SIMULATION-BASED EVALUATION OF BLASTHOLE DRILLING KEY PERFORMANCE METRICS IN SURFACE MINING

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ABSTRACT

SIMULATION-BASED EVALUATION OF BLASTHOLE DRILLING KEY PERFORMANCE METRICS IN SURFACE MINING

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Open-pit mining is prominently recognized as one of the principal techniques in surface mines. In this complex process, operations flow smoothly from the initial stages of drilling and blasting to the subsequent steps of loading and hauling the material. In nearly all mining methods, drilling and blasting are the common techniques for rock breakage. Generally, drilling is performed to open holes where explosives can be placed to blast material for production. This condition highlights the importance of drilling and blasting within the broader context of mining operations.

The multifunctional role of drilling is observed in a range of mining activities, from aiding in the in-depth exploration of mineral deposits, creating precise blast holes, playing a role in soil stabilization through grouting, ensuring adequate drainage mechanisms, to fortifying the mining terrain through ground support. Here, the current thesis study intends to develop an advanced event simulation algorithm tailored to clarify the dynamic interplay occurring during the production drilling operations at open-pit mines. This algorithm is designed to monitor, quantify, and evaluate the Key Performance Indicators (KPIs) of the production drilling operations where multiple and interactive uncertainties can arise.

Using event analysis simulations becomes vital in understanding primary and secondary factors involved in drilling activities. These flowcharts highlight the complex interactions and help to reveal the variability in performance across different components of a drilling operation. By employing such a comprehensive approach, operators can be equipped to account for and manage uncertainties due to changing operational, environmental, and equipment conditions. This enhanced perspective offers a more robust framework for decision-making and fine-tuning drilling processes to maximize efficiency. This study shows that geological structures, especially the distinction between clay/mud and rock materials, significantly impact penetration rates. While the average penetration rate in a complex environment (both clay/mud and rock) is 1.36 m/min, it can drop to as low as 0.66 m/min when confronted with clay or muddy materials. Penetration rates are directly influenced by these geological structures, leading to a 51% reduction in this instance. In addition, maintenance policies play a crucial role in equipment reliability, with proactive approaches often resulting in reduced downtime and reinforced operational efficiencies. The study identified that, within a year, a total of 225 malfunctions occurred due to the failures in driller components. Remarkably, 50% of these failures stemmed from bit wear. Moreover, operator competency stands out as another critical factor influencing drilling operations. Experienced crews can harness machinery optimally, achieving superior performance. Last, prolonged halts, averaging 300 hours per year, mainly due to weather conditions, emphasize the necessity for adaptable operational strategies. Analysis results affirm that equipment, when regularly maintained and monitored, and operated by skilled crews across varied geological settings, ensures optimal drilling operations.

Keywords: Surface Mining, Blasthole Drilling, Driller (Drill Rig), Key Performance Indicators, Discrete-Event Simulation

ÖZ

AÇIK OCAK MADENCİLİĞİNDE PATLATMA DELGİLERİ İÇİN ANAHTAR PERFORMANS GÖSTERGELERİNİN SİMÜLASYON TABANLI DEĞERLENDİRİLMESİ

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Açık ocak madenciliği, yüzeyden maden çıkarma metodolojilerindeki başlıca tekniklerden biri olarak öne çıkmaktadır. Bu karmaşık süreçte, delme ve patlatma ile başlayıp yükleme ve taşıma ile devam eden operasyonel döngü sorunsuz bir şekilde ilerler. Neredeyse tüm madencilik yöntemlerinde, delme ve patlatma kayayı parçalamak için kullanılan yaygın tekniklerden biridir. Genel olarak delgi, üretim için yapılan patlatma işlemlerinde patlayıcıların yerleştirileceği delikleri oluşturmak için kullanılmaktadır. Bu durum, delme ve patlatmanın madencilik alanındaki önemli rolünün altını çizmektedir.

Delgilerin çok işlevli rolü, maden yataklarının derinlemesine araştırılmasına yardımcı olmaktan, hassas patlatma delikleri oluşturmaya, enjeksiyon yoluyla toprak stabilizasyonunda rol oynamaya, yeterli drenaj mekanizmaları sağlamaya ve zemin desteği yoluyla madencilik arazisini güçlendirmeye kadar bir dizi madencilik faaliyetini kapsar. Bu bilgiler ışığında, bu çalışma, açık ocak madenlerindeki üretim delgi operasyonları sırasında meydana gelen dinamik etkileşimi netleştirmek için özel olarak tasarlanmış gelişmiş bir olay simülasyon algoritması oluşturmak için kapsamlı bir yolculuğa çıkmaktadır. Bu algoritma, sadece gözlemlemek için değil,

aynı zamanda açık ocak madencilik alanlarının geniş yelpazesinde üretim delgilerinin verimliliğini belirleyen Anahtar Performans Göstergelerini (APG) detaylı bir şekilde ölçmek için kalibre edilmiştir.

Olay analizi akış şemalarının kullanımı, delgi faaliyetlerinde yer alan birincil ve ikincil faktörler arasındaki karmaşık etkileşimin anlaşılmasında hayati önem taşımaktadır. Bu akış şemaları yalnızca karmaşık dinamikleri aydınlatmakla kalmaz, aynı zamanda bir delgi operasyonunun farklı bileşenleri arasındaki performans değişkenlerine de ışık tutmaya yardımcı olur. Operatörler böylesine kapsamlı bir yaklaşım kullanarak, değişen operasyonel koşullar nedeniyle ortaya çıkan belirsizlikleri hesaba katmak ve yönetmek için daha donanımlı hale gelirler. Bu gelişmiş bakış açısı, verimliliği en üst düzeye çıkarmak için karar verme ve delgi süreçlerine hakim olmak konusunda daha sağlam bir çerçeve sunar. Bu çalışmada, özellikle kil/çamur ve kaya zemin arasındaki ayrım olmak üzere jeolojik yapıların, penetrasyon oranı üzerinde önemli bir etkisi vardır. Ortalama penetrasyon hızı karmaşık bir ortamda (kil/çamur ve kaya içeren ortam) 1.36 m/dakika iken, kil veya çamurlu yüzeylerle karşılaşıldığında 0.66 m/dakika'ya kadar düşmektedir. Penetrasyon oranları doğrudan jeolojik yapılar tarafından etkilenmektedir. Bu durumda, penetrasyon oranında %51'lik bir azalma olmuştur. Bakım politikaları, ekipman güvenilirliğini doğrudan etkiler ve proaktif stratejiler genellikle daha az duruş süresi ve gelişmiş operasyonel verimliliklerle sonuçlanır. Yapılan çalışmada, bir yıl içerisinde delici ekipman parçalarının aşınmasından/yıpranmasından kaynaklı toplam 225 arıza meydana gelmiştir. Arızaların %50'si bit aşınmasından kaynaklanmaktadır. Ekip yetkinliği de kritik olan ve delgi operasyonunu etkileyen faktörlerden biridir. Deneyimli ekipler, makineleri optimize ederek üstün performans elde edebilirler. Buna ek olarak, özellikle hava koşullarından kaynaklı ortalama 300 saat/yıl süren uzun duruşlar, uyarlamalı operasyon stratejilerinin gerekliliğini vurgulamaktadır. Analiz sonuçları, bakım ve onarımı düzenli yapılıp kontrol edilen ekipmanların, çeşitli jeolojik yapılarda yetenekli ekipler tarafından işletilmesinin, optimal delgi operasyonu sağladığını göstermektedir.

Anahtar Kelimeler: Açık Ocak Madenciliği, Üretim Delgisi, Delici Makine, Anahtar Performans Göstergeleri, Ayrık Olay Simülasyonu

To My Family

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CHAPTER 1

INTRODUCTION

1.1 Background

Mining refers to extracting valuable minerals or other geological materials from the earth’s crust. Mining is a multidisciplinary field involving aspects of geology, engineering, economics, and environmental science, and it needs the accomplishment of several stages, such as exploration, development, extraction, processing, and closure. Exploration identifies potential mineral deposits through various methods, such as geological mapping, geophysical surveys, and drilling. Once a potential deposit is identified, the development stage is started after validating its feasibility with economic and technical considerations. It requires constructing access roads, additional drilling activities to better understand the geology and composition of the deposit and conducting environmental assessments. The extraction stage is needed to remove the valuable mineral or ore from the deposit with changeable methods, depending on the type of deposit and the available technology. The processing stage separates the valuable minerals or metals from the gangue material and coordinates crushing, grinding, and various chemical and physical processes, depending on the type of deposit and the desired product. Finally, the closure stage is completed by decommissioning the mine site and restoring the surrounding environment to its original state by removing equipment and infrastructure, re-vegetating the area, and monitoring the site for environmental impacts in the years following closure.

One of the most widely employed activities from exploration to the end of mine is drilling activity. Drilling can be performed differently as exploration, production, and pre-split drilling for different purposes, such as acquiring crushed or core samples in exploration stages to define waste and ore materials' content and geomechanical properties, developing empty spaces to charge for blasting in pre-blasting activities (production and pre-split drilling) and acquiring grade control samples from the boreholes. Pre-blasting drills require various types of drilling equipment, depending on the nature of the relevant rock material and the drill size required. It is a critical activity in mining operations since the effectiveness of blasting and the resultant production rates are affected remarkably in cases where drilling is not performed in compliance with the required design parameters and the pre-determined schedule. Drillers with varying advance rates and bit diameters are employed in these pre-blasting operations concerning energy requirements for the unit volume of blasted material. On this basis, several uncertainties related to pre-blasting drilling stages may become available in the field and affect the overall productivity and profitability of mining activities. For a comprehensive understanding of production drilling activities, it is required to consider i) geological uncertainties such as geologic structures, groundwater condition, availability of clay, mineralogy of rock and rock properties, ii) equipment uncertainties such as capacity and capabilities of drilling equipment and their availability and maintainability concerns, iii) weather and environmental conditions including seasonal changes, topography, extremely hot and cold conditions, and iv) drilling crew competency. At this point, event simulations can help to construct the dependencies between major and minor parameters available in those activities and measure the performance variations of drillers and their performance indicators in varying working conditions.

1.2 Problem Statement

Different aspects influence the effectiveness and sustainability of drilling performance. Problems associated with unfavorable drilling operations can disrupt waste and ore production and lead to safety deficiencies following blasting operations. Multiple uncertainties should be addressed to fully understand a production drilling operation. These uncertainties are generally due to the uncertainties in i) geological formations in the operation area, ii) failure rates of driller components, iii) weather and environmental conditions, iv) drilling crew competency, and iv) managemental considerations. Therefore, characteristics of the production area, driller fleet configuration, formational alteration types, maintenance policy available in the area, age and surviving behaviors of drillers, frequencies of different failure modes, and weather conditions are required to be evaluated jointly.

1.3 Objectives and Scopes of the Study

The main objective of this study is to analyze the dependencies that can be available in a pre-blasting drilling operation by developing a discrete-event simulation algorithm. Through the simulation, mining companies can evaluate different drilling patterns, drill rig (driller) configurations, and equipment maintenance schedules and optimize the drilling process to improve performance and reduce costs. The developed algorithm can help to derive policies to improve equipment availability, reduce stoppage during operation, increase the performance of drillers, and enhance drilling advance.

The study focuses on production drilling KPIs in surface mining areas. The discrete-event simulation technique was used to simulate the drilling process. Drilling parameters, site geology, rock properties, weather conditions, equipment reliability and maintenance, and crew competency were utilized to build the algorithm. The algorithm was also implemented for an actual drilling operation embodying seven different drillers, nine driller operators, and different formation types in an open pit mine.

1.4 Research Methodology

The study employs a stochastic and dynamic simulation technique to investigate production drilling KPIs at surface mining areas. The research methodology of the study entails the following steps:

i. Identification of a production drilling system
    a. Identifying the system components (variables, parameters, and constraints)
    b. Evaluation of technical and hypothetical datasets to be used for initial trials

ii. Development of a dynamic drilling simulation algorithm
    a. Introducing system configuration into a simulation environment
    b. Integration of drilling procedures and policies
    c. Debugging and verification steps

iii. Generation of Scenarios for a Case Study
    a. Validation of the algorithm using a real dataset
    b. Monitoring key performance indicator results

iv. The sensitivity analysis
    a. Sensitivity analysis of the system outputs, parameters, costs, and equipment performance
    b. Optimizing the strategies particular to the case study

1.5 Expected Contributions of This Thesis

The current study intends to develop an event simulation algorithm for production drilling operations in surface mines for a detailed evaluation of the triggering factors effective in the drilling key performance indicators. The model will consider daily drilling pattern geometry, formational differences in each pattern that may change the advance rate of the driller, configuration and reliability of drillers, driller operator behaviors, and the available operation downtime factors. In this way, it is expected to improve the availability and utilization of drillers and the performance of drilling operations by revealing the dynamic interactions in the system. The study will provide insights into the system's behavior under different conditions, including drilling parameters, geology and rock characteristics, weather conditions, equipment reliability, and human factors. The decision-makers of the relevant fields can use the algorithm to reveal bottleneck points of their drilling activities in terms of drilling profiles of equipment, and potential internal and external uncertainties that can interrupt the activities.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a comprehensive literature review and background information on drilling and event simulations. First, some background information on drilling will be provided to better understand the thesis topic. After that, KPIs that affect production drilling operations and the related uncertainties will be discussed. Then, the factors affecting drilling activities' overall productivity and profitability will be evaluated. Later, the previous studies conducted to improve drilling operations are comparatively discussed. This section is concluded by theory and mining applications of event simulation, the computational method utilized in the current study.

