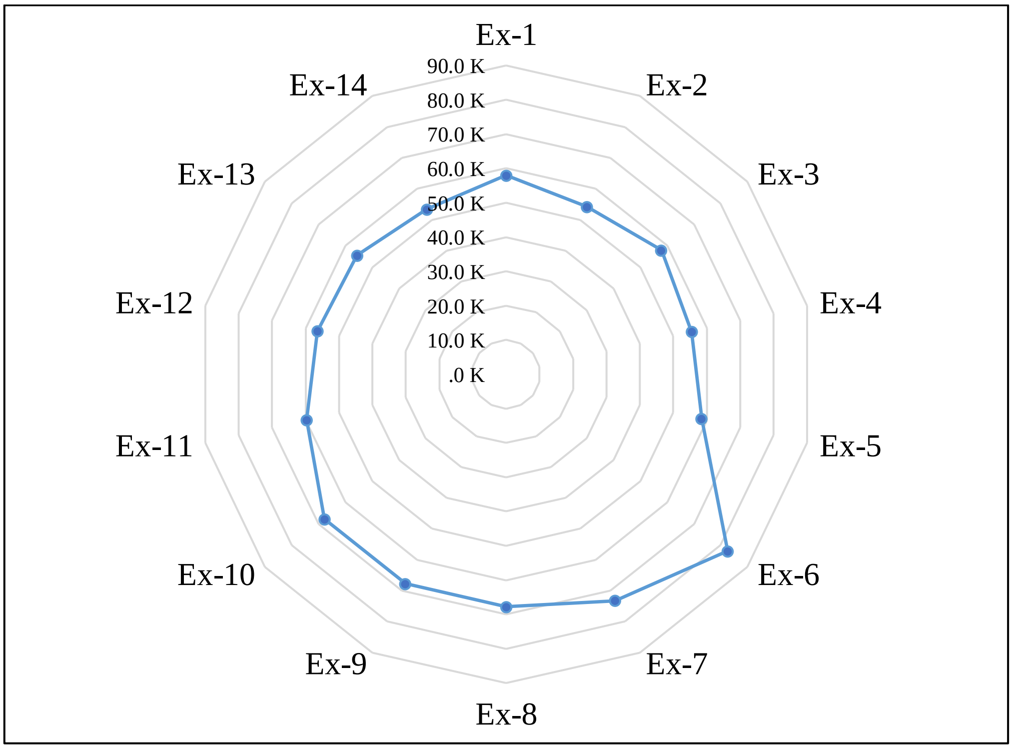


Figure 4.36 Production rate of excavators in excavation area 1 in the revised study of the year 2025

Production rate distribution of the excavators' work in excavation area 2 is similar to the production rate distribution of the excavators' work in excavation area 1. However, excavator 24 shows outstanding performance, and its production rate is higher than the other excavators, as seen in Figure 4.37. Heavy traffic condition is not observed at the road network of the excavation area 2 of the year 2026. Production rates of the excavators are similar, and there are no significant differences in the excavators' production rates, as seen in Figure D.3.

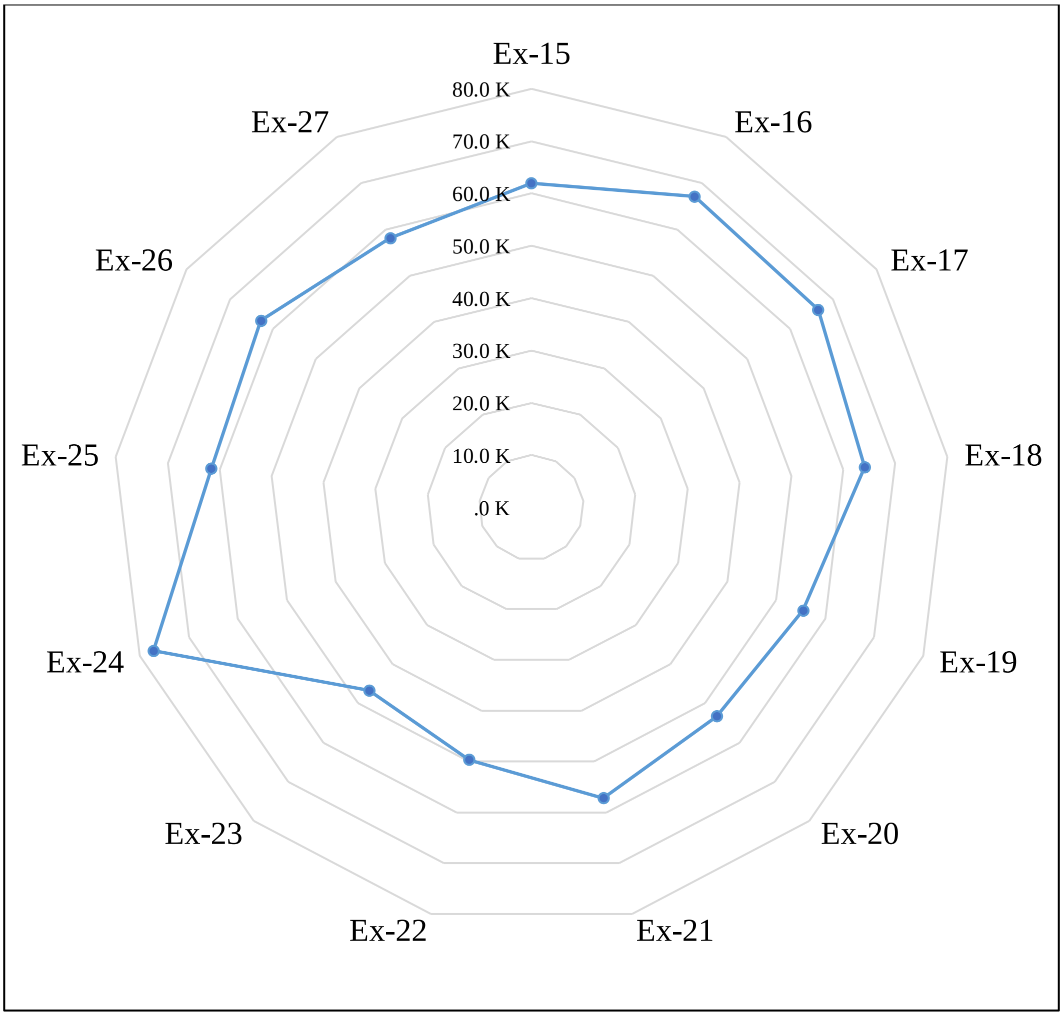


Figure 4.37 Production rate of excavators in excavation area 2 in the revised study of the year 2025

4.2.5 Production Output of Simulation Model of the Year 2027

Two excavation areas are designed for the year 2027. Targeted annual production amount, ten days production amount, and the number of excavators of the excavation area 1 and excavation area 2 are given in Table 4.12. There are 18 and 25 excavators in excavation area 1 and excavation area 2, respectively. It was planned to have 461 trucks for the year 2027 for both excavation areas. The number of trucks could meet the production requirements for this year according to the simulation results.

Table 4.12 Production Rate and Number of Excavators of the Year 2027 of Revised Simulation Study

Excavation Areas	Annual Production Amount (m³)	10 Days Production Amount (m³)	Number of Excavators
Excavation-1	32,600,000	1,090,000	18
Excavation-2	22,800,000	760,000	13
	22,000,000	730,000	12

The design concept of excavation area 1 of the year 2027 is similar to the design concept of the previous year. There are three distinct production levels in the excavation area 1. Excavation area 2 has two sub excavation areas, and each production level of sub excavation areas are connected to the dumping level with a separate road network, as seen in Figure 4.38. Each sub excavation area is connected to a separate dumping area.

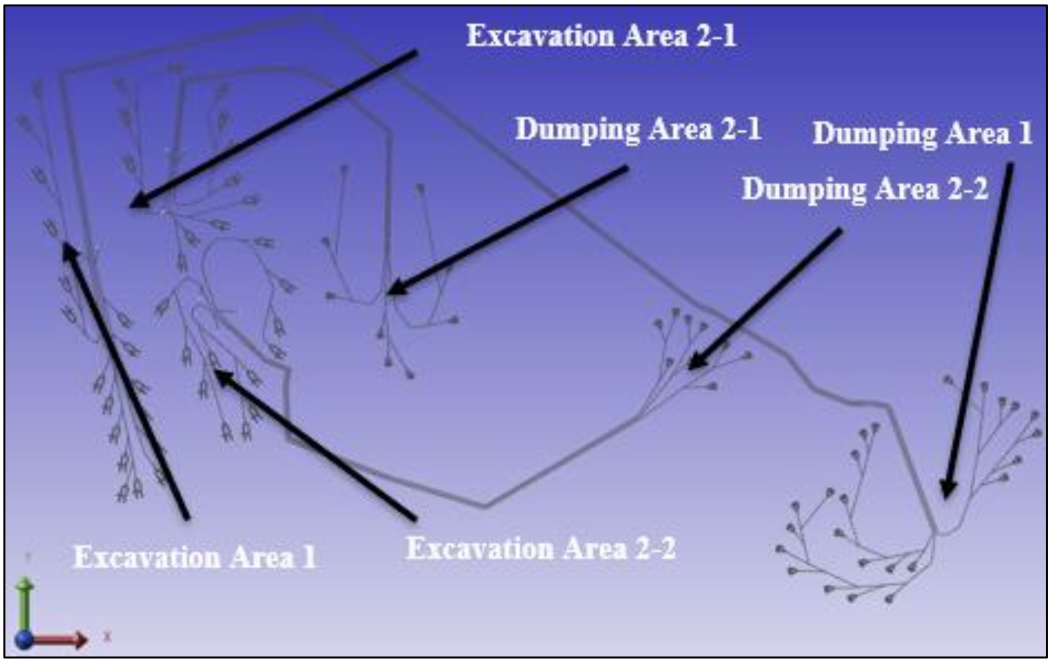


Figure 4.38 Revised road network design of the year 2027

The traffic issue is not observed for the year 2027 as well. Trucks blocked on the main road for short periods, as seen in Figure 4.39, and these blocked states are the minor parts of the recorded discrete events.