2.1 Background Information about Drilling Operations

Drilling is a process that creates an empty space in solid materials, such as the earth, wood, metal, or other surfaces, using specialized tools and equipment. Over the years, it has played a crucial role in numerous applications, ranging from exploration and extraction of natural resources, construction, and engineering to scientific research and medical procedures. One of the primary uses of drilling is to extract natural resources such as oil, gas, and minerals from the earth's crust. It is typically done by drilling wells or boreholes, which can also access deep underground deposits. Since the late 19th century, the petroleum industry has relied heavily on drilling to access underground crude oil and natural gas reservoirs. This condition has led to the development of sophisticated drilling techniques, such as rotary drilling, which employs a rotating drill bit to cut through rock formations and reach the target resource. The oil and gas extracted from these drilling operations have provided fuel and energy for the modern world, powering transportation, heating homes, and generating electricity. In 1859, William Smith and Edwin Drake drilled the first oil well in Titusville, Pennsylvania, using a steam-powered rotary drill (Curiale, 2017). It was a significant breakthrough that revolutionized the oil industry and led to the development of modern drilling techniques.

Typically, there are two main techniques for drilling, the cable or percussion method and the rotary or boring method. Percussion drilling is a method of drilling where an impact tool or bit is repeatedly dropped onto the bottom of the hole to crush the rock. A cuttings basket is attached to the mechanism to trap debris, emptying after a few impacts before the process is repeated. In the earliest drilling operations in Pennsylvania, manila hemp or steel ropes were used to suspend the wooden rods and drilling tools, which later became the most common drilling method across the United States. However, percussion drilling lost popularity in the 1930s and practically disappeared from oilfields by the early 1950s, giving way to newer techniques. Wooden cable tools were favored for speculative drilling work due to their low operating costs and ability to penetrate greater depths. Once a well was completed or abandoned, the derrick would often be left standing and stripped of any materials that could be salvaged or left to decay. These rigs were not considered economically efficient enough for continuous drilling operations. On the other hand, rotary drilling involves a constant circular motion of the entire drill string from the surface to turn the drill bit and break rock at the bottom of the hole. Unlike percussion drilling, rotary drilling is nearly continuous, making it more efficient. When using rotary drilling, drilling fluids circulate all over the bit and up the wellbore to the surface, removing cuttings along the way. It means the process is almost continuous and more efficient than percussion drilling. The first rotary rig for oil exploration was installed in 1894, and it quickly gained popularity relative to percussion rigs in the following decades. The Spindletop well was drilled with a rotary rig (Douet, 2020). The principles and techniques used in drilling oil and gas wells have remained the same over time, even though the equipment used for rotary drilling today vastly differs from those used in the 1950s and 1960s. Technological advancements have led to significant changes in the equipment used, but the fundamental approach to drilling remains the same (Craig, 2021).

In civil engineering works, drilling is used to create deep foundations for buildings, bridges, and other structures. By drilling holes into the ground and filling them with concrete, engineers can establish a stable base for large-scale projects. Additionally, drilling is used to create tunnels, shafts, and wells for various purposes, such as transportation, water supply, or waste disposal. Civil engineers commonly employ several drilling techniques. These include rotary, percussion, auger, and directional drilling. Rotary drilling is a method that uses a rotating drill bit to penetrate the soil or rock. The drill bit can be either a tricone bit, which has three cones with sharp teeth, or a diamond bit, which has diamond-impregnated cutting surfaces. Rotary drilling is commonly used for borehole drilling, geotechnical investigation, and mineral exploration. Rotary drilling can be used for deep geotechnical investigations to collect core samples of rock and soil. It can also be used in mineral exploration to drill holes in the ground to extract ore samples (Gokhale, 2011). Percussion drilling is a method that uses a chisel-like bit that is repeatedly struck by a heavyweight. The impact fractures the soil or rock, and a bailer removes the broken pieces. This method is commonly used for shallow boreholes and geotechnical investigation. In shallow soil investigations, with the help of percussion drilling, soil samples for geotechnical testing or the installation of monitoring wells can be collected easily. Percussion drilling is used when auger or wash boring is impossible in stiff soil or rock. It involves lifting and dropping a heavy cutting or hammering bit attached to a cable, which is lowered into an open hole or casing. A tripod is used to support the cable, and the stroke of the bit varies according to the ground condition. This method cannot obtain good-quality undisturbed samples, but down-the-hole (DTH) drilling can be used in very hard rock. DTH drilling uses a hammer located behind the drill bit inside the hole, providing deeper percussion drilling. However, DTH drills are typically more expensive than open percussion drilling (Patel, 2019). Auger drilling is a drilling method that uses a helical screw blade to remove soil and rock from the ground. The auger is rotated while pushing it into the soil, which causes the blade to cut through the ground and move the soil to the surface. This method is commonly used for soil investigation, geotechnical sampling, and environmental drilling. It is used to determine the properties of the soil, such as its density, strength, and permeability. Auger drilling can also be used for environmental investigations to collect samples of contaminated soil or groundwater for analysis. In challenging soil conditions and fully saturated cohesion-less soils, it is not feasible to use auger drilling. Even when using this technique, it is not easy to obtain high-quality soil samples because the auger mixes the soil during drilling. Additionally, the pressure exerted on the soil by the auger can cause soil disturbance before it reaches the sampling depth. However, auger drilling is faster, less expensive, and less limited in access than other drilling methods (Longchen et al., 2014). In civil engineering, directional drilling is used to create a wellbore that deviates from the vertical and follows a predetermined path to reach a specific target underground. It is used for various applications such as underpasses, pipeline installations, and utility installations. With the help of directional drilling, the placement of utilities or pipelines beneath highways, waterways, or environmentally sensitive areas can be done without causing significant disruption to the surface.

The directional drilling process involves using specialized equipment, such as a steerable drill bit and a downhole motor, which allow the drill operator to steer the drill bit in any direction. The drill operator monitors the drill path using measurements and feedback from sensors and instruments located in the drill string. The drilling fluid is pumped down the drill string and out through the drill bit to cool and lubricate the bit and remove the cuttings from the hole. The drilling fluid can also help stabilize the hole walls and prevent collapse (Willoughby, 2014).

Drilling is essential to mining operations and plays a critical role in a mining project. There are different types of drilling performed in mining areas, mainly classified under two types as exploration drilling and production drilling.

i. Exploration Drilling: This type of drilling is conducted to acquire core or crushed samples from underground for the determination of the size, shape, and grade of a mineral deposit. It is usually the first step in the mining process and is used to gather data to evaluate a mining project's feasibility and profitability. Exploration drilling identifies mineral resources and determines the ore body's location, size, and quality. This information is critical in the planning and development of a mining project. In some areas, exploration drill holes must be cemented to prevent water from different aquifers from migrating. If the hole is left unsupported, soil or weak rock can cave in and block the hole, making it difficult to treat from the surface. Additionally, if an underground working is connected to a hole with water access, it may enter with gas at high volume and pressure, making sealing from below difficult (SME, 2011).

ii. Production Drilling: Once a mineral deposit has been identified and a mine has been developed, production drilling is done to extract the mineral ore. This type of drilling is generally done with smaller rotary or percussion drills and is used to create holes for blasting or to extract ore directly. The size and depth of the drill holes depend on several factors: the size and shape of the ore body, the type of equipment used for extraction, and the mining method being used. The drill holes are typically drilled in a specific pattern or layout designed to optimize the efficiency of the extraction process. This layout can be determined by various factors such as the ore deposit's geometry, the size and shape of the excavation area, and the type of mining equipment used. To extract mineral ore from the ground in mining operations, drill rigs are utilized, which are categorized into three types: rotary, top hammer, and down-the-hole (DTH) hammer drill rigs (SME, 2011).

2.2 Factors Affecting Drilling Operations

Mining is a vital industry that plays a significant role in global economies by providing raw materials for various products and services. Mining operations involve several crucial aspects necessary for successfully and safely extracting minerals. The most critical and fundamental aspect of mining activities is drilling operation. Drilling and blasting operations in mining are the most common methods used to break up rock in virtually all forms of mining except in dimension stone quarrying. Drilling is typically used in mining operations to create blast holes that can be charged with explosives. The drilling process is also used for other purposes in surface mining, such as exploration for obtaining drill hole samples and during development for drainage, slope stability, and foundation testing purposes. The drilling process can help identify the characteristics of the rock formation and can guide the placement of explosives for efficient blasting. In the mining cycle, drilling that is performed for the placement of explosives is called production drilling (Kennedy, 1990).

Production drilling is a critical part of the mining process, and its success can impact the efficiency and productivity of mining operations. The drilling process must be carefully planned and executed to ensure the accuracy of the blast hole placement and the safety of workers. In surface mining, unique or specialized drilling methods are employed during the production phase. Technical drilling methods can improve the accuracy of blast hole placement, reduce waste, and minimize environmental impacts. In addition, drilling and blasting activities affect the efficiency and sustainability of mine production. For a comprehensive understanding of production drilling activities, it is required to consider the geological formation on the site, drilling machine capabilities, drilling crew competency, and effects of the failure condition of the equipment on the activity efficiency (Ugurlu, 2018).

Drilling operations in mining areas can embody various geological, technical, and operational uncertainties. In addition, there are other uncertainties affecting the drilling operation significantly. Some economic, environmental, and safety parameters can also affect the drilling operation. For example, the profitability of a mining project can be influenced by commodity prices, which can be volatile and difficult to predict. In some cases, the cost of drilling operations may exceed the value of the extracted minerals, leading to a loss of investment. Moreover, mining operations can significantly impact the environment, such as water pollution, erosion, and habitat destruction. Uncertainties in environmental regulations or community opposition to mining can also be effective in the feasibility and profitability of drilling operations. Furthermore, mining is a hazardous occupation, and drilling operations can pose risks to workers' safety, such as falling rocks, equipment malfunctions, or exposure to hazardous materials. Managing and mitigating these risks is essential for workers' health and the success of the mining project.

Rais et al. (2017) indicated that penetration rate (PR) is the main factor of drill ability. An experimental study is conducted under varying rotation and pressures on the drilling bit for different geological formations. To define drilling ability, it is necessary to identify multiple parameters such as rock properties of rock and drilling technology. It was indicated that geological factors significantly impact drilling performance and bit wear, while machine and operational parameters can be adjusted and controlled. On the other hand, rock properties and geological conditions cannot be controlled. They carried out experiments with varying rotational and push pressures on drill bits in diverse geological formations, using the design of experiments method to establish drilling parameter settings. The importance of these parameters was assessed through variance analysis.

Aalizad et al. (2012) developed a model for predicting the penetration rate in rotary-percussive drilling using artificial neural networks (ANN) for four types of rocks in the Sangan mine located in Iran. The study considers three categories in defining parameters: rock properties, drilling conditions, and drilling pattern. The ANN model was trained with 77 data and tested with 25 data. The optimized model showed a high correlation coefficient of 86% and low root mean square error of 0.1865. The sensitivity analysis revealed a strong correlation between penetration rate and rock quality designation, rotation, and blasthole diameter.

The significance of drilling process efficiency cannot be ignored. As a result, it is crucial to identify the geological structure of the drilling site, the properties of the rock materials, and the parameters associated with the drilling equipment. Failing to consider the site's geological structure and machine-related parameters may lead to numerous challenges during drilling operations. Many factors impact drilling equipment performance, with ongoing research to optimize adjustable parameters for increased efficiency. The penetration rate is a crucial metric in drillability analysis, especially in mining projects. However, few models exist for estimating core drilling penetration rates. Bilim and Karakaya (2021) developed models to estimate penetration rates based on rock properties and performed experiments on eight different rock types using eleven different pressure forces. Some equations were derived to estimate the penetration rate based on rock samples' physico-mechanical properties. By examining the impact of pressure force on these models, equations were derived to estimate penetration rates considering both rock properties and applied pressure force.

The penetration rate (PR) in rock drilling is affected by various factors, such as rock properties, machine parameters, and the working process. The Rock Drillability Characterization Index (RDCi) is proposed as a model to predict PR across different drilling methods, incorporating uniaxial compressive strength, P-wave velocity, and rock density (Taheri et al., 2016). The RDCi system demonstrates strong correlations between PR and RDCi values when applied to diamond rotary drilling, non-coring rotary drilling, and percussive drilling, indicating its relevance and effectiveness in predicting rock drillability in any operating environment. It was indicated that drillability is affected by numerous factors, such as rock properties, machine parameters, and the working process, which can cause significant variations in Penetration Rate (PR) even in similar conditions. Five datasets, including two diamond rotary drilling, two percussive drilling, and one rotary non-coring drilling, were used in the study by Taheri et al. (2016) to examine the impact of rock properties like UCS, P-wave velocity, and density on PR. Multiple regression analyses led to the development of two Rock Drillability Characterization indices (RDCi) for diamond and percussive drilling to predict PR across various drilling methods. The model incorporates the UCS of intact rock, P-wave velocity, and density.

The drilling process itself can have technical uncertainties, such as the accuracy and reliability of drilling equipment, the effectiveness of drilling fluids and lubricants, and the efficiency of the drilling parameters (e.g., drilling speed, weight on bit, rotation speed). Equipment breakdowns or malfunctions can cause costly delays or require emergency repairs. Real-time monitoring of drilling parameters and regular maintenance of equipment can help to manage these uncertainties.

Eren et al. (2010) showed that real-time optimization of drilling parameters can optimize weight on bit and bit rotation speed to obtain maximized drilling rate and minimized costs. In this study, the weight on bit and string rotation for the drilling rate of penetration was optimized using a formation-specific approach. The multiple linear regression technique is used to develop a model that predicts the drilling penetration rate based on available parameters. A computer network is developed to continuously collect and analyze drilling site data to optimize real-time parameters. This technique is expected to reduce drilling costs and minimize problems encountered during drilling.

One of the significant technical uncertainties in drilling operations is equipment breakdowns. Drilling equipment can be complex, and any breakdown can result in costly downtime. The failure of a drill rig or any other equipment can also cause delays and impact on the overall efficiency of the drilling operation. To mitigate this uncertainty, regular maintenance of drilling equipment is necessary to ensure it is in good working order and reduce the risk of equipment breakdowns.

Uğurlu (2018) developed a model that helps in production scheduling and assesses the associated risks related to technical uncertainties. The method uses reliability analysis to associate the production amount with the number of holes to be drilled based on the number of available drilling machines, considering the stochastic nature of equipment availability. Two stochastic modeling methods were used to assess the performance of the proposed approach, and multiple simulations were generated to quantify the risk of uncertain events such as drill bit changing time, maintenance time, drilling time, equipment availability, the required number of drill bits, and the number of intended drill holes.

The proficiency, expertise, and training of drilling operators are crucial in influencing the drilling performance and productivity in mining operations. The competence of the drilling crew can improve drilling equipment performance, with a consequential reduction in downtime and maintenance expenses. It is achieved by their ability to identify potential hazards, take appropriate measures to mitigate them and ensure the safety of both personnel and equipment. Such an approach can positively impact the overall cost-effectiveness of mining operations and enhance the achievement of set targets. Penetration rate data can be affected by various sources, including the drilling equipment, geological variations due to inherent variations, and the actions of drilling operators. The penetration rate (PR) may experience variations upon encountering discontinuities such as faults, fractures, joints, and bedding planes. Therefore, in any anomaly in drilling operation due to discontinuities can be detected by experienced operators and the rate can be adjusted accordingly. In addition, drilling operators may need to stop the drilling process to address unforeseen circumstances like changes in drill rods or shifts (Park & Kim, 2020).

According to Ugurlu (2018), in field operations, the decision to replace a drill bit is often based on the experience of the operator, also in charge of replacement, when they observe excessive vibration. However, in some instances, the operator may let the bit fall into a hole, which can lead to safety issues during blasting or cause crusher failures due to feeding both bits and blasted material into the crusher of the processing plant. Alternatively, monitoring and optimizing drilling parameters and subsequently using statistical methods to determine the optimal time for drill bit replacement can offer a more effective solution. Furthermore, Ugurlu (2018) developed a simulation model that estimates drill bit usage for four drilling machines. Generating multiple scenarios, bit wear and the number of drill bits used for each drilling machine were detected to be different. Performance differences can primarily be attributed to variations in machine conditions and operator experience.

Ozdemir and Kumral (2019) investigated the influence of human factors on the reliability of mining equipment. Their analysis also incorporated a case study specifically focusing on haul trucks used in mining operations. This case study revealed that the reliability of these trucks might decrease by a range between 0.84% and 2.45% per shift. Moreover, the findings suggested a significant connection between operator skills and equipment reliability. Specifically, it was determined that 16.9% of these reliability drops could be attributed to the operators' skills. The researchers emphasized that the insights derived from this study could serve as valuable input for simulations of material handling systems. By highlighting the role of human factors in the reliable operation of mining equipment, the study underscores the importance of considering not only technical but also human aspects in mining operations. These findings can have direct implications for training and management strategies in mining, aiming to improve operator skills and consequently enhance overall equipment reliability.

Last, weather conditions can significantly affect drilling operations in open pit mines. Rain, snow, wind, fog, and temperature extremes can create hazardous working conditions, cause equipment malfunctions, and disrupt the drilling process. Heavy rainfall can cause an accumulation of excessive water in the pit base, making drilling equipment challenging to operate safely. Water can also cause the ground to become unstable, increasing the risk of landslides and equipment sinking into the ground. Additionally, water can fill into already-drilled boreholes, causing them to collapse. All these issues lead to significant downtime and increase the risk of accidents. Furthermore, fog and heavy snow can reduce visibility at the drilling site, making it unsafe to operate heavy equipment. Drilling operations often need to be suspended until visibility improves.

2.3 Previous Studies for Improvement of Drilling Operations in Mines

As discussed in detail previously in Section 2.2, drilling factors are generally handled in three classifications: Technical, operational, and environmental aspects. Therefore, the improvement studies of the related literature have concentrated on explaining, optimizing, and discussing these factors using different methods, which rely on mathematical models, evolutionary algorithms, or event simulations.

Drilling rate, type of bit, type of drilling machinery, and their effects on drilling operation efficiency are commonly studied under technical aspects. At this point, Ugurlu and Kumral (2020) utilized a combination of data evaluation, dependability analysis, the equal-weighted moving average approach, and DES to evaluate the number of drill bits and drillable holes over a specified timeframe. Factors influencing drill bit performance and drilling activity from the very first hole to the end of the drill bit's lifespan were identified. The findings demonstrated that the impact of operational factors shifted over time due to bit deterioration, and these changes can serve as indicators for determining when to replace the drill bit.

Song et al. (2022) demonstrated the effectiveness of the constrained Bayesian optimization algorithm in optimizing drilling parameters. By applying the algorithm to actual drilling operations, the unit footage cost and mechanical specific energy of the bit were reduced by 18% and 20%, respectively, compared to pre-optimization values. This approach can improve mechanical penetration rate, optimize drilling efficiency, and reduce drilling costs. A comparison of other optimization algorithms showed that the Bayesian optimization algorithm has a fast convergence speed, is suitable for real-time optimization of drilling parameters, and ensures timeliness.

Basarir et al. (2014) examined the use of soft computing techniques, such as ANFIS and multiple regression, to predict the penetration rate of drilling machinery. The models were constructed using data from drilling operations in four different cities of Türkiye, with input parameters including rock properties and operational parameters of the drilling equipment. Rock properties were represented by the uniaxial compressive strengths of various rock types, while the rock mass was characterized by the rock quality designation (RQD) values of structural units at the drilling sites. The bit load and bit rotation were considered operational parameters of the drilling equipment in predicting penetration rate.

Although the drilling process is essential to mining operations, a clear and detailed understanding of the different factors contributing to its efficiency and effectiveness is often challenging. While some studies have attempted to address this issue, the current literature lacks extensive evaluation of drilling operations that can adequately express and reveal the complex dynamics associated. This condition highlights the requirement for further research to provide a more comprehensive and detailed understanding of the drilling process and enable the development of more effective and efficient drilling strategies in the mining industry.

2.4 Event Simulations in Mining

The current study aims to develop an event simulation algorithm to reveal dynamic interactions during the production drilling operation of open pit mines. Therefore, this section will briefly define the simulation theory and discuss how this technique can be utilized to solve mining-related problems.

2.4.1 Definition of Event Simulation

Simulation is a scientific technique that emulates the function of real-world processes or systems over a given duration, whether manually or via computational means. It generates a pseudo-history of a system for inferential study of its real-life operational traits. By constructing a simulation model, a set of operational assumptions represented in mathematical, logical, and symbolic terms, the system's evolving behavior can be studied. Once verified, this model can examine potential alterations to the system and their effects and aid in the design stage of new systems by predicting their performance under different conditions. In cases where the model is simple, solutions can be derived mathematically, resulting in numerical performance measures of the system. Yet, for more complex real-world systems that defy mathematical resolution, computer-based numerical simulations are adopted, which mimic the system's behavior and yield data for performance evaluation (Banks et al., 2014).

Simulation, as a tool, has a wide array of applications that aid in understanding, optimizing, and developing complex systems. The various purposes of employing a simulation model can be discussed below. Figure 2.1 provides a structured sequence of actions that directs model developers through a comprehensive and systematic simulation analysis. Using simulation, environmental, organizational, and informational changes can be emulated, allowing the observation of their effects on the system's behavior.

i. It can help to identify critical variables and their interactions by modifying simulation inputs and studying the resultant outputs.
ii. Simulation can verify the validity of analytic solutions and can be employed as a teaching tool to solidify analytic solution methodologies.
iii. It also enables learning through simulation models tailored for training, thus avoiding the cost and disruption associated with on-the-job instruction.
iv. It can help to determine machine requirements by simulating various capabilities.

System or simulation models can be categorized as stochastic or deterministic, static or dynamic, and discrete or continuous. Including random input variables characterizes stochastic models, whereas deterministic models are defined by a specific set of inputs devoid of or displaying minimal randomness. Static simulation models overlook the impact of time on the state of the system; contrastingly, dynamic models recognize time as a critical determinant of system behavior. If a system's state alters at discrete points in time, it is classified under a discrete model, while a continuous model corresponds to a system experiencing continuous changes over time (Rossetti, 2015). A single system could potentially be defined using several of these types. The subdivision of system types is visually represented in Figure 2.2.

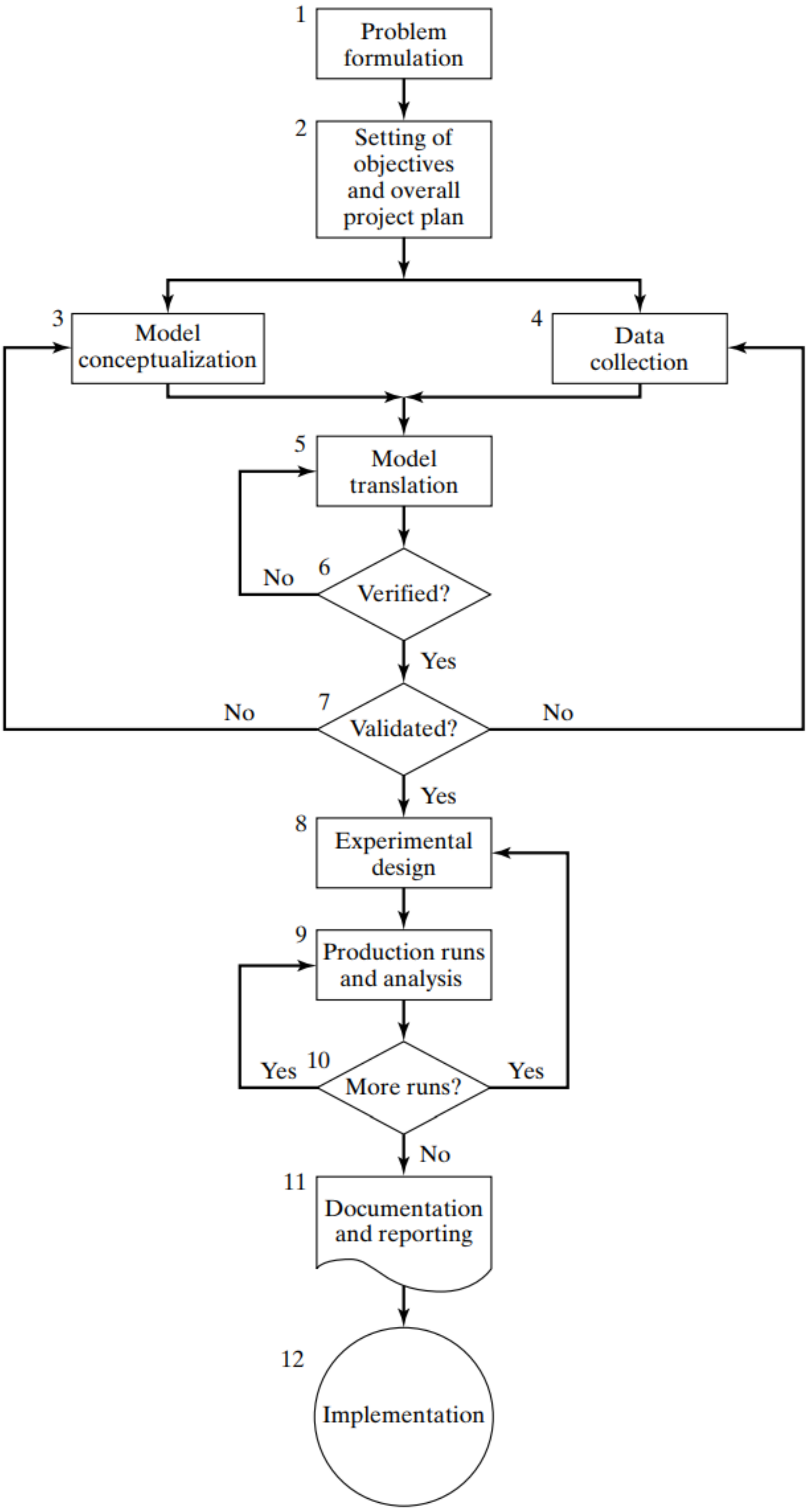


Figure 2.1 Basic Structure of a Simulation Algorithm (Banks et al., 2014)