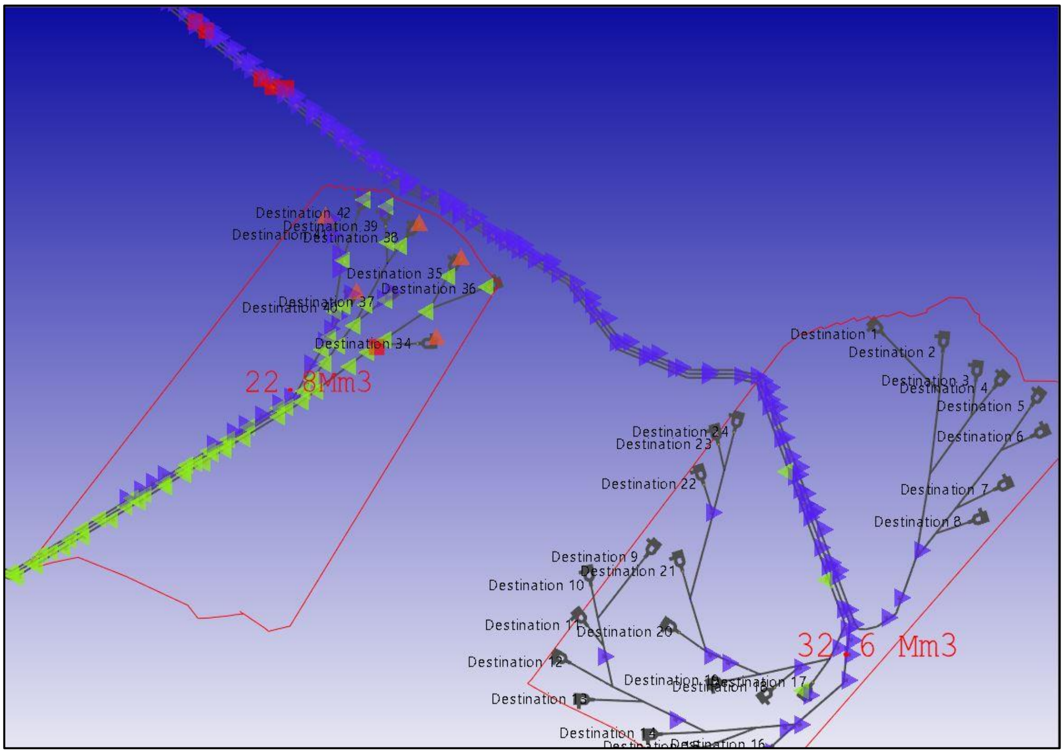


Figure 4.39 Traffic density at dumping areas

Since traffic issues are not observed during the simulation study, excavators that work at excavation area 1 show similar performances as seen in Figure 4.40. The maximum and minimum production rates are held by excavator 13 and excavator 18, respectively. The production rate of excavator 13 and excavator 18 are 71,189 m³ and 54,929 m³. There is no significant difference between the production rates of the excavators located in excavation area 1. Excavator 13 shows the best performance among excavators in excavation area 1 due to its location. Similar to the previous cases, the excavator located at the entrance of the excavation area is held the maximum production rate.

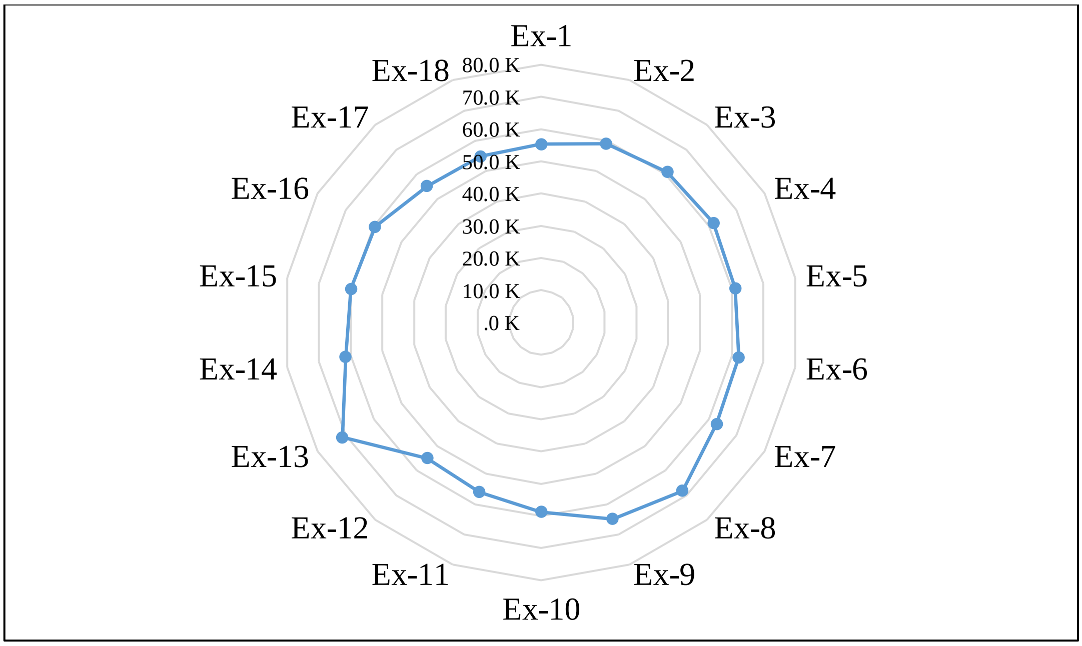


Figure 4.40 Production rate of excavators in excavation area 1 in the revised study of the year 2027

There are no sharp decreases between the excavators' production rates in excavation area 2-1, as seen in Figure 4.41. Excavator 27 and excavator 30 hold maximum and minimum production rates, respectively.

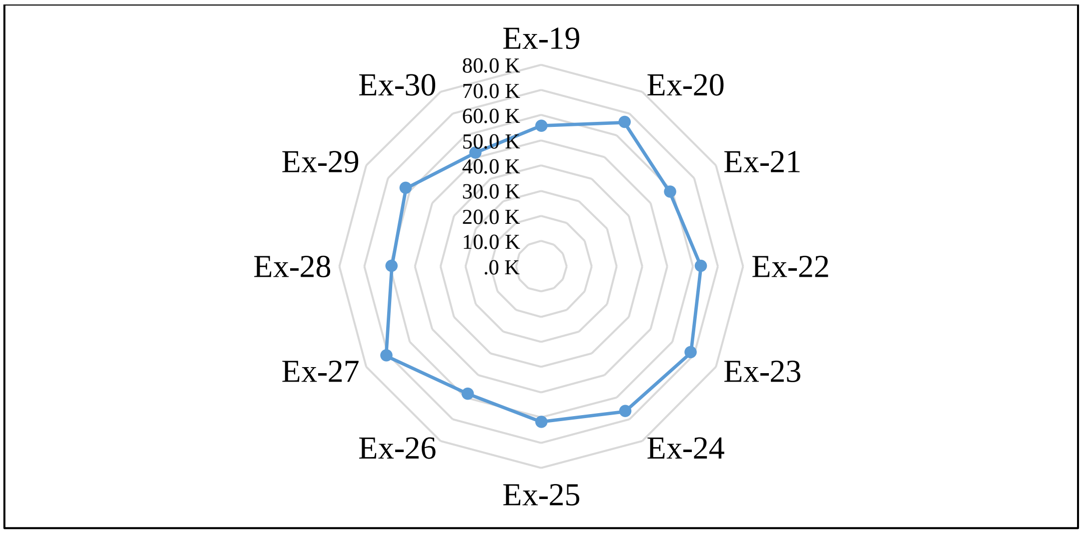


Figure 4.41 Production rate of excavators in excavation area 2-1 in the revised study of the year 2027

The number of excavators that work in excavation area 2-2 is more than the number of excavators work in excavation area 2-1. Production rates are homogenously distributed among the excavators, as seen in Figure 4.42.

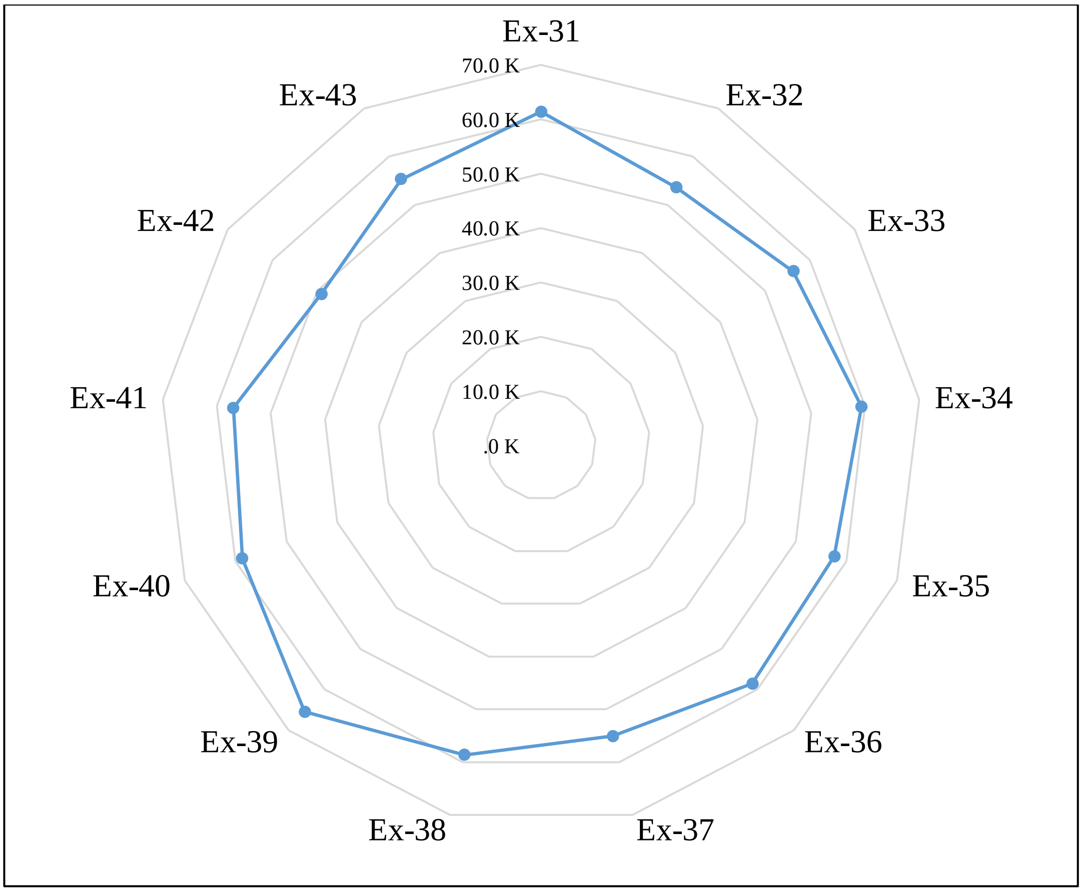


Figure 4.42 Production rate of excavators in excavation area 2-2 in the revised study of the year 2027

4.2.6 Production Output of Simulation Model of the Year 2028

One excavation area is designed for the year 2028. Targeted annual production amount, ten days production amount, and the number of excavators of the excavation area 1 are given in Table 4.13. There are 16 excavators in excavation area 1. It was planned to have 220 trucks for the year 2028 for both excavation areas. The number of trucks could meet the production requirements for this year according to the simulation results.