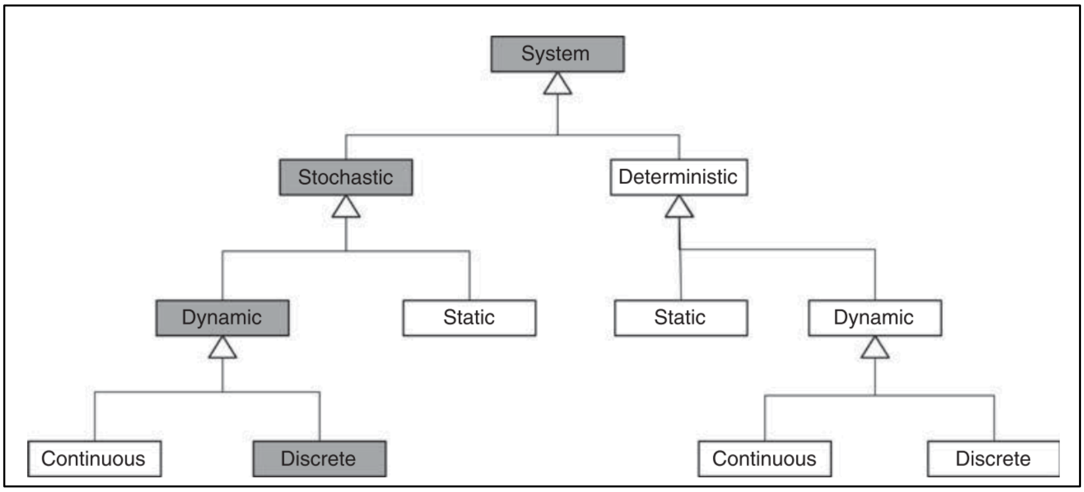


Figure 2.2 General System Types (Rossetti, 2015)

Discrete Event Simulation (DES) is a computer-based modeling and simulation technique used to study complex systems or processes that involve discrete events. In DES, the behavior of a system is modeled as a sequence of events, where each event occurs at a specific point in time and induces a modification in the system's condition. Discrete event simulation (DES) models have been used in mining operations to model and analyze the performance and efficiency of various processes and systems. On the other hand, Continuous Event Simulation (CES) is constructed whenever a change in system status should be observed regularly with pre-defined time intervals. Regular observation of fuel consumption, water accumulation, or pressure increase can be evaluated using CES models effectively.

2.4.2 Application of Event Simulations in Mining-Related Problems

Various event simulation models have been developed in the literature to evaluate transportation systems, equipment sizing, and production estimation in general. Louit and Knights (2001) constructed an event simulation algorithm to examine the impacts of different maintenance policies to decrease planned and unplanned downtime durations. Erdogan et al. (2005) developed a discrete event simulation model powered by the General Purpose System Simulator (GPSS). It was applied to identify the most efficient transportation technique in mining. Three models were created and tested, each representing a unique transfer method. The results were used to compare the efficiency of existing transportation methods, and the best system was suggested for similar mines. The analysis concluded that the monorail system was the most efficient for the Middle Anatolian Lignite and Park Mines, while the winch system was the least effective.

In addition, Albrecht (2005) proposed using discrete event simulation to optimize equipment sizing in material handling systems. Traditionally, equipment sizing has relied on design material balance and rules of thumb to ensure that systems can handle fluctuations. However, with the advent of discrete event simulation modeling software, it is now possible to model systems more accurately and better understand their capacity. The study employs an event graph-based discrete event simulation package (SIGMA©) to evaluate a coarse ore material handling system and determine whether equipment is undersized or oversized. By simulating the proposed system, the study analyzes the effect of different equipment capacities on throughput, providing designers with valuable insights and enabling modifications that maintain desired capacity while lowering installation costs. Additionally, the tool can help operators identify bottlenecks when considering increased capacity alternatives.

Hashemi and Sattarvand (2014) created a model in a discrete-event simulation environment that could develop the relationship between loading and hauling processes in mining operations. They designed different productivity evaluation scenarios to enhance the dispatching systems, aiming to decrease the amount of time trucks spent in queue. When this model was applied to a particular case, they were able to achieve a 7.8% decrease in total waiting time. This improvement was achieved by shifting from a fixed loader-hauler assignment system to a more adaptable allocation approach. Dindarloo & Osanloo (2015) developed a DES model to optimize the haulage system in Golegohar open pit iron ore mine located in Iran. The study began with observing the mine's current system and identified shortcomings in the system's efficiency. A DES model of the material loading and haulage process was then constructed, verified, and validated. The model was used to simulate and analyze the dynamics of mining operations, evaluate the system's performance, and conduct sensitivity analyses.

On the other hand, Kaba et al. (2016) formulated a novel stochastic discrete event simulation model that forecasted the output for two excavators at a pit, employing Arena® Software. The time and motion behaviors of the shovel-truck system were investigated to construct the stochastic model. Accordingly, a four-week production prediction was performed. The total mean production demonstrated a 2.34% discrepancy from the actual production of 215,341 BCM, a relatively low deviation compared to the 5.44% variance of the deterministic planned production.

Golbasi and Demirel (2017) developed a continuous event simulation to optimize inspection intervals of production equipment with varying component reliability and maintainability profiles. The model evaluated corrective maintenance decisions when determining the inspection times, where preventive maintenance activities take place, in a way to minimize the overall maintenance cost of direct and indirect cost items. The developed model was applied to two different draglines employed in a coal mine. The findings showed that if the current inspection interval of 160h is extended to 232 and 184h for the draglines, a total maintenance cost drop of 5.9 and 6.2% could be achieved.

Moreover, Fadin et al. (2017) introduced a look-ahead algorithm as a novel strategy to tackle the truck dispatch issue in open-pit mining areas. Using real-world data, a simulation-based optimization model was developed. The objective of the dispatching process was to optimize production numbers and deliver substantial cost savings in mining operations. Different truck dispatch scenarios were tested using a discrete event simulation, including the LP-Gap, percentage of LP-Gap, multi-stage algorithm, and look-ahead algorithm. The research findings indicate that the look-ahead algorithm scenario was the most effective, yielding the highest production and productivity rates for loaders and trucks.

Upadhyay and Nasab (2018) offered a discrete-event simulation and optimization framework designed to evaluate uncertainties inherent in mining activities. This model improved short-term production planning, facilitating a more proactive decision-making process. Furthermore, this model could encapsulate the interdependencies between multiple variables. These included failure modes and their effects on truck performance, the influence of road conditions on tire costs, as well as the relationship between dispatching algorithms and truck availability. The study incorporates a comprehensive cost analysis of production operations. This detailed analysis contributes to a more thorough understanding of the financial implications of operational decisions, thereby supporting more informed decision-making in mining operations. The study highlights the significance of multi-dimensional considerations in optimizing mining operations by developing a complex model that embodies various crucial factors.

Afrapoli et al. (2019) proposed an innovative simulation-optimization framework. This integrated framework was designed to facilitate the determination of an optimal haul fleet configuration in surface mining operations. However, the algorithm did not consider the impact of downstream processes in operation nor the influence of the fleet management system. Despite these limitations, it was demonstrated that the developed framework could significantly improve fleet efficiency. Notably, the study revealed that the proposed framework could potentially reduce the number of trucks by as much as 13% compared to traditional manual and deterministic calculations. The proposed framework allows for a more efficient and effective allocation of resources, which ultimately can lead to notable cost reductions and enhanced productivity. Nevertheless, future research could further improve this model by incorporating the effects of downstream processes and fleet management systems, potentially leading to an even more comprehensive and effective tool for haul fleet configuration.

Golbasi and Turan (2020) constructed a discrete event simulation algorithm to optimize maintenance policies for production equipment that can perform a mono- or interactive operation. Corrective, preventive, and opportunistic maintenance policy items are allowed to be evaluated simultaneously, considering equipment components' random lifetime and repair time characteristics. The developed model could optimize maintenance policies particular to the equipment fleet itself via one of two objective functions that can minimize maintenance cost or maximize equipment availability. The algorithm was applied to a multi-shovel and a dragline operation separately.

Yilmaz and Erkayaoglu (2021) developed a discrete event simulation model to assess the shearers' performance in underground coal production by including a double-drum shearer, belt conveyor, loading stage, and armored face conveyors. The daily production profile of a shearer was investigated, and the most critical parameter in the production routine was detected as shearer stoppages.

Besides, Golbasi and Kina (2022) examined the kinematic fuel consumption factors of haul trucks operating in a multi-route operation network and the impact of stochastic payload and precipitation conditions on fuel usage. The study introduces a discrete-event simulation algorithm that links significant parameters in a material haulage system with time and location-based fuel usage behavior. The study uses a large-scale cement production network comprising two mines and a processing plant involving 29 trucks and 15 routes to validate the model. The simulation results reveal that precipitation conditions may cause fuel consumption variation by 15-25%. Moreover, the study shows that trucks with the same capacity in the clay mine consume 40% more fuel during loaded travel than those in the limestone mine due to the higher frequency of uphill loaded travels. Additionally, the clay mine trucks emit 1.48 kg/km of carbon dioxide during a complete production cycle, which is 17.5% higher than the limestone mine trucks.

CHAPTER 3

EVALUATION OF THE SIMULATION INPUT REQUIREMENT

3.1 Introduction

This section evaluates the activities and sub-activities that can be available for drilling operations and all the relevant factors, including procedures, administrative and technical aspects, and driller profiles. In this way, the basis and boundaries of the simulation algorithm that will be discussed in Section 4 will be detailed. It should be remembered that the discussion performed in the current section is particular to a gold mine operated in Türkiye.

3.2 General Information about the Driller Specifications

There are two drill rigs (driller) used in the mine. The first rig is the FlexiRoc T35, and the second is the SmartRoc T40. The FlexiRoc T35 has a primary drill rod length of 6.9 meters; additional drill rods of 3.6 meters can be connected. On the other hand, the SmartRoc T40 has a primary drill rod length of 4.2 meters, and like the FlexiRoc T35, additional drilling rods of 3.6 meters can be connected to it. Additional drilling rods can be connected end-to-end for the FlexiRoc T35 and the SmartRoc T40. Indeed, these drill rigs have some advantages and disadvantages experienced in the mining area.

The FlexiRoc T35 has a longer primary drilling rod with a length of 6.9 meters, which can be advantageous for specific drilling applications. Since the initial drilling rod length of the FlexiRoc T35 model is 6.9 meters and the average drill length is 5.5 meters, there is no need for a second rod in general. In addition, since there is no need for additional rod, the FlexiRoc T35 model saves time during the drilling operation, resulting in a faster drilling performance than the SmartRoc T40 model.

However, the disadvantage of having a long drill rod is that when the drilling process continues with a single rod, there may need more flexibility during drilling, which can lead to bending and breakage of the rods during drilling operations. The FlexiROC T35 is a flexible and versatile surface drill rig developed and designed for high performance in demanding construction and quarry applications.

On the other hand, the SmartROC T40 is a highly automated, efficient, and accurate surface drill rig. It's designed for bench drilling in quarries and open pits. The SmartROC T40 is equipped with the Hole Navigation System (HNS), allowing for automated drilling. It also has a fuel efficiency advantage due to its COP Logic system. The main differences between the two models lie in their intended applications and the level of automation. The FlexiROC T35 is more versatile and can be used in a broader range of applications, while the SmartROC T40 is more specialized for bench drilling in quarries and open pits. The SmartROC T40's automation features, such as the Hole Navigation System, can increase productivity and accuracy and reduce operator fatigue. Its COP Logic system can also provide better fuel efficiency. On the other hand, the FlexiROC T35's versatility is an advantage in situations where a range of drilling tasks are required. However, it may have a different automation or fuel efficiency level than the SmartROC T40. Some comparative features of these two drillers are listed in Table 3.1.

Spacing and burden distances between drillholes are 3.25 and 3 meters, respectively. Drilling patterns are the arrangements of blast holes drilled for blasting operations in mining, quarrying, or construction. The pattern selection depends on various factors, including the type of rock, the desired size of the fragmented rock, the specific mining technique, and safety considerations. Staggered pattern is used in the mine. In this pattern, the blast holes are arranged in a grid, but the holes in every other row are offset, creating a staggered pattern. This arrangement is observed to provide better rock breakage than a square pattern. Design parameters in drilling and blasting operations can be seen in Figure 3.1, and the drilling pattern sample can be examined in Figure 3.2.