Table 4.13 Production Rate and Number of Excavators of the Year 2028 of Revised Simulation Study

Excavation Areas	Annual Production Amount (m³)	10 Days Production Amount (m³)	Number of Excavators
Excavation-1	28,300,000	940,000	16

A similar design approach is applied for the year 2028 as well. The excavation area consists of three distinct production levels, and each production level is connected to the dumping level with an independent road network, as seen in Figure 4.43.

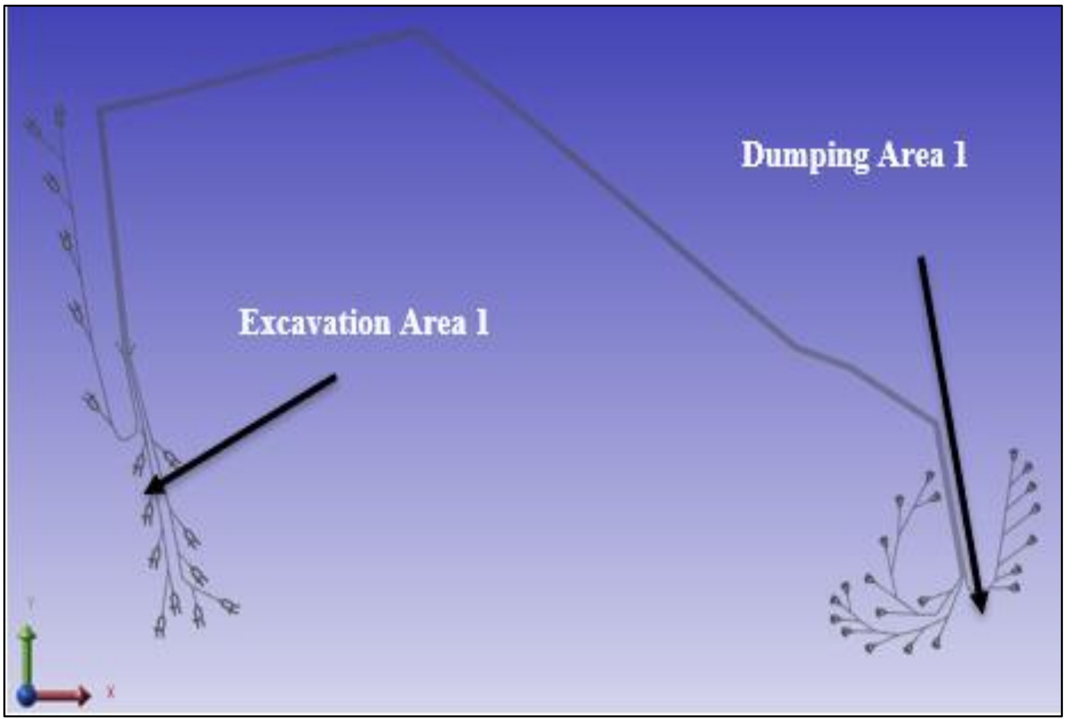


Figure 4.43 Revised road network design of the year 2028

Trucks are blocked on the main road during the simulation run, as seen in Figure 4.44. Despite the heavy traffic situation on the main roads, the targeted production rate is met by the available equipment assigned for the year 2027.

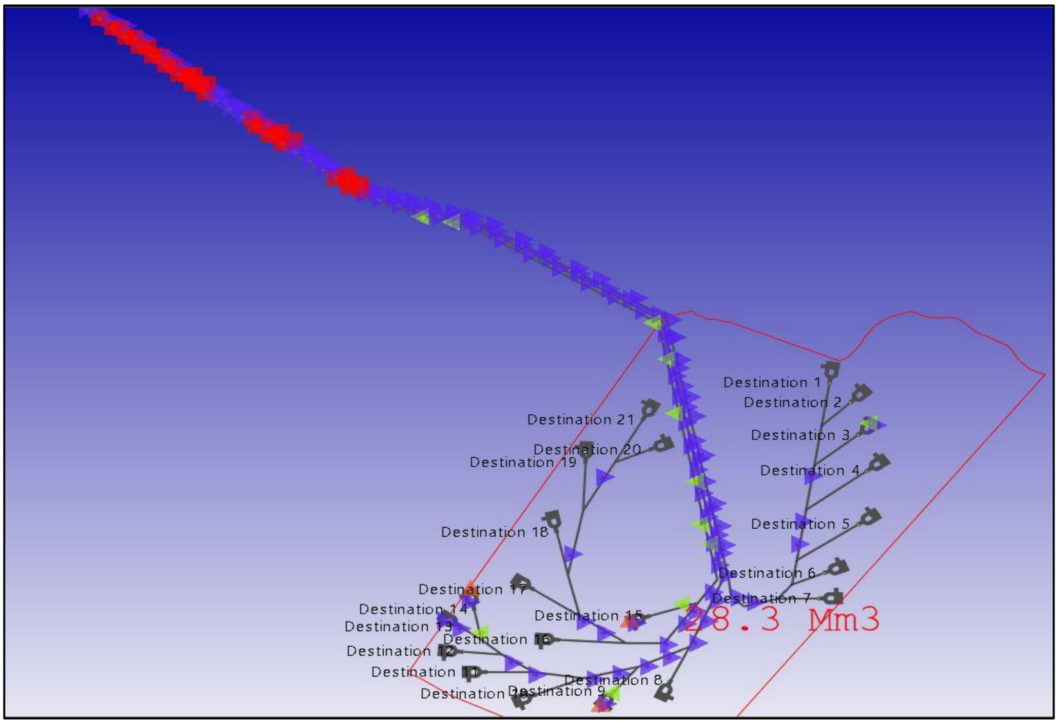


Figure 4.44 Traffic density on main roads

Excavators show similar performances during the simulation run of the year 2028, as seen in Figure 4.45. Excavator 12 holds the maximum production rate among excavators that work in the year 2028.

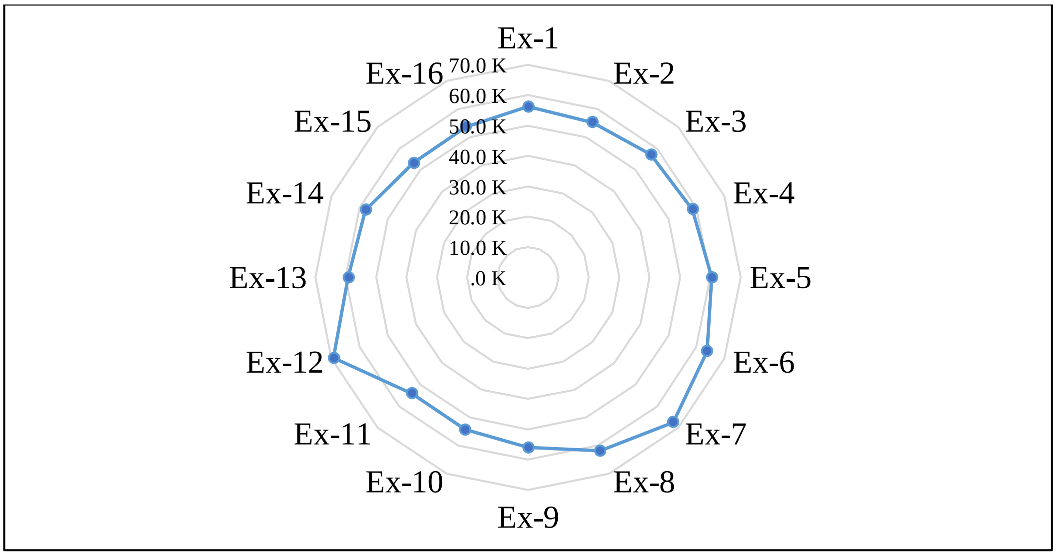


Figure 4.45 Production rate of excavators in excavation area 1 in the revised study of the year 2028

4.2.7 Production Output of Simulation Model of the Year 2029 and 2030

Two excavation areas are designed for the year 2029. Targeted annual production amount, ten days production amount, and the number of excavators of the excavation area 1 and excavation area 2 are given in Table 4.14 and Table A.3. There are 15 and 11 excavators in excavation area 1 and excavation area 2, respectively, for the year 2029. For the year 2030, there are 14 and 13 in excavation area 1 and excavation area 2, respectively. It was planned to have 280 trucks for the year 2029 and 334 trucks for the year 2030 for both excavation areas. The number of trucks could meet the production requirements for these years according to the simulation results.

Table 4.14 Production rate and number of excavators of the year 2029 of revised simulation study

Excavation Areas	**Annual Production Amount (m³)**	**10 days Production Amount (m³)**	**Number of Excavators**
Excavation-1	26,700,000	890,000	15
Excavation-2	19,300,000	640,000	11

Each excavation area has three distinct road networks that connect the production level to the dumping level, as seen in Figure 4.46. The design concept of excavation area 1 and excavation area 2 are similar to each other. Each excavation area is connected to the separate dumping area via an independent road network. For the last year, excavation area 2 is designed closer to excavation area 1 rather than other years, as seen in Figure B.3. However, the design approach is still the same with previous years. Three distinct production levels for each excavation are designed in the year 2030.

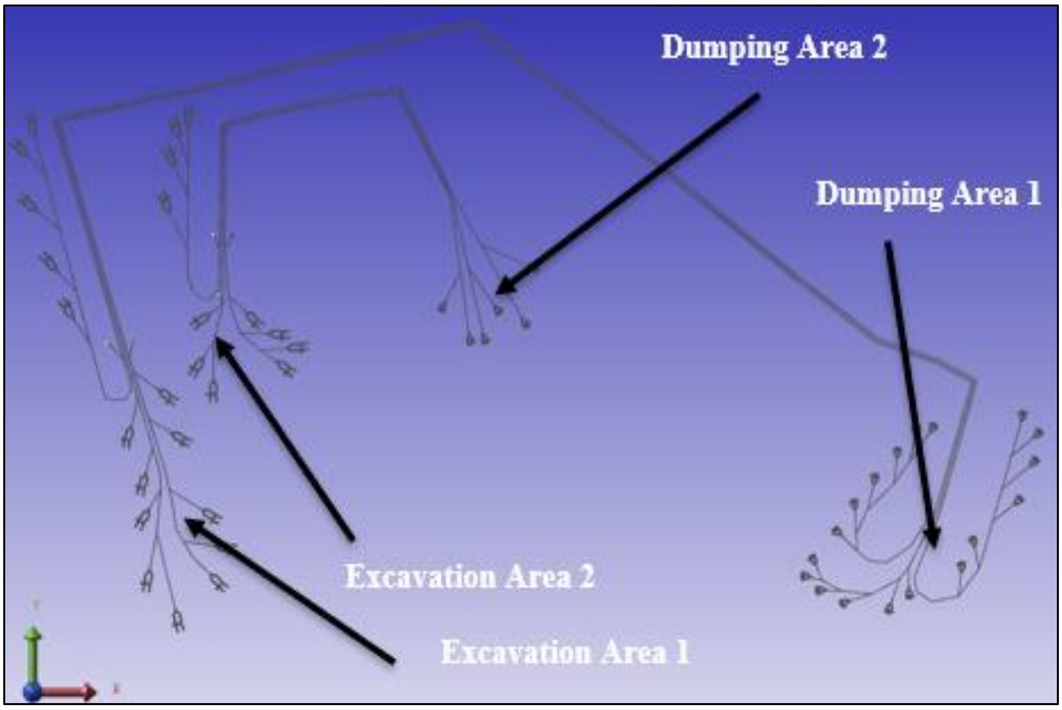


Figure 4.46 Revised road network design of the year 2029

Similar to the previous years, trucks are blocked instantly at the main roads of the year 2029, as seen in Figure 4.47. However, these blockages do not cause the decrease in production rates of the excavators' work in excavation area 1, and the targeted production amount is met. Instantaneous blockages are not significant since the targeted production rate is met; however, these states could be examined for future studies to understand the effect of these blockages on production. Blocked states should be examined for safety concerns, as well. The software allows users to define the distance between the trucks for safety reasons; however, since a considerable number of trucks are used in this operation, the fleet must be monitored to ensure that trucks keep a distance during the overburden stripping operation.

Similar traffic issues mentioned earlier for previous years are valid for the year 2030, as well. In addition, there are several sports on the main road that heavy traffic conditions occur, as seen in Figure C.3. However, these spots do not affect the production rates of the excavators.

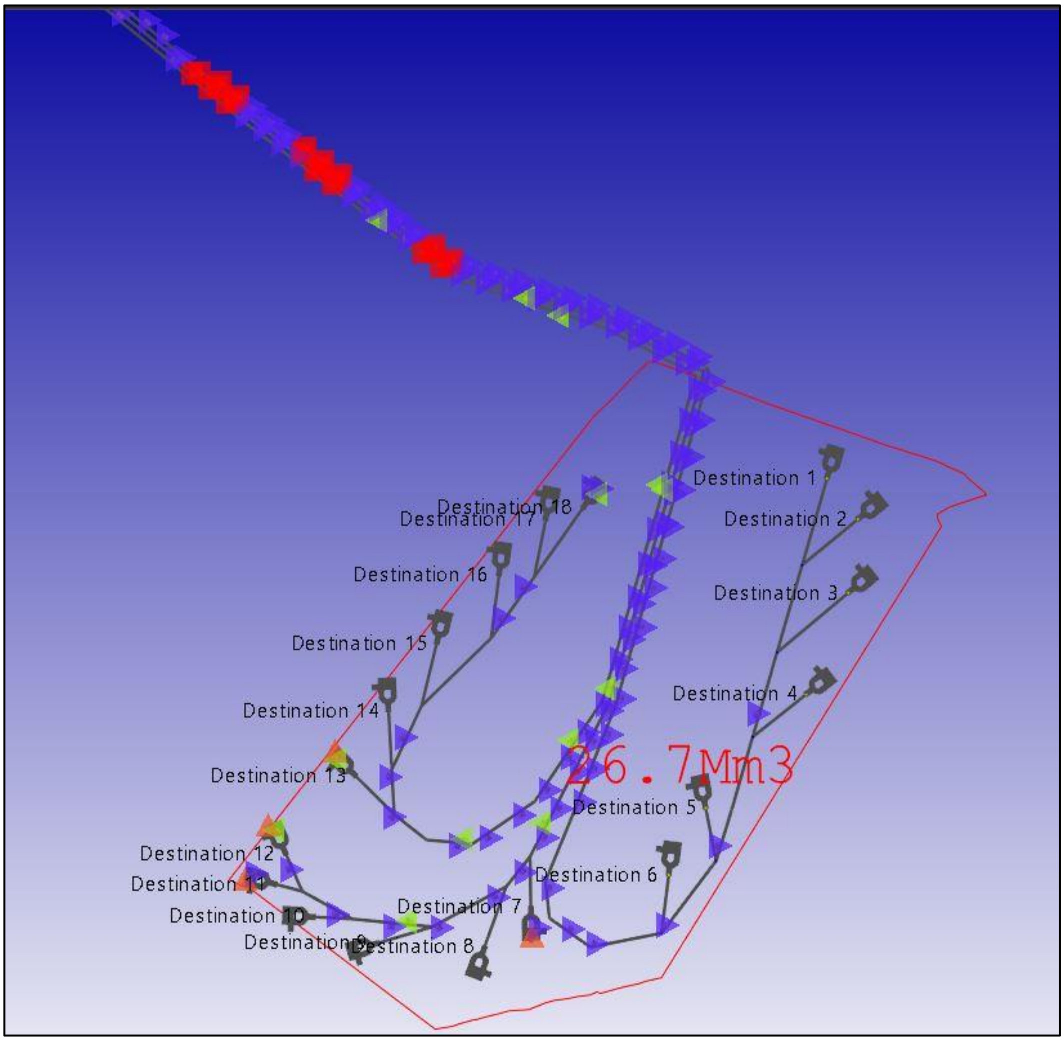


Figure 4.47 Traffic density on main roads

Production rates of the excavators' work in excavation area 1 are given in Figure 4.48. According to the results of the simulation run of the year 2029, it could be said that excavators show similar performances. Excavators 6 and 11 hold the maximum production rate in the excavation area 1.

Excavators works in production levels of the excavation area show similar performances as seen in Figure D.4 since there are no dense traffic spots on the roads connecting production level to dumping level of the year 2030.

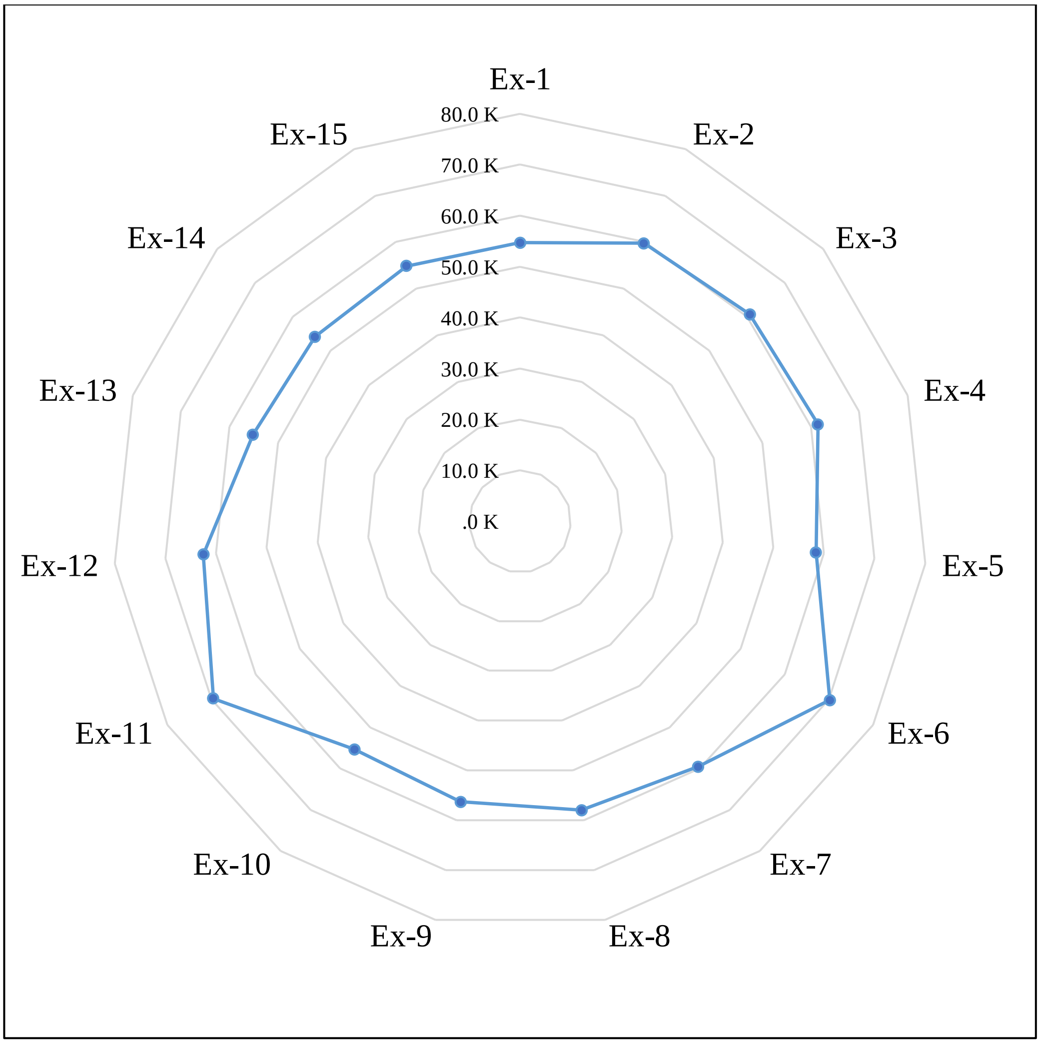


Figure 4.48 Production rate of excavators in excavation area 1 in the revised study of the year 2029

Excavator 23 and excavator 20 have the highest production rates among excavators who work in excavation area 2 of the year 2029, as seen in Figure 4.49. However, differences between the production rates of the excavators are not significant.

There are no significant differences between the production rates of the excavators that work at the excavation area 2 of the year 2030, as seen in Figure D.5. Excavators 18 and 20 hold the maximum production rate in the excavation area 2.