Table 3.1 Some Technical Features of the Drill Rigs (Driller)

	FlexiROC T35	SmartROC T40
Hole diameter	64 - 115 mm (2.5 - 4.5 in)	64 - 127 mm (2.5 - 5 in)
Drill steel	T38, T45, T51	T45, T51
Engine	Caterpillar C7, 168 kW (225 hp)	Caterpillar C7.1, 168 kW (225 hp)
Flushing air capacity	11.3 - 20 m³/min, up to 24 bar	11.3 - 20 m³/min, up to 24 bar

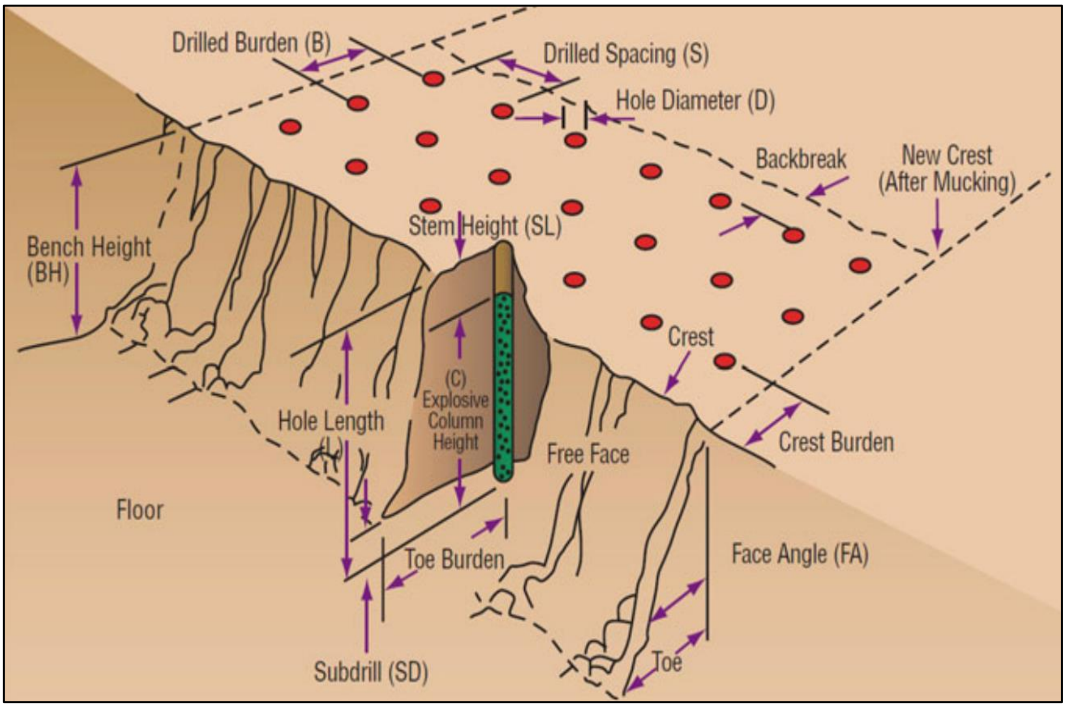


Figure 3.1 Design parameters in drilling and blasting (Nobel, 2010)

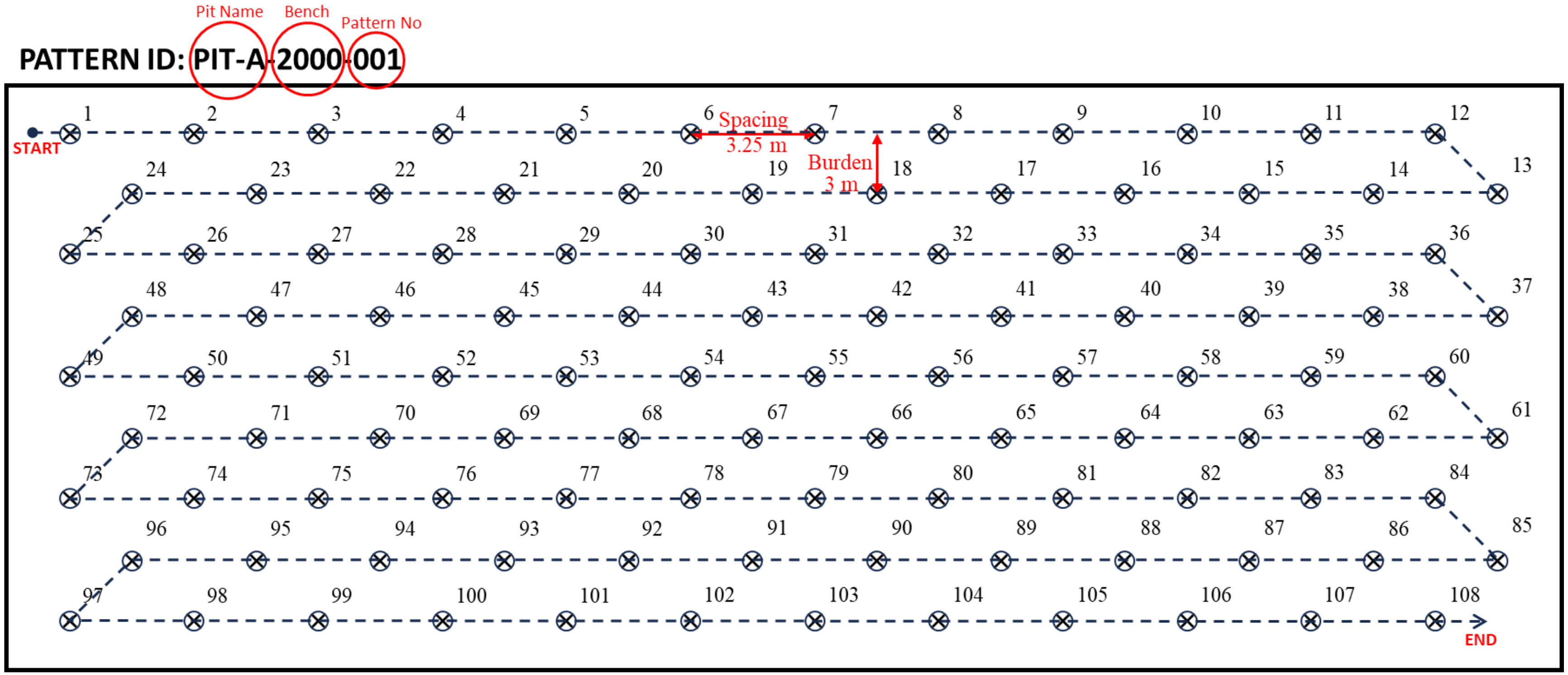


Figure 3.2 A Sample Drilling Pattern

3.3 Effective Conditions and Procedures before Starting Drilling Operation

A drilling operation can be divided into two main parts: Before and after starting an active drilling operation. Before an active operation, the procedures and applications generally aim to prepare the area for drilling, transport and position drillers, and pre-check equipment application.

The drill rigs (driller) are transported to the mine site using low-bed trailers. Firstly, the field that will be drilled needs to be surveyed. After the survey is completed, drill lengths are calculated for each drillhole. Each drillhole is numbered for identification purposes. Later, the ore control team uses these labels/numbers when taking samples from the crushed materials of the drilled holes. Labels are written on small wooden wedges, then placed next to each drillhole. The drill operator should complete the checklist and perform equipment inspections before using the drill rig in each shift. At the beginning of each shift, completing the checklist takes roughly half an hour. In the checklist, engine hour is written at the beginning of the drilling operation, and the checklist needs to be filled in to start. The checklist can be seen in Table 3.2. The responses highlighted by dark color refer to negativity, and in those circumstances, the equipment may require additional action before the drilling operation.

The checklist items (CL) listed in Table 3.2 can be experienced unfavorably in the drilling area. Some may cause equipment unavailability or delay equipment operation for active pattern drilling. Therefore, they are discussed in detail below so that they will be characterized in Section 4 in terms of their occurrence and severity profiles.

Table 3.2 Pre-check List of the Drill Rigs (Driller)

Pre-drilling equipment inspection checklist						
Operator Name:					**Engine Hour**	
Driller ID:					**Start:**	
Date:						
Shift:					**End:**	
Diesel Amount:						
	Pre-drilling Operation	**Y?**	**N?**	**Operator Comment**	**Supervisor Comment**	
1	Have you come well-rested and adequately slept?					
2	Is there any oil leakage under the machine or on its right or left side?					
3	Are there any issues with the machine's moving gear?					
4	Is the engine oil sufficient?					
5	Is the radiator coolant sufficient? (Check from the gauge)					
6	Are there any issues with the rails, slides, and securing bolts on the boom?					
7	Are there any issues with the seat, gauges, and seat belt?					
8	Is the hydraulic oil sufficient?					
9	Is the fire extinguisher empty? (Also check the expiration date)					
10	Is there a sufficient amount of diesel fuel in the machine?					
11	Is there any issue with the rotation of the machine?					
12	Is there any damage to the body, cabin, or boom of the machine?					
13	Are there any cracks or damage on the windows?					
14	Are the steps or handholds in good condition?					
	Start the engine and turn on the lights!	**Y?**	**N?**	**Operator Comment**	**Supervisor Comment**	
1	Are the headlights, signals, and beacon lights working?					
2	Are the rear lights working?					
3	Is there any trapped debris between the hydraulic hoses or any rupture in the lubrication lines					
4	Is the engine oil sufficient?					

CL01: Operators should be on duty well-rested and have had adequate sleep. It is crucial since it ensures the safety and efficiency of the drill operator and the overall drilling operation. Being well-rested reduces the risk of accidents, operational errors, and impaired decision-making. It promotes a positive work environment, complies with safety regulations, and mitigates potential fatigue-related risks. Ensuring operators are physically and mentally ready for operation is crucial for maintaining a safe, productive, and responsible work environment.

CL02: The question about oil leakage is vital because it maintains environmental safety, ensures equipment integrity, and prevents accidents. Checking for leaks allows prompt repairs, reducing downtime and costly damages. It also provides compliance with regulations and promotes responsible and efficient drilling operations. If oil leaks beneath the driller body, the driller cannot be operated. The oil leakage should be investigated, and the source of the leak should be identified and addressed correctly. In general, leakage is addressed to drill rig boom. It is crucial to inspect the boom components, such as hydraulic hoses, fittings, and seals, to identify the source of the leak. Once the source is determined, appropriate repairs or replacements can be performed to resolve the issue and prevent further leakage. Regular maintenance and inspection of the boom components can help to identify and address potential leaks before they become significant problems. Instances of leakages occurring directly from the engine are infrequent. Generally, the prime source of such leakage is attributed to the air compressor. Such malfunctions are typically amenable to on-site repairs.

CL03: Regularly checking the machine's moving gear is essential for safety, performance, and equipment longevity. Proactive actions for moving gear assist in preventing accidents, ensure efficient drilling, reduce downtime, and extend the machine's lifespan. Proper gear maintenance leads to optimal drilling results and reliable operation. If a drilling machine is exposed to a complete halt and cannot be moved even by a low-bed trailer, it can still be repaired on-site, but this is typically contingent upon the availability of the necessary parts. If these parts are not available in spare part inventory, ordering and receiving them can take a week or longer.

However, this process can be completed within a single shift if the required parts are available.

CL04-05: Ensuring sufficient engine oil allows a smooth, safe, and efficient drilling operation. It provides lubrication, cools the engine, prevents damage, and improves performance. Adequate oil levels extend the machine's lifespan and reduce the risk of mechanical failures during drilling tasks. The levels of engine oil and radiator fluid also play a critical role. In both cases, low levels can hinder the machine's ability to operate correctly. Addressing these shortages typically offers a swift and effective solution. Under field conditions, the machine usually requires 1-2 liters of oil (in case of oil leakage). If the radiator fluid level is low, this is replenished after the drilling operation is completed. A low level of radiator fluid does not stop the drilling operation. Rectifying these deficiencies ensures that the machine operates efficiently.

CL06: Checking the rails, slides, and securing bolts on the boom is vital for safety, proper functioning, and equipment longevity. It prevents accidents, ensures smooth operation, and reduces the risk of breakdowns during drilling. Regular maintenance optimizes drilling results and enhances workplace efficiency. If notable wear is observed on the boom’s components, such as slides, the replacement process in the workshop typically lasts a single shift. If wear is minor, maintenance is conducted after the completion of the drilling operation.

CL07: The drilling process continues even when issues with the seat, indicators, or safety belts occur. These malfunctions are rectified once the drilling operation has concluded.

CL08: In addition, sufficient hydraulic oil should be satisfied the drilling machine's proper functioning and safety. It provides lubrication, dissipates heat, and prevents damage to hydraulic components. Adequate oil levels maintain system integrity, reduce wear, and optimize the machine's performance during drilling tasks. In hydraulic oil shortages, it usually takes approximately one hour for the maintenance team to arrive and resolve the issue.

CL09: The depleted fire extinguisher does not stop the ongoing drilling process. Nevertheless, it is necessary to replace the depleted fire extinguisher with a new one after completing the operation.

CL10: Diesel is typically replenished during breaks, not during production, and additional diesel is not supplied while drilling is underway. However, diesel may be added in certain situations during winter, which takes approximately half an hour.

Such procedures are of utmost importance in ensuring worker safety and the effective and efficient use of equipment.