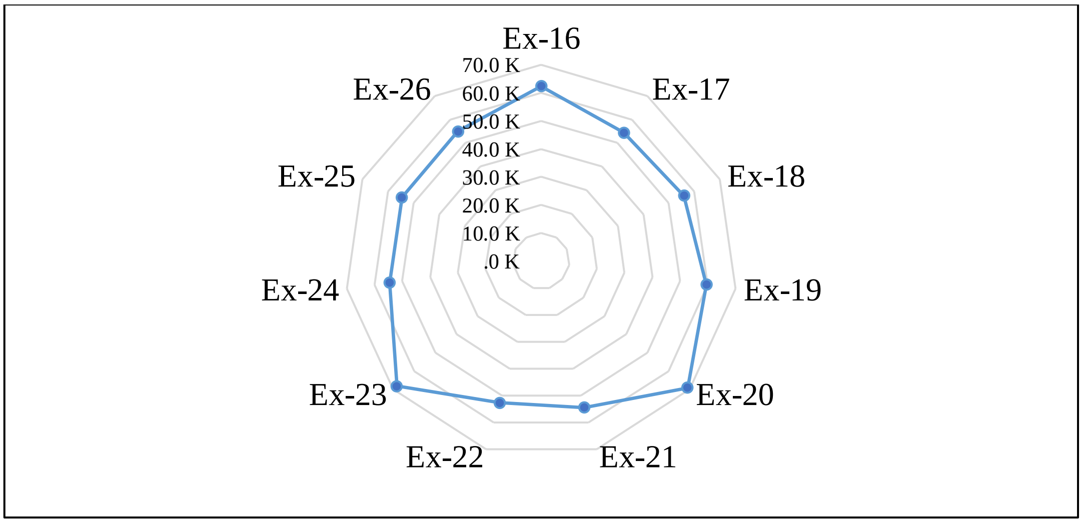


Figure 4.49 Production rate of excavators in excavation area 2 in the revised study of the year 2029

4.3 Comparison of First and Revised Studies

In the first study, five different production years are examined to understand whether available equipment is capable of meeting the targeted annual production rate or not. According to the results given in Table 4.15, during the simulation run of years 2025 and 2030, targeted annual production is almost reached by the available equipment. On the other hand, target annual productions of years 2024, 2026, and 2028 could not be met by the current equipment.

Table 4.15 Simulation results of the first simulation study

	Annual Production in First Simulation Study (m^3)	**Targeted Annual Production (m^3)**	**Available Production (%)**
2024	57,771,930	77,000,000	75
2025	72,451,710	76,000,000	95
2026	52,996,260	79,000,000	67
2028	58,749,240	76,600,000	77
2030	78,171,300	80,500,000	97

After these results were obtained, plans were revised, and roads that connect production levels to dumping levels were separated. Road network designs are revised as well to make roads more suitable for the high number of trucks. Sharp turns are eliminated, and distance between excavators is extended to avoid the queue in loading areas. As a result of these revisions, targeted annual production amounts are met for all years during the simulation studies according to the results given in Table 4.16.

Table 4.16 Simulation results of the revised simulation study

	Annual Production in Revised Simulation Study (m³)	**Targeted Annual Production (m³)**	**Available Production (%)**
2024	44,955,990	44,700,000	101
2025	49,509,120	48,700,000	102
2026	57,021,330	56,700,000	101
2028	28,157,460	28,300,000	99
2030	48,040,500	48,000,000	100

According to the comparison of the available productions of the first study and revised study given in Table 4.17, improvement in available production is not observed for the year 2025 and 2030 since available productions of these years was almost met for the first simulation study. On the other hand, maximum improvement is obtained for the year 2026 since there are significant traffic issues for the year 2026. Available production improved by 33% for the year 2026, and targeted annual production is met, as mentioned earlier.

Table 4.17 Improvement in available production

	Available Production in First Simulation Study (%)	**Available Production in Revised Simulation Study (%)**	**Improvement (%)**
2024	75	101	26
2025	95	102	6
2026	67	101	33
2028	77	99	23
2030	97	100	3

Production rates and the number of trucks used for the first and revised studies are given in Table 4.18. There is a 22% decrease in the annual production rate of the year 2024. On the other hand, a decrease in the number of trucks is recorded as 27% for 2024. According to these results, it could be concluded that overburden stripping operation in the revised study is more efficient than the first study since the decrease in the number of trucks is more than the decrease in the production rate.

Table 4.18 Comparison of production rates and number of trucks

	Annual Production in First Simulation Study (m³)	Annual Production in Revised Simulation Study (m³)	Number of Trucks in First Simulation Study	Number of Trucks in Revised Simulation Study
2024	57,771,930	44,955,990	430	316
2025	72,451,710	49,509,120	463	298
2026	52,996,260	57,021,330	362	362
2028	58,749,240	28,157,460	314	220
2030	78,171,300	48,040,500	395	334

4.4 Assessing Fuel Consumption Data

Fuel consumption data were exported from the software. The sum of fuel consumed by trucks was recorded in liters, and metric tons during the simulation runs at each state of trucks mentioned earlier, as given in Table 4.19. The software records the fuel consumption data in liters. The volume of fuel consumed is converted into the mass to calculate the carbon dioxide emissions during the production. Conversion is done by multiplying the volume of fuel consumed by the density of diesel which is 0.00085 metric tons per liter.

Table 4.19 Fuel consumption data of the year 2024

	In Liters	**In Metric Tons (x10^3)**
Total Fuel Used in First Study:	238,334,354	203
Total Fuel Used in Revised Study:	417,980,837	355

Through this chapter, the results of the investigations of carbon dioxide emissions in mining area are presented. As mentioned earlier, the Tier-1 method mentioned in the energy volume of 2019 Refinement to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories is used to calculate the total amount of carbon dioxide emitted during the production year of 2024. According to the Tier-1 calculations, 650.16 Gigagrams of carbon dioxide were emitted during the production year 2024, as given in Table 4.20.

Table 4.20 Carbon dioxide emission derivation for first simulation study of the year 2024

Step 1	**Step 2**		**Step 3**		
A Consumption (10^3 metric tons)	**B Conversion Factor (TJ/10^3 metric tons)**	**C Consumption (TJ)**	**D Carbon Emission Factor (t C/TJ)**	**E Carbon Content (t C)**	**F Carbon Content (Gg C)**
203	43.33	8777.97	20.20	177315.06	177.32
Step 4			**Step 5**		**Step 6**
G Fraction of Carbon Stored	**H Carbon Stored (Gg C)**	**I Net Carbon Emissions (Gg C)**	**J Fraction of Carbon Oxidized**	**K Actual Carbon Emissions (Gg C)**	**L Actual CO2 Emissions (Gg CO2)**
-	-	177.32	1.00	177.32	650.16

During the revised study, 1140.22 gigagrams of carbon dioxide are emitted, as given in Table 4.21. In the revised study, 75% more carbon dioxide is emitted. In both studies, 2.73 kg of carbon dioxide was emitted per liter of diesel since all parameters used to calculate carbon dioxide emission are the same for both studies.

Table 4.21 CO_2 emission derivation for revised simulation study of the year 2024

Step 1	Step 2		Step 3		
A Consumption (10^3 metric tons)	**B Conversion Factor (TJ/10^3 metric tons)**	**C Consumption (TJ)**	**D Carbon Emission Factor (t C/TJ)**	**E Carbon Content (t C)**	**F Carbon Content (Gg C)**
355	43.33	15394.44	20.20	310967.75	310.97

	Step 4		Step 5		Step 6
G Fraction of Carbon Stored	**H Carbon Stored (Gg C)**	**I Net Carbon Emissions (Gg C)**	**J Fraction of Carbon Oxidized**	**K Actual Carbon Emissions (Gg C)**	**L Actual CO2 Emissions (Gg CO2)**
-	-	310.97	1	310.97	1140.22

CHAPTER 5

CONCULUSIONS AND RECCOMMENDATIONS

5.1 Conclusions

In the scope of this thesis study, a different approach to dispatch strategy is analyzed from different points of view to understand the increasing capacity could be met by increasing the number of conventional mining equipment for selected years to study. Analyses are conducted with the discrete event simulation method by using HAULSIM® software that allows users to simulate haulage operations realistically. In the scope simulation studies, different dispatch strategies are evaluated from different perspectives, such as production rate, number of trucks, fuel consumption, and carbon dioxide emission. After the first simulation studies are completed, it is seen that existing mine and road plans are not capable of meeting the annual demand of the production. Trucks are stuck on several spots on the road network, such as excavation areas, dumping areas, and main roads. Thus, new mine and road plans are made with a new design approach. During the planning of the new mine plans, production levels are separated to avoid heavy traffic on the spots that potentially have heavy traffic conditions. In these road plans, a maximum of three to five excavators work on the same level, and each level is connected to the dumping level with a separate road network. By applying this strategy, heavy traffic conditions are avoided, production rates improved up to 33%, and targeted annual production is met for all selected years to study.

Moreover, this strategy also helps to reduce fuel consumption and carbon dioxide emission. Fuel consumption studies are carried out for the year 2024 to understand the effects of heavy traffic conditions on fuel consumption and carbon dioxide emission since heavy traffic conditions occurred in 2024. Despite there is a 22% decrease in the annual production in the revised study due to the lighter traffic density on the main road, 75% more fuel consumed during the simulation runs of the revised study of the year 2024. Similarly, 75% more carbon dioxide is emitted into the atmosphere. Despite there is an increase in overall fuel consumption, fuel consumption and carbon dioxide emission of the trucks in the blocked states are decreased. Moreover, while the decrease in production rate for the year 2024 is 22%, the decrease in the number of trucks is recorded as 27%. Decrease in fuel consumption of trucks in blocked state and decrease in the number of trucks are the indications of the increase in the efficiency of the operation.

5.2 Recommendations

The new mine plan and road design helped to increase the production rate; however, the road network designs should be prepared monthly and re-evaluated to represent the actual production more accurately. Moreover, monthly mine plans with more detail could also aid in evaluating the required number of trucks more realistically. In this case study, an availability factor was used since it was assumed that the applied factor represents the maintenance and shift change-related events of the trucks and excavators. Breakdown, repair, and maintenance data should be collected and implemented to represent the actual case more accurately in the proposed dispatch model. The simulation software allows users to use maintenance data or define a probabilistic breakdown function for each piece of equipment. This study assumed that the road conditions are good, and maintenance of the road is carried out in periodic time intervals. It should be considered that; unfavorable weather conditions will change the equipment efficiency, and because of that, the average speed of trucks could decrease. Through this study, a single-sided loading approach was used for loading operation. However, double-sided loading could also be considered to increase the efficiency of the dispatch system. While considering the double-sided loading approach, the number and specifications of required auxiliary equipment should also be considered. Since there are many trucks operated on-site, trucks should be monitored in real-time to increase the efficiency of the operation. A fleet management system (FMS) is suggested as loading time, maneuvering time, production amount, the average speed of trucks, and queuing time can be monitored instantaneously. By monitoring these operations instantaneously, targeted production amounts could be met. FMS is also essential in terms of occupational health and safety as well. Operator efficiency was assumed as the same for all operators. However, in real the case, there will be differences between the efficiencies of operators. FMS can also monitor the operator efficiency instantaneously, and feedback could be provided to operators.

REFERENCES

Almgren, T. (1990). Probabilistic time planning for underground mines. International Journal of Mining and Geological Engineering, 8(2), 91–109. https://doi.org/10.1007/BF00920498

Bharathan, B., Sasmito, A. P., & Ghoreishi-Madiseh, S. A. (2017). Analysis of energy consumption and carbon footprint from underground haulage with different power sources in typical Canadian mines. Journal of Cleaner Production, 166, 21–31. https://doi.org/10.1016/j.jclepro.2017.07.233

Billhardt, H., Fernández, A., Lemus, L., Lujak, M., Osman, N., Ossowski, S., & Sierra, C. (2014). Dynamic coordination in fleet management systems: Toward smart cyber fleets. IEEE Intelligent Systems, 29(3), 70–76. https://doi.org/10.1109/MIS.2014.41

Bogert, J. R. (1964). Electronic eyes and ears monitor pit operations. Met. Min. Process.

Brannon, C. A., Carlson, G. K., & Casten, T. P. (1992). Block Caving in SME Mining Engineering Handbook 2nd Edition Volume 1 (Vol. 1).

Chaowasakoo, P., Seppälä, H., Koivo, H., & Zhou, Q. (2017). Improving fleet management in mines: The benefit of heterogeneous match factor. European Journal of Operational Research. https://doi.org/10.1016/j.ejor.2017.02.039

Diesel Engine Reference Book. (1999). In B. Challen & R. Baranescu (Eds.), Butterworth-Heinemann. https://doi.org/10.1016/0378-3804(87)90022-2

Dindarloo, S. R., & Siami-irdemoosa, E. (2016). Determinants of fuel consumption in mining trucks. Energy, 112, 232–240. https://doi.org/10.1016/j.energy.2016.06.085

Douglas, J. (1964). Prediction of Shovel-Truck Production: A Reconciliation of Com- puter and Conventional Estimates. Issue 37 of Technical Report (Stanford

Univer- Sity Department of Civil Engineering), Department of Civil Engineering, Stanford University.

EIA. (2019). EIA projects nearly 50% increase in world energy usage by 2050, led by growth in Asia - Today in Energy - U.S. Energy Information Administration (EIA). 24.09.2019.

European Commision. (2019). A European Green Deal | European Commission. European Commission, 24. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

European Commission. (2016). Transport emissions | Climate Action. EU Commission. https://ec.europa.eu/clima/policies/transport_en#tab-0-0

Golbasi, O., & Turan, M. O. (2020). A discrete-event simulation algorithm for the optimization of multi-scenario maintenance policies. Computers and Industrial Engineering, 145(May), 106514. https://doi.org/10.1016/j.cie.2020.106514

Hoare, R. T., & Willis, R. J. (1992). A Case Study of Animated Computer Simulation in the Australian Mining Industry. The Journal of the Operational Research Society, 43(12), 1113–1120.

International Energy Agency. (2019). Electricity Information 2019 Final Edition Database Documentation. https://iea.blob.core.windows.net/assets/ad39859e-97e3-4dd7-ad2d-845da89e6737/Ele_documentation.pdf

International Energy Agency. (2020). World Energy Balances 2020 Edition. 112.

IPCC. (2005). Carbon Dioxide Capture and Storage (B. Metz, O. Davidson, H. de Coninck, M. Loos, & L. Meyer (Eds.)).

IPCC. (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. In S. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici (Ed.), IPCC, Switzerland (Vol. 2). https://doi.org/10.21513/0207-2564-2019-2-05-13

Jassim, H. S. H., Lu, W., & Olofsson, T. (2018). Assessing energy consumption and carbon dioxide emissions of off-highway trucks in earthwork operations: An artificial neural network model. Journal of Cleaner Production, 198, 364–380. https://doi.org/10.1016/j.jclepro.2018.07.002

Kelton, W. D., Sadowski, R. P., & Swets, N. B. (2010). Simulation with Arena (5th ed.).

Law, A. M., Kelton, W. D., & Schervish, M. J. (2015). Simulation Modeling and Analysis. In Journal of the American Statistical Association (Vol. 78, Issue 383). https://doi.org/10.2307/2288169

Moradi Afrapoli, A., & Askari-Nasab, H. (2019). Mining fleet management systems: a review of models and algorithms. International Journal of Mining, Reclamation and Environment. https://doi.org/10.1080/17480930.2017.1336607

Moradi Afrapoli, A., Tabesh, M., & Askari-Nasab, H. (2019). A multiple objective transportation problem approach to dynamic truck dispatching in surface mines. European Journal of Operational Research. https://doi.org/10.1016/j.ejor.2019.01.008

Morgan, W., & Peterson, L. (1964). Determining shovel-truck productivity. Mining Engineering.

Mueller, E. R. (1977). Simplified dispatching board boosts truck productivity at Cyprus Pima. Min. Eng. Littleton.

Ozdemir, B., & Kumral, M. (2019). Simulation-based optimization of truck-shovel material handling systems in multi-pit surface mines. Simulation Modelling Practice and Theory. https://doi.org/10.1016/j.simpat.2019.04.006

Peralta, S., Sasmito, A. P., & Kumral, M. (2016). Reliability effect on energy consumption and greenhouse gas emissions of mining hauling fleet towards sustainable mining. Journal of Sustainable Mining, 15(3), 85–94. https://doi.org/10.1016/j.jsm.2016.08.002

Rist, K. (1961). The solution of a transportation problem by use of a Monte Carlo technique. Proceedings of the 1st International Symposium on Computer Application in Mining (APCOM-I), L2.

Robinson, S., Brooks, R., Kotiadis, K., & van der Zee, D.-J. (Eds.). (2011). Conceptual Modelling for Discrete-Event Simulation.

Rodovalho, C., Mota, H., & Tomi, G. De. (2016). New approach for reduction of diesel consumption by comparing different mining haulage configurations. Journal of Environmental Management, 172, 177–185. https://doi.org/10.1016/j.jenvman.2016.02.048

Ta, C. H., Ingolfsson, A., & Doucette, J. (2013). A linear model for surface mining haul truck allocation incorporating shovel idle probabilities. European Journal of Operational Research, 231(3), 770–778. https://doi.org/10.1016/j.ejor.2013.06.016

Upadhyay, S. P., & Askari-Nasab, H. (2018). Simulation and optimization approach for uncertainty-based short-term planning in open pit mines. International Journal of Mining Science and Technology. https://doi.org/10.1016/j.ijmst.2017.12.003

Wang, Q., Zhang, R., Lv, S., & Wang, Y. (2021). Open-pit mine truck fuel consumption pattern and application based on multi-dimensional features and XGBoost. Sustainable Energy Technologies and Assessments, 43(July 2020), 100977. https://doi.org/10.1016/j.seta.2020.100977

Yilmaz, E., & Erkayaoglu, M. (2021). A Discrete Event Simulation and Data-Based Framework for Equipment Performance Evaluation in Underground Coal Mining. Mining, Metallurgy and Exploration, 0123456789. https://doi.org/10.1007/s42461-021-00455-2

Zhang, F., Obeid, E., Bou Nader, W., Zoughaib, A., & Luo, X. (2021). Well-to-Wheel analysis of natural gas fuel for hybrid truck applications. Energy Conversion and Management, 240(May), 114271. https://doi.org/10.1016/j.enconman.2021.114271

APPENDICES

APPENDIX A: TARGETED PRODUCTIONS AND NUMBER OF EXCAVATORS

Table A. 1 Production rate and number of excavators of the year 2022 of revised simulation study

Excavation Area	Annual Production Amount (m³)	10 Days Production Amount (m³)	Number of Excavators
Excavation-1	20,600,000	690,000	11

Table A. 2 Production rate and number of excavators of the year 2026 of revised simulation study

Excavation Areas	Annual Production Amount (m³)	10 Days Production Amount (m³)	Number of Excavators
Excavation-1	32,600,000	1,090,000	18
Excavation-2	24,100,000	800,000	13

Table A. 3 Production rate and number of excavators of the year 2030 of revised simulation study

Excavation Areas	Annual Production Amount (m³)	10 Days Production Amount (m³)	Number of Excavators
Excavation-1	24,500,000	820,000	14
Excavation-2	23,500,000	780,000	13