CL11-12: Issues such as rotation problems, body, cabin, or boom damage necessitate the dispatch of the machine to the workshop. These situations generally demand a more in-depth investigation and a potential failure report. A detailed examination is conducted to determine the cause of the damage and its potential consequences.

CL13-14: On the other hand, the machine typically continues with production if there are cracks or damage in the cabin windows. When the operation is completed, broken parts must be replaced at the workshop.

3.4 Effective Conditions and Procedures after Starting Drilling Operation

Before starting drilling operations, each driller operator is given a list specifying the drillhole numbers they will drill on the active pattern. The workflow of a drilling operation is as follows:

- Positioning and Preparing for Drill Stages: The initial drilling process begins with the machine moving towards the hole and preparing by positioning its rock drill at a 90-degree angle. On average, drill rigs move the distance between holes at a 1.7 to 3.6 km/h speed. Once started, the operator checks the ground where drilling will take place. If the ground is composed of clay or mud, a change in the drill bit is necessary. For clayey and muddy surfaces, cross bits are used. On the other hand, rock bits are used for hard rock. If the operator realizes that the used bit is ineffective for drilling the ground, the drill rig will be halted. The operator then descends from the drill rig and installs a cross bit suitable for drilling clayey material. The bit change typically takes about 10 minutes. After completing the bit change, the drilling process continues.

- Drilling Stages: The rod is pulled out once the initial drilling is finished. The drilling machine empties the dust from its tank and cleans it with air. After completing this process, the machine moves toward the next blasthole. On average, pulling out the rod and moving to the next blasthole takes about 1 minute. In SmartRoc T40, it takes 10-15 seconds to install the second rod. In total, the process of installing and removing takes about 30 seconds. FlexiRoc T35 on the other hand, completes the drilling process directly with a single rod because its rod length is longer than the SmartRoc T40. However, if the location where the operator is working is inclined, adjusting the rock drill can take a bit more time. Such terrain causes the drill rig to lose time transitioning from flat to inclined surfaces. This process can extend on inclined terrain from 1 minute to 2 minutes. Drill rigs generally continue drilling operations, leaving an empty row between rows. This condition is due to the necessity for sample collection and ensuring enough space for other drill rigs regarding safety concerns at the same drilling pattern. To prevent confusion, samples should be collected systematically by the blasthole numbers.

- After Drilling Stages: After the drilling operation is completed in the field, drill rigs are moved aside to the area where the next drilling operation is planned. If there is no planned drilling operation, drill rigs are moved out of the operation area. When a drilling plan is made, drill rigs are moved back to the area before the operation starts.

Drilling machines encounter three main problems in the field. These problems can stem from bit, rod, and shank issues.

i. If the bit is worn out, it is replaced with a spare one. Each operator has a spare bit in their inventory. If no spare bit is available, a new one is requested from the workshop. Bringing the new bit from the workshop to the site usually takes about half an hour. The operator must have a certain level of expertise to determine whether a bit change is necessary. If the boom judders against the ground during the drilling operation, it could indicate that drill bit tooths are missing. In this case, the operator should stop working and check the drill bit condition. If they do not replace the bit in time, it could cause problems with the rod and the shank.

ii. Rods can become bent or broken. If the drilling area is muddy during drilling, the rod could strain and bend. Typically, a friction sound can be heard under such circumstances. The operator can infer from these indicators that there may be issues with the rods or shanks. If cracks are detected on the rod, the operator should know there might also be an issue with the shank. Rod replacement usually takes around 10 minutes.

iii. Shank replacement, on the other hand, can take between 45 minutes in average. If the first rod in the Smartroc T40 drill rig with a length of 4.20 meters fails, a 3.60-meter rod can be used instead. When a rod is to be replaced, the bit is examined. If the bit is new, no check is needed. When a rod is requested, if there is wear on the bit, a new one is ordered from the workshop. The rod and bit are also inspected in case of a problem with the shank. If these components make a noise, all the components are examined.

iv. In addition to those three major problems, drillers can be exposed to different failure modes, such as mechanical, hydraulic, and rock drill. There can also be issues related to rock drill movements. Depending on the ground, pressure and impact can be adjusted automatically on these drill rigs. Moreover, problems may arise with dust suction. If the ground where drilling occurs is clayey or muddy, it can block suction channels. In such cases, the pipe and dust collector are cleaned. This issue frequently occurs in both types of machines. If the terrain is very muddy and clayey, it would be beneficial to avoid forcing the driller, as it will not result in an efficient operation.

There is uncertainty due to weather conditions, especially during the winter season. Drilling operations cease when snowfall covers the markers. There are also stoppages in excessive fog and other weather conditions. If the visibility drops to 5-10 meters, the operation stops. In severe circumstances, drillhole markers can disappear, thus causing a stoppage. Excessive wind can also carry away the markers, making the sample collection unreliable. Due to unfavorable weather conditions, operational stoppages usually occur in February, March, and April. In addition, seasonal changes can also affect blasting operations indirectly. Due to harsh weather conditions, sample collection might be stopped, or ore and waste production in active production areas can be halted. Thus, it indirectly affects the drilling operation.

Different failure modes can be encountered depending on the type of drill rig. For example, The SmartRoc T40, generally having more electronic components, can experience more severe malfunctions that can need more extended time to recover. Maintenance workers have to exert extra effort on these machines. SmartRoc T40s require annual software updates. If these updates are not installed, it can lead to errors in both movement and drilling. The drill rigs can slow down. Such malfunctions do not occur in the FlexiRoc T35. Furthermore, drill rigs with high engine hours encounter more problems with the rods and shanks.

Uncertainties on the ground condition affect drilling operations significantly because it impacts the bit selection. The drilling speed can drop by half on the clayey ground if the right bit choice is not made. Typically, a drill rig can drill 70-80 holes per shift, but this falls to 30-40 in case of wrong bit selection. Due to the wrong bit selection, more problems can arise from the shank and rods. Sometimes, drilling can only be carried out to a depth of 2-3 meters in 5-meter blasting holes. If the rock bit and cross bit are selected appropriately for the ground, one can drill at 1.2-1.3 meters per minute, while the wrong bit choice can drop the penetration rate to 0.4-0.5 meters per minute. An operator who can promptly detect problems in the drill rigs (driller) typically progresses faster in drilling.

In addition to correctively maintaining drill rigs in case of component failure, scheduled maintenance is executed when the engine accumulates milestones of 250, 500, 1000, 2000, and 6000 engine hours. The application content of these scheduled maintenance activities is detailed as follows:

i. At the initial 250-engine-hour interval, the maintenance involves a singular operation: substituting engine oil. This operation is a fundamental procedure to ensure the efficient running of the drill rig's engine, and it is typically concluded within an hour.

ii. Once the drill rig reaches 500 engine hours, the maintenance procedure becomes slightly more complex. It does not only include the replacement of engine oil but also entails the substitution of hydraulic oil. Hydraulic oil plays a critical role in powering and cooling the hydraulic systems in the rig. Despite the additional operation, the total estimated completion time remains at around one hour. This condition reflects the efficiency and proficiency of the maintenance process.

iii. Upon reaching the 1000-engine-hour threshold, the maintenance procedures further broaden in scope. They now involve, in addition to the replacement of engine and hydraulic oils, a full-scale alteration of all filters within the rig. These filters are vital components of the rig, purifying the oil and air circulating within the system, thus protecting it from potential contaminants and ensuring optimal performance. Given the complexity of the task, it typically takes around two hours.

iv. The maintenance procedure carried out at the 2000-engine-hour milestone includes the operations implemented during the 1000-engine-hour service, plus a couple of more intricate tasks. These involve replacing the belt cover gasket and performing necessary valve adjustments. The belt cover gasket ensures a proper seal against oil leaks, and valve adjustments are crucial for maintaining optimal engine performance. Due to the sophisticated nature of these tasks, the procedure at this stage is more time-consuming and typically requires a whole day for completion.

v. Finally, the maintenance procedure followed once the drill rig reaches the 6000-engine-hour mark mirrors the extensive process applied at the 2000-engine-hour interval. This comprehensive maintenance routine requires the same full-day commitment for its completion, indicating adherence to rigorous standards of drill rig servicing.

The input requirements of a production drilling simulation in a surface mine were discussed in the current section. The quantification of these inputs will be detailed in Section 4.3, following a technical discussion on the algorithm logic of the simulation in Section 4.2.

CHAPTER 4

DEVELOPMENT OF THE BLASTHOLE DRILLING SIMULATION ALGORITHM FOR A SURFACE MINE

4.1 Introduction

This section will discuss the development of the simulation algorithm that mimics the time-based interactions of production drilling operations at surface mines. Accordingly, the algorithm logic will be mentioned in Section 4.2, while the implementation results of the algorithm using the input data given in Section 4.4 will be discussed in detail in Section 4.5. It should be remembered that the algorithm logic will be discussed under the current section by stating the site conditions available in a particular surface mine. However, the algorithm is applicable for the surface production drilling at any mine by introducing the site-specific information.

4.2 The Algorithm Logic

The logic flow among the algorithm modules is as follows:

i. The model starts with introducing all variables, parameters, and functions into the system. The input dataset, including parameters and functions, covers four main types of data:

a) Maintenance Dataset: This data embodies corrective and preventive maintenance characteristics of the driller components, which may be effective in driller active utilization. Accordingly, corrective maintenance data is a set of probability distribution functions (PDF) of survival and repair times of major failure-inducing components for the drillers. Here, PDFs of survival times provide reliability $f(x)_i$, i.e. time between failure, the behavior of failure mode i, while PDFs of the repair times give maintainability $g(x)_i$, i.e. time to repair, characteristics in case of any component failure. On this basis, $f(x)_i$ and $g(x)_i$ functions of the failure modes given in Table 4.1 are used. In this study, it was assumed that both types of drillers show similarities in the three primary component failures linked to the bit, rod, and shank, as well as in other failure modes. However, these failure patterns may vary based on the driller's age, working conditions, and specific usage under particular circumstances.

Table 4.1 Some Technical Features of the Drillers

Components	**Failure Mode Code (i)**	**Failure Mode Abb.**
Bit	1	B01
Rod	2	R01
Shank	3	S01
Rock Drill	4	R01
Hydraulic	5	H01
Mechanic	6	M01

Here, each failure mode requires different maintenance interventions with varying repair time requirements, and each failure mode occurs with its own frequency behavior. In addition to corrective maintenance, scheduled maintenance works are also performed for particular components. As mentioned briefly earlier in Section 3.4, the intervals given in Table 4.2 will be active for scheduled preventive maintenance (PM):

Table 4.2 Some Technical Features of the Drillers

Scheduled PM Invervals (engine hours)	**Work Package**
250	Engine Oil Substituion
500	Hydraulic Oil Substituion
1000	Full-scale Alteration of all Filters
2000	Replacement of belt cover gasket Valve Adjustments
6000	Replacement of belt cover gasket (extensive) Valve Adjustments (extensive)

In Table 4.2, scheduled PM activities are expected to contribute positively to the occurrence of related failure modes by extending the remaining time to the expected failure. For instance, hydraulic oil substitutions every 500h will add an extension in approaching the shank failure.

Moreover, each driller is controlled before drilling each pattern with a pre-checklist mentioned in Section 3.3. In case of any unfavorable condition, a recovery attempt will take place. These attempts can have three different effects on the operability of the driller for the current pattern operation. First, if the attempt is minor and can be done in a short period, then this attempt will only create a delay in starting the driller operation. Second, suppose the attempt requires a major recovery. In that case, the driller's operation for the current operation will not be possible (postponement), and the driller will be prepared for the next pattern drilling operation. Third, if the attempt is not causing the inoperability of the driller for the current pattern drilling, then it will not contribute to any equipment unavailability since it will be recovered just after the operation. Pre-checklist codes (CL) and their effectiveness on the driller operation are summarized in Table 4.3. If issues arise with CL items 3, 8, and 10, delays of 6 hours, 1 hour, and 30 minutes are assumed, respectively. The impact of CL items on drillers, which could result in delays or cancellations for the specified driller, can be adjusted based on real-world data.

Table 4.3 Characteristics of the Pre-check List Items

CL Code	Action Required	Resultant Unfavorable Attempt	Affected Failure Mode
1	-	No effect	-
2	-	No effect	-
3	CM	Postponement	M01
4-5	-	No effect	-
6	-	No effect	-
7	-	No effect	-
8	CM	Postponement	H01
9	-	No effect	-
10	-	No effect	-
11-12	-	No effect	-
13-14	-	No effect	-

b) Weather Dataset**:** Weather conditions remarkably influence the start and continuity of drilling operations. In some unfavorable weather conditions, the pattern drilling for the active date can be canceled. In some circumstances, drilling operations can be started but can have less progress with an extended completion time due to difficulties in the movement and drilling of the drillers. Therefore, the seasonality effect is reflected in the model, specific to the weather conditions in the application area, not regarding calendar seasons winter, spring, summer, and fall. The effects of seasonality on movement speed are determined using expert opinions from a driller operator and a drilling and blasting engineer. In this context, the probability of cancellation and delay in an operation was considered, and the assumed probabilities are presented in Table 4.4. If there are no cancellations and only delays occur, the assumed delay durations are also in the table. These durations are based on the experience of the operators and can be revised with the collected data.