APPENDIX B: REVISED ROAD NETWORK DESIGNS

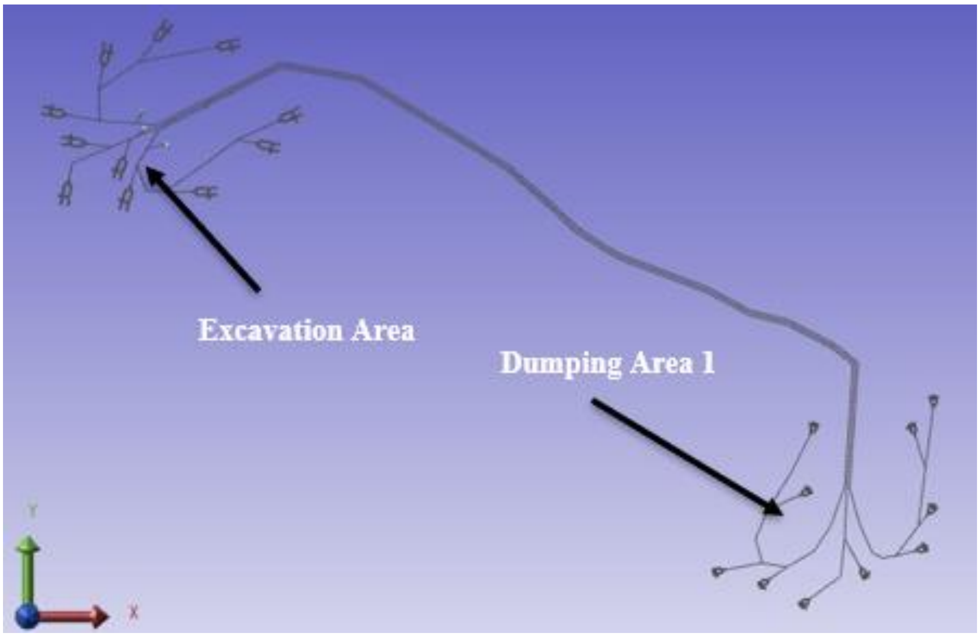


Figure B. 1 Revised road network design of the year 2022

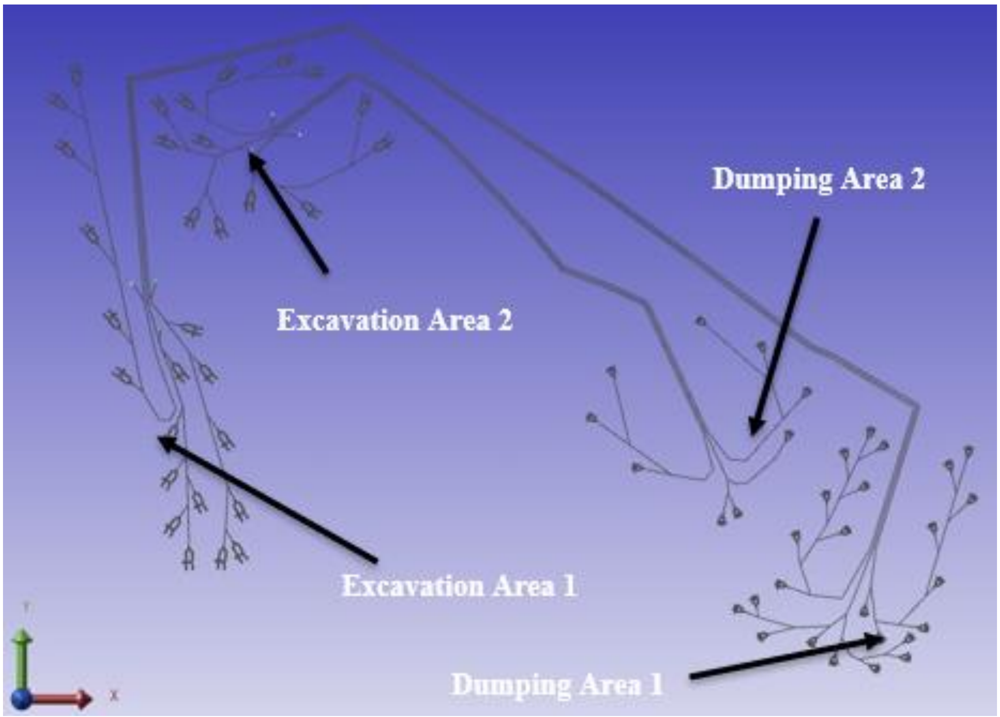


Figure B. 2 Revised road network design of the year 2026

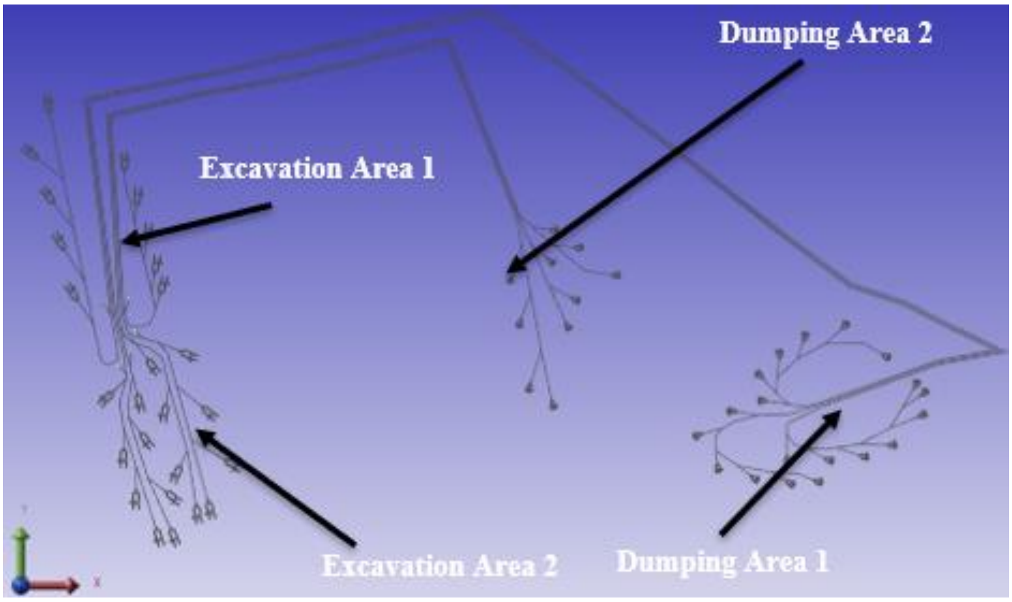


Figure B. 3 Revised road network design of year 2030

APPENDIX C: TRAFFIC DENSITY

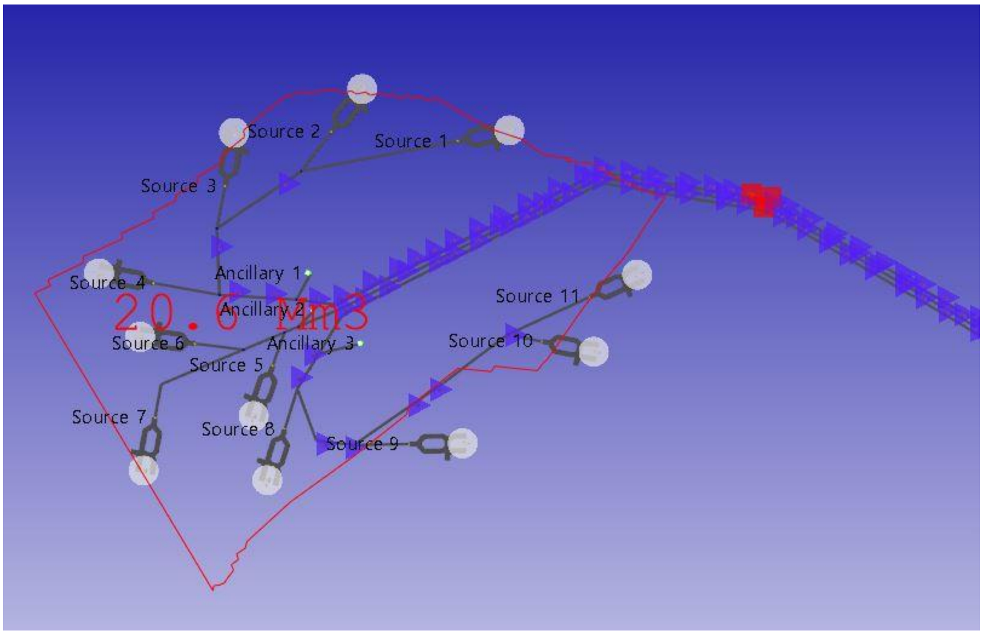


Figure C. 1 Traffic density in excavation area

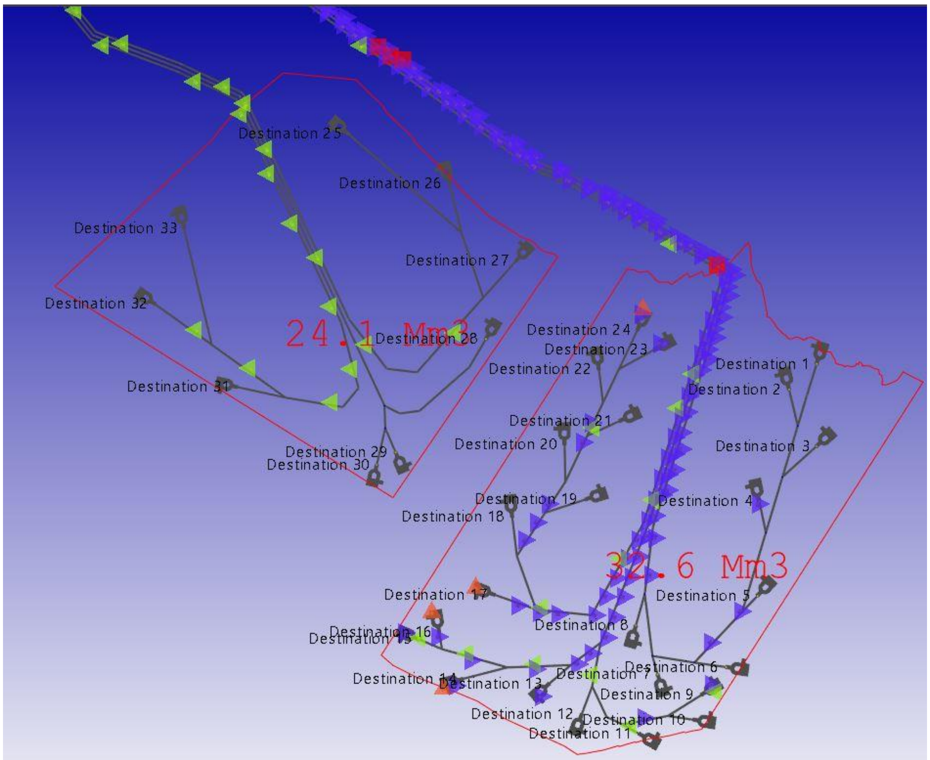


Figure C. 2 Traffic density in dumping areas

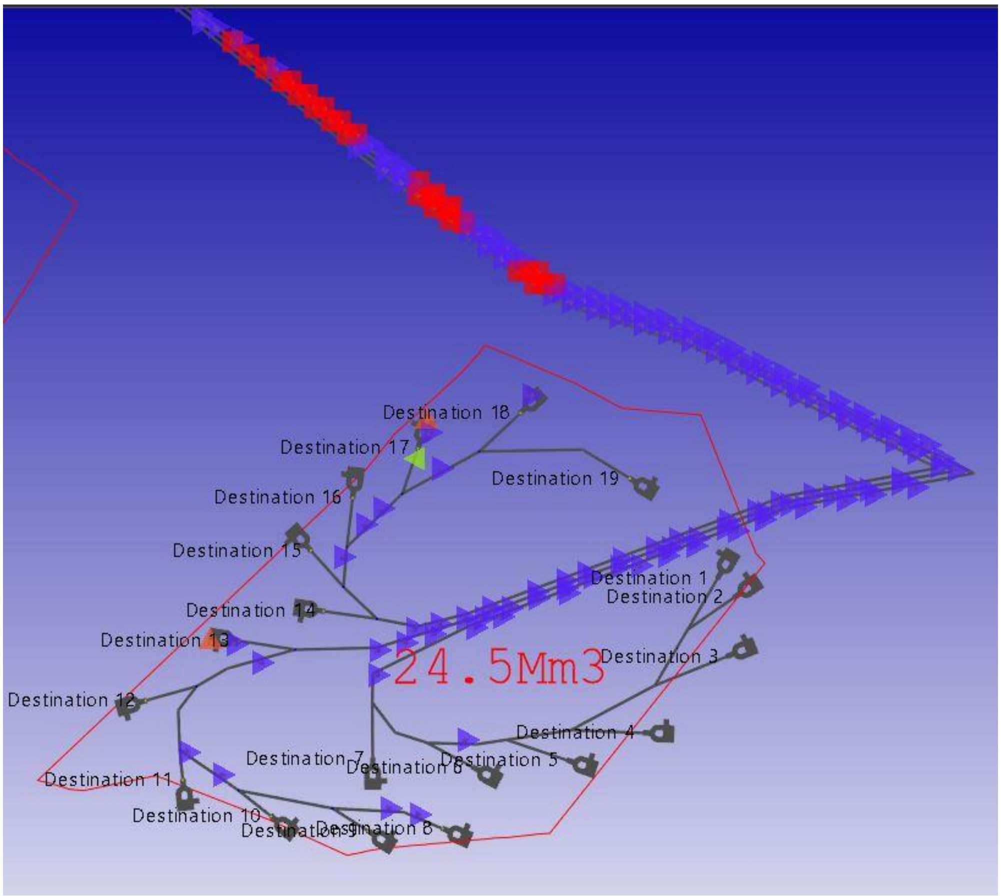


Figure C. 3 Traffic density on main roads

APPENDIX D: PRODUCTION RATES OF EXCAVATORS