Table 4.4 Seasonality Information

Seasonality Code	**Active Dates**	**Probability to cancel**	**Probability to delay**	**Delay Hours**	**Effect on Movement Speed**
1	1-120	8%	30 %	6	[-15%; -25%]
2	121-190	4%	16%	2.5	[-15%; -25%]
3	191-310	0%	7%	1	[0%; -3%]
4	311-365	5%	24%	5.5	[-5%; -20%]

c) Operational Dataset**:** Operational dataset covers administrative and technical decisions on drilling operations, such as the number of drillholes, their spacing and burden distances, expected time to start operations, availability of clay material in each drillhole, operator effectiveness in drilling time progress and administrative holidays (Table 4.5). The clay availability was used as a function in this study to reflect the impact of clay presence on drilling operations. Even if the geological model indicates clay content, it might not always provide precise guidance for the drilling operation. In this algorithm model, clay availability was assumed to be 20% of the total blastholes. It might be modified by using real collected data.

Table 4.5 Operational Information

Data Type	Units
Spacing Distance	Meter
Burden Distance	Meter
Number of Drills	Amount
Starting DH of Each Driller	Number
Ending DH of Each Driller	Number
Clay Condition	Binary (1/0) for each drillhole
Operator Effectiveness	Percentage
Start Time	Calander time
Administrative Holidays	Dates of the active year

d) Equipment Dataset: This dataset includes the drillers' movement, positioning, and penetration rate specifications since the time between actions will be affected by this dataset (Table 4.6).

Table 4.6 Equipment Information

	Data Type	T35	T40
Walking Rate (km/h)	Prob. Dist.	1.7 – 3.6	1.7 – 3.6
Positioning Time (min)	Prob. Dist.	7 - 20	7 - 20
Penetration Rate w clay (m/s)	Prob. Dist.	0.4 - 0.5	0.4 - 0.5
Penetration Rate w/h clay (m/s)	Prob. Dist.	1.2 – 1.3	1.2 – 1.3
Rod Length (m)	Constant	6.9	4.2
Number of Rods (#)	Constant	1	2

ii. After introducing the input dataset and variables into the model, a starting date is assigned to the active date (t_{ad}). The model assigns the first date of January as the starting date as default. Whenever the drilling operation is completed for ta, its value is incremented to evaluate the operation at the next date. One single simulation is completed when the active date is the target observation date (t_t). For instance, if a complete one-year operation is intended to be simulated, then $t_{td} = 365$.

iii. The weather conditions are first checked to decide if the drilling operation will be performed or canceled for the given date. Accordingly, each season specified for the date intervals in Table 4.4 has a different probability of operating particular to the mining area. Especially wind and snow conditions above allowable threshold values and invisibility situations due to fog may cause cancellation of the operations. Therefore, a binary decision (1/0) will be assigned randomly from the probability functions related to cancellation due to unfavorable weather conditions. If the algorithm is agreed on unfavorable conditions, the model will skip the operations at that date. Otherwise, the algorithm will advance to the next decision point to determine if there's a delay. The probability of delay is randomly determined using probability functions, varying depending on the season. If a delay occurs, a specific delay time will be generated and added to both the active time and day time. Moreover, if weather conditions are favorable but accompanied by rain or snow, the drilling operation will start; however, the efficiency of the operation, reflected in its progress speed, will decrease. Following these assessments, the pre-start checklist evaluation module will be started.

iv. If a drilling operation is decided to take place, each driller is controlled according to the pre-checklist items listed in Table 4.3. Pre-check items have different occurrence frequencies. Different maintenance actions can be decided as discussed earlier, depending on the attempt type. If none of the pre-start checklist items has an unfavorable decision, the driller engine hour starts and takes its first movement.

v. In addition to equipment condition monitoring, blasting pattern information is retrieved simultaneously. The number of patterns, starting and ending drillhole codes of each driller, and clay availability of each drillhole are called. For instance, if three drillers operate jointly, the first driller can drill between DH01-70, the second between DH71-140, and the third between DH141-200. DH IDs are sequentially incremented values according to the advanced direction of each driller. Each drillhole code is coupled with a binary value (1/0) that points to clay availability.

vi. An active driller can be in one of three actions: Movement, positioning, and penetration. There can be three major types of movement, from the initial point to the first drillhole, between the drillholes in a similar row, and between the rows. Movement speed is assigned randomly from the drillers' related distribution functions, including the effect of unfavorable ground and weather conditions on it. Once any movement is completed, the driller is positioned according to the drillhole markers. The time required for positioning is different for drillers and is assigned randomly. Once the positioning is completed, the driller starts to penetrate the ground with a random value of penetration rate affected by driller type and availability of clay in the active drillhole. This study examined the presence and role of clay in drilling operations. Geological models can provide a guide by showing how much clay might be in the drilling site, but they sometimes give a partial picture of what drilling teams will encounter on the ground. Clay was assumed to be present in roughly 20% of all blastholes examined. This percentage gives a general idea but should be treated cautiously, as the actual amount can vary. Gathering more data from the drilling sites and comparing it to the initial findings can provide a more accurate understanding. Starting and ending drillholes of each driller for a multi-driller operation should be defined previously. Once the drilling operation is completed, the drillers move to their initial parking condition.

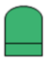
vii. After completion of pattern drilling for the active date, since there is generally a single blasting activity per day, the active date t_{ad} is incremented, and the decisions valid for the sequential dates are taken. In addition to the active date, the active hour (t_{ah}) is also captured during the operation, where t_{ah} takes the zero value by the start of January 1st as default. In this way, operation and maintenance decisions and the resultant availability and unavailability status can be recorded according to a reference point. As stated, one simulation is completed when the target observation time is over. The same simulation environment is simulated multiple times, representing almost all possible scenarios that can occur in a year. In addition to the active time, Day Time (DT) is also captured. The operation is assumed to be completed within the specified time interval during the day. If the DT exceeds 24 hours, the operation ends, and the active date increases by one.

viii. Various types of data are stored during the simulation to evaluate key performance indicators (KPIs) of drilling operation: Average penetration rate of each driller, the ratio between cumulative time to penetrate and cumulative engine hour of each driller, the average penetration rate of each driller according to weather and ground conditions, total expected time spent per drillhole, utilization and availability values of drillers, total corrective maintenance time per annum, and total preventive maintenance time per annum.

4.3 Construction of the Algorithm in Reliasoft Reno Software

ReliaSoft Reno offers an advanced simulation platform tailored for system reliability, availability, and maintainability analysis. Catering to both repairable and non-repairable systems, it serves as an essential tool for product engineers and asset managers. The software offers an intuitive graphical interface wherein users can construct and analyze complex systems via block diagrams (Table 4.7). These features empower users to explore multifaceted system architectures, highlighting the interrelations and dependencies inherent within them. Moreover, Reno is equipped with a robust simulation engine, emulating real-world system behaviors. This feature offers invaluable foresight into potential system vulnerabilities or strengths, facilitating preemptive action or strategy formulation. The software stands out in its ability to manage complex probabilistic or deterministic events through event analysis. It integrates inquiries within its algorithmic flowcharts, streamlining the decision-making hierarchy in event evaluations. This thesis study actively utilizes Event Analysis flowcharts to simulate the algorithm.

Table 4.7 Block Diagrams of the Event Analysis in Realisoft Reno

Event Analysis Flowchart Module Name	Symbol	Description
Standad Block		It evaluates a mathematical expression and then delivers the outcome of the expression (output value) to the flowchart's next block(s).
Result Storage Block		It saves numerical values that are provided to it during simulations and then computes or stores the outcome.
Conditional Block		A conditional block works in the same way as a "if" statement does. It compares the entering value to a conditional statement, with true and false as potential outputs.
Binary Node		A binary node multiplies an incoming value by a predetermined value. The "true" path receives the resulting value. The primary purpose of binary nodes is to make developing decision trees easier.
Summing Gate		It performs a basic mathematical operation on all incoming values and delivers a single value to all outgoing routes.
Logic Gate		A logic gate compares several incoming values to a conditional expression, with true and false as potential outputs.
Branch Gate		It is acting as a switch button. It compares the input value to a set of scenarios and returns different results depending on whether case or branch evaluates to true.
Flag Marker		The flag marker indicates a place in the flowchart's route.
Go to Flag Blocks		The Go to flag sends the execution flow to the place.
Counter Block		The number of times the simulation has gone through a counter block is recorded, and the value is subsequently sent to the next block in the flowchart.
Reset Block		While the simulation is running, the software is forced to produce new values for all static functions by reset block.
UI block		Until the user offers some type of input, a UI block pauses flowchart simulation.
Subchart Block		Other flowcharts in the project are represented by subchart blocks. Subchart blocks are commonly used to simplify the whole flowchart.

The developed algorithm is designed to manage and quantify Key Performance Indicators (KPIs) of production drilling activities in surface mines. Here, the event analysis flowcharts will be crucial in realizing mutual interactions between the principal and secondary parameters inherent in drilling activities. In this way, some insights into the performance fluctuations in the elements of a drilling operation will be offered, particularly as the operator can consider the uncertainties in varying operational conditions. Each block of Table 4.7 within the event analysis flowchart varies in appearance and utility depending on its type. These shapes aren't mere aesthetic choices but indicative of specific computational purposes.

Integration of an algorithm into a simulation environment necessitates a flexible approach. Various factors must influence its architecture, including the monitoring's temporal nature, frequency, and inherent unpredictabilities due to model uncertainties. Within the context of this thesis, the simulation model is characterized by three fundamental behaviors: stochasticity, dynamism, and discreteness. These characteristics ensure the model's robustness and ability to incorporate many random input variables, revealing the stochastic nature of drilling operations. The system state is monitored in some time intervals where the system state is exposed to a variation. In brief, a comprehensive understanding of drilling operations' performance metrics across diverse conditions on a time frame will be evaluated through detailed flowcharting, adaptive simulation, and rigorous monitoring.

The algorithm model possesses a high degree of adaptability, designed to accommodate many variables. These are diverse failure modes, different types of equipment, seasonal impact, the skill levels of the crew, and geological uncertainties. When assessing the Key Performance Indicators (KPIs) that significantly influence drilling operations, the system elements that encapsulate the uncertainties stemming from weather and environmental factors, the unpredictable nature of geological conditions, the varying competencies of the drilling crew, and the unpredictability related to equipment in the context of its maintainability and availability are captured. This comprehensive system design can allow determining a holistic view of many challenges and variables that drilling operations might encounter. Accordingly, the developed model is structured around five primary submodules, each with a unique identifier and function, as shown in Figure 4.1.

ID01 – Seasonal Check Module: This module evaluates the impact of various seasonal conditions on drilling operations, considering the challenges and advantages of each seasonal period particular to the implementation area.

ID02 - Preventive Maintenance Monitoring Module: A critical module focusing on proactive maintenance measures, it evaluated regular equipment checks and maintenance to prevent potential operational interruptions.

ID03 - Pre-start Checklist Evaluation Module: This module ensures all prerequisites and checklist items are controlled for each driller before starting any drilling operation, guaranteeing a smooth commencement of activities.

ID04 - Drilling Operation Module: This module deals with the core drilling processes, incorporating the complexities of geological uncertainties and crew competencies.

ID05 - Corrective Maintenance Module: When equipment failures or malfunctions are experienced, this module outlines the necessary corrective actions and strategies to restore driller productivity.

ID06 – Result Storage and Monitoring Module: At the end of each simulation cycle, this module collates and presents the outcomes, revealing the effectiveness of the operations and areas of potential improvement by storing data on the KPIs.

In summary, a comprehensive simulation model, which integrates many variables that drilling operations are susceptible to, is proposed. Its ability to account for seasonality, equipment conditions, crew competencies, and geological uncertainties offers a broad perspective on the uncertainties that can be experienced in drilling operations. As depicted in Figure 4.1, the modular design ensures a systematic approach, from preparatory checks to the actual drilling and eventual performance review, aiming for optimal operational efficiency.