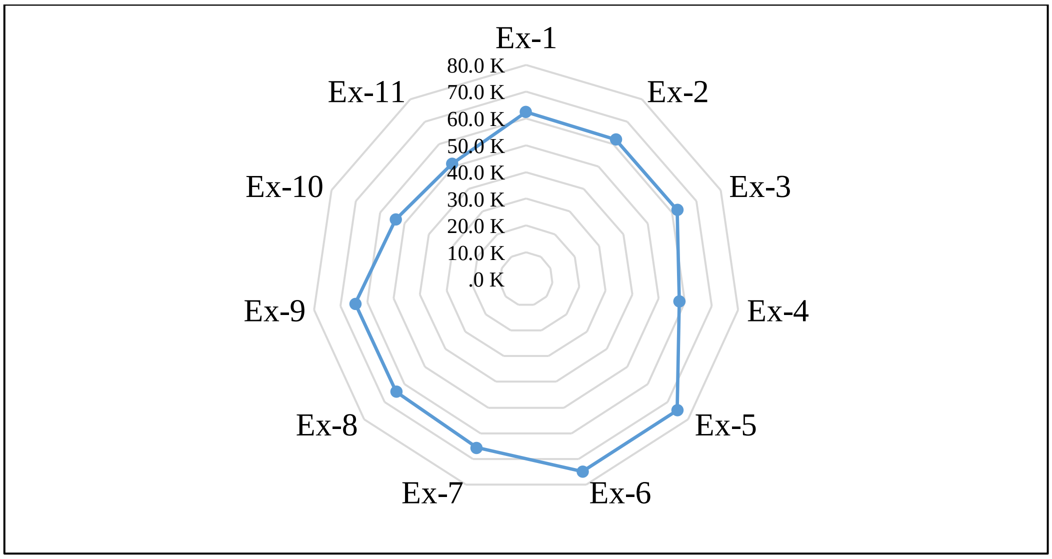


Figure D. 1 Production rate of excavators in excavation area 1 in the revised study of the year 2022

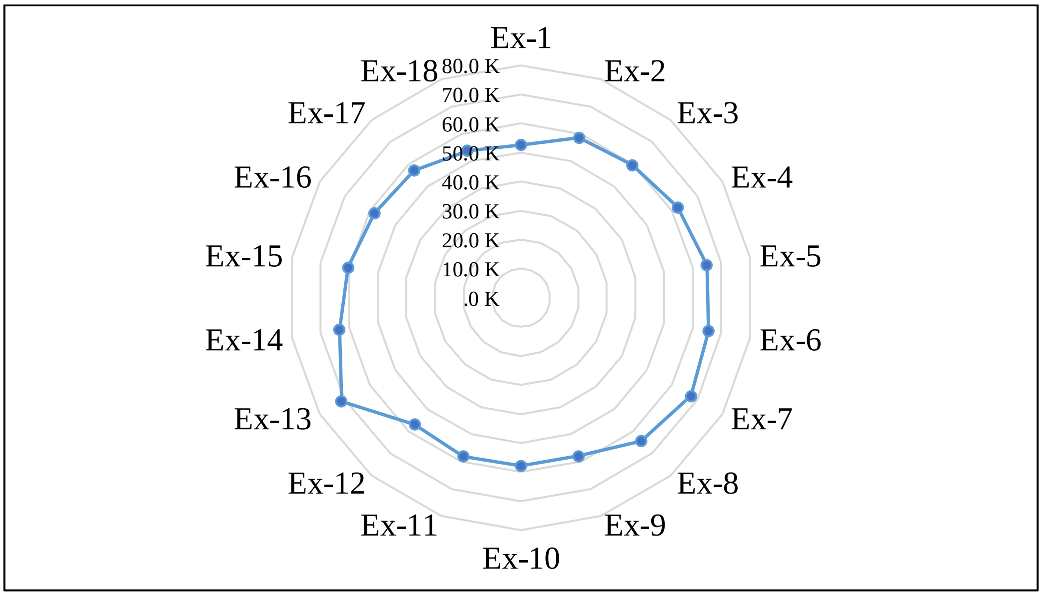


Figure D. 2 Production rate of excavators in excavation area 1 in the revised study of the year 2026

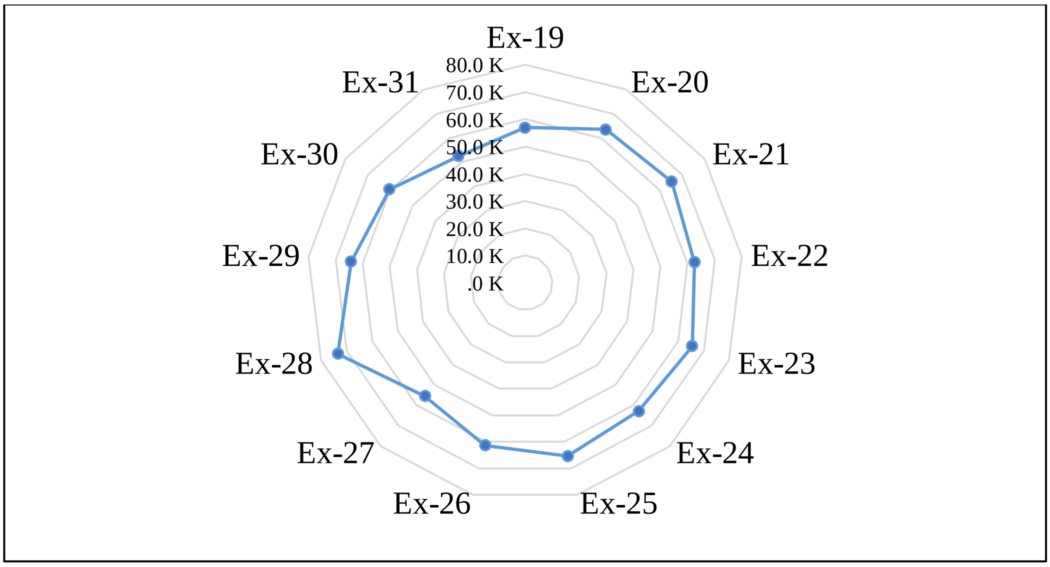


Figure D. 3 Production rate of excavators in excavation area 2 in the revised study of the year 2026

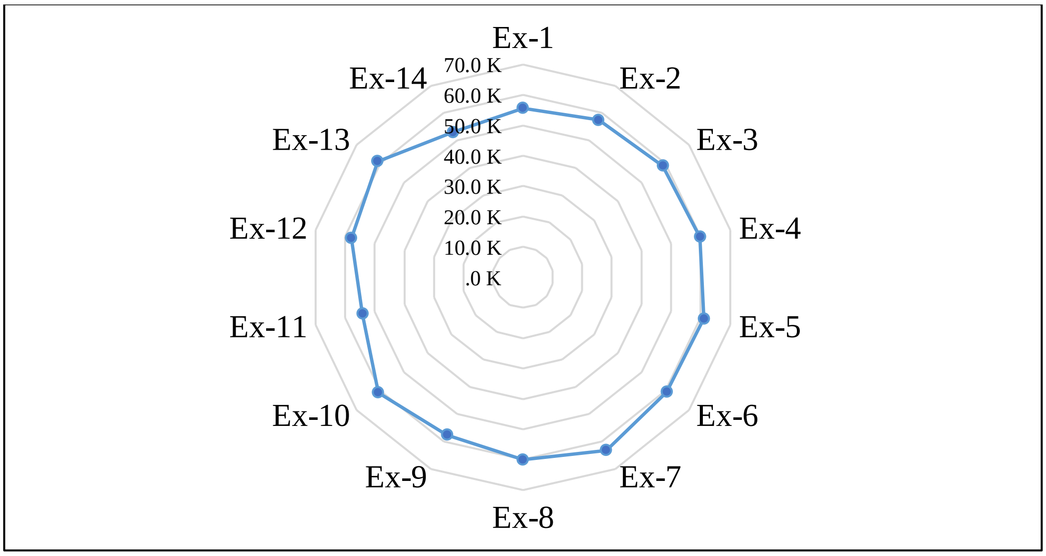


Figure D. 4 Production rate of excavators in excavation area 1 in the revised study of the year 2030

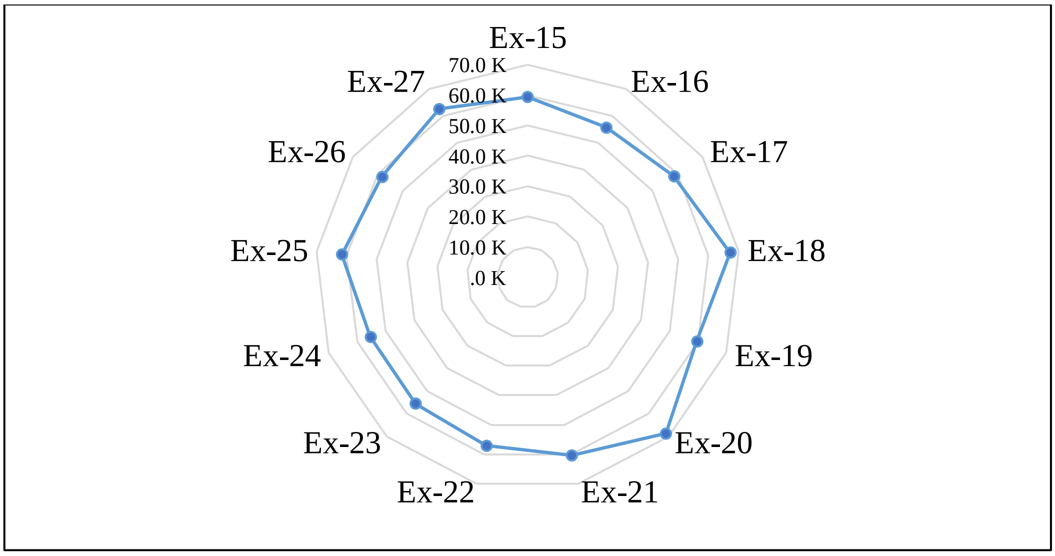


Figure D. 5 Production rate of excavators in excavation area 1 in the revised study of the year 2030