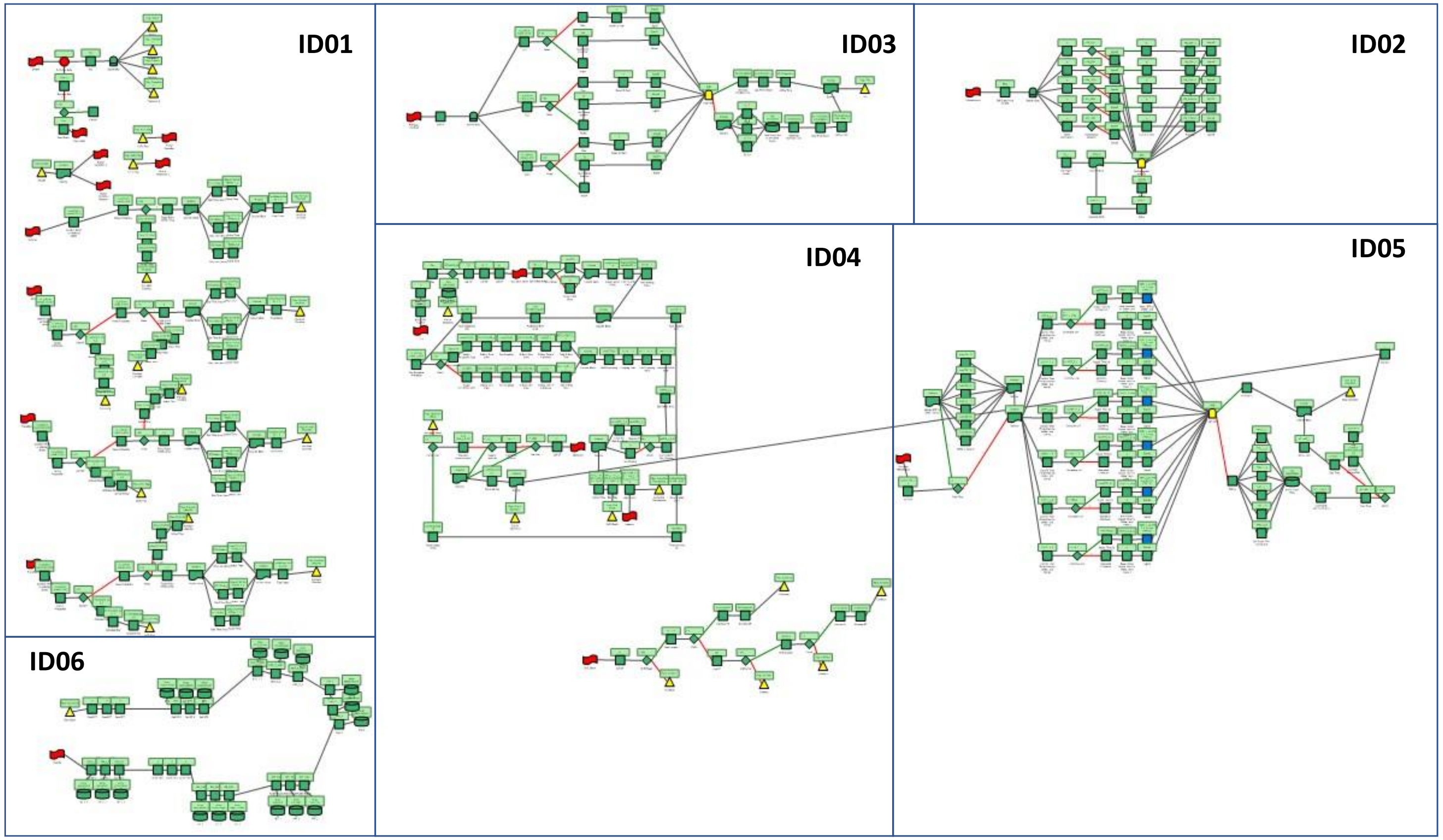


Figure 4.1 A General View of the Submodules

The computational model introduces different resource types, such as probability distribution functions, parameters/sets of parameters, and variables. Variables can be introduced with an initial value; however, their values change by overwriting new values on the old values whenever called. On the other hand, the parameters are introduced with their initial values but remain constant throughout the simulation without any data overwriting. The resources utilized in the Reliasoft Reno Model can be investigated in Table 4.8.

Table 4.8 The Resources Defined in the Relisoft Reno Environment

Parameters and Probability Distribution Functions (PDF)	
Abbreviation	**Definition**
$\mathrm{TBF_{component}(t)}$	PDF of Time between Failure
$\mathrm{TTR_{component}(t)}$	PDF of Time to Repair
$\mathrm{TBR(t)}$	PDF of Walking Time between Rows
$\mathrm{PR(t)}$	PDF of Penetration Rate
$\mathrm{Positioning(t)}$	PDF of Positioning Time
$\mathrm{FM(t)}$	PDF of First Move
$\mathrm{DCPC_{driller}(t)}$	PDF of Dust Collector Pipe Cleaning Time
$\mathrm{CT_{driller}(t)}$	PDF of Rod Coupling Time
$\mathrm{Checklist(t)}$	PDF of Checklist Time
$\mathrm{W.Speed(t)}$	PDF of Waking Speed
Burden	Distance from the free face to the nearest row of holes
Spacing	Distance between Drillholes in Row
Drillhole Length	Total Drillhole Length
BHN	# Blasthole
LB	Lunch Break
NOD	# of Drill Rig
ST	Simulation Target
Shift	Shift in a Day
Variables	
Abbreviation	**Definition**
$\mathrm{ART_{driller}}$	Active Repair Time of Driller
$\mathrm{AT_{driller}}$	Active Time of Driller
CT	Coupling Time
Day	Day
$\mathrm{DCPC_{driller}}$	Dust Collector Pipe Cleaning Time
$\mathrm{DT_{driller}}$	Day Time of Driller
Delay	Delay Time due to Weather Condition
TotalDelay	Total Delay Time due to Weather Condition
$\mathrm{EH_{driller}}$	Engine Hours of Driller
$\mathrm{EHT_{driller}}$	Total Engine Hours of Driller
$\mathrm{LTFP_{driller;\ component}}$	Life Time Finish Point of Driller Component
$\mathrm{PM250_{driller}}$	# of Preventive Maintenance (250h) of Driller
$\mathrm{PM500_{driller}}$	# of Preventive Maintenance (500h) of Driller
$\mathrm{PM2000_{driller}}$	# of Preventive Maintenance (2000h) of Driller
$\mathrm{PM6000_{driller}}$	# of Preventive Maintenance (6000h) of Driller
$\mathrm{PT_{driller}}$	Positioning Time of Driller
$\mathrm{RDH_{driller}}$	Rock Drill Hours of Driller
$\mathrm{TTR_{driller;\ component}}$	Time to Repair of Driller Component
$\mathrm{TWT_{driller}}$	Total Walking Time of Driller

After introducing the resources to the model with their initial values, the model initiates the seasonal check module (Figure 4.2). This process triggers the Day variable. Initially, this variable is set to one, referring to January 1st as default. Then, the Day variable proceeds to the BranchGate, where it undergoes a seasonal classification process. In this study, the mining site where the algorithm will be implemented is detected to experience four different seasons according to productional interruptions, called Season01, Season02, Season03, and Season04. When the Day value ranges between 1 and 120, it signifies the Season01, as determined by the *Classify the Season* gate (Figure 4.3). Upon entry into Season01, operational outcomes for any specific day are contingent on predefined probability measures. According to this probabilistic model, daily operations might either undergo a full postponement or experience delays, which can be attributed to environmental factors such as snow, fog, rain, or wind.

In scenarios where the Day is between 121 and 190, Season02 is assigned as the designated period (Figure 4.4). During this season, operational downtimes are considerably reduced compared to Season01. The embedded probability function determines the likelihood of any operational interruption on a given day. It is essential to highlight that this probability function is crucial in the decision-making phase, especially concerning operational delays across different seasons. This function is grounded in historical data amassed over three years, providing a robust framework for predictive analytics. If the Day variable is between 191 and 310, Season03 is assigned for the defined period (Figure 4.5). In this period, there are no cancellations or postponements for the Day. Delays may only occur due to unfavorable weather conditions such as strong wind, fog, or rain. However, the delay duration in this season is shorter than in any other season, as indicated in Table 4.4. Lastly, if the Day value is between 311 and 365, the active period turns to Season04, which is the transition season (Figure 4.6). In this interval, operational downtimes are higher than Season02 and Season03 yet remain lower than Season01. A predominant feature of Season04 is the recurrent impact on operations due to environmental challenges, specifically snow, fog, and wind. The Day variable increments upon the completion of daily operations. It will be further explained in the following modules. When the daily operations are ended, and the Day value is incremented, the Day Time (DT) is reset to zero, which is assumed to signify that the time is 13:00 p.m.

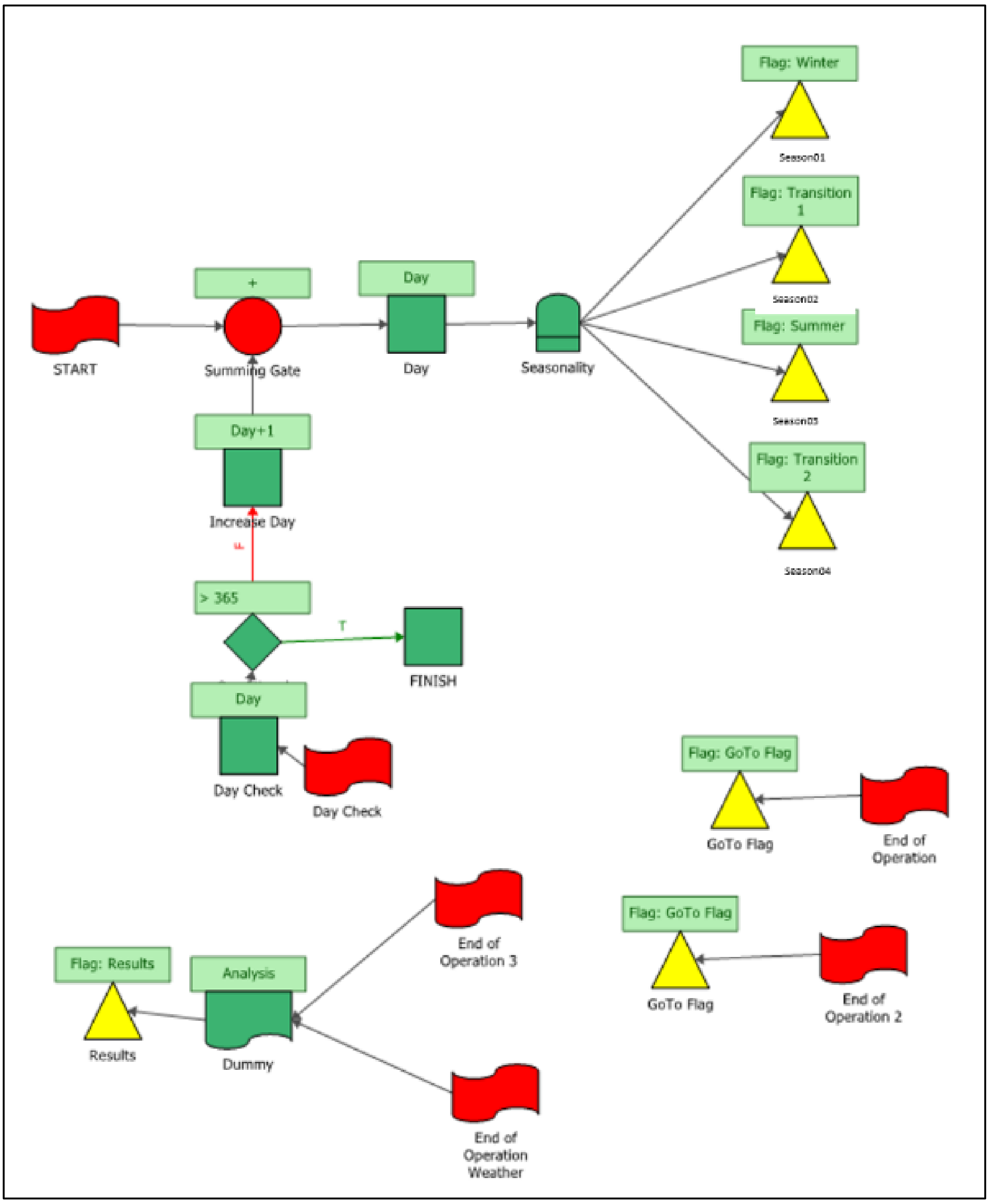


Figure 4.2 The Seasonal Check Module (ID01)

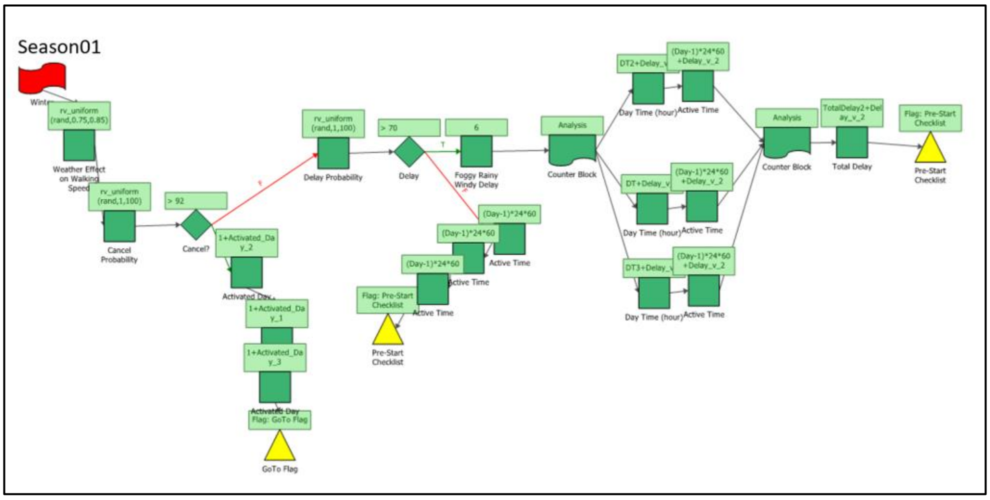


Figure 4.3 Season01 Module (ID01-01)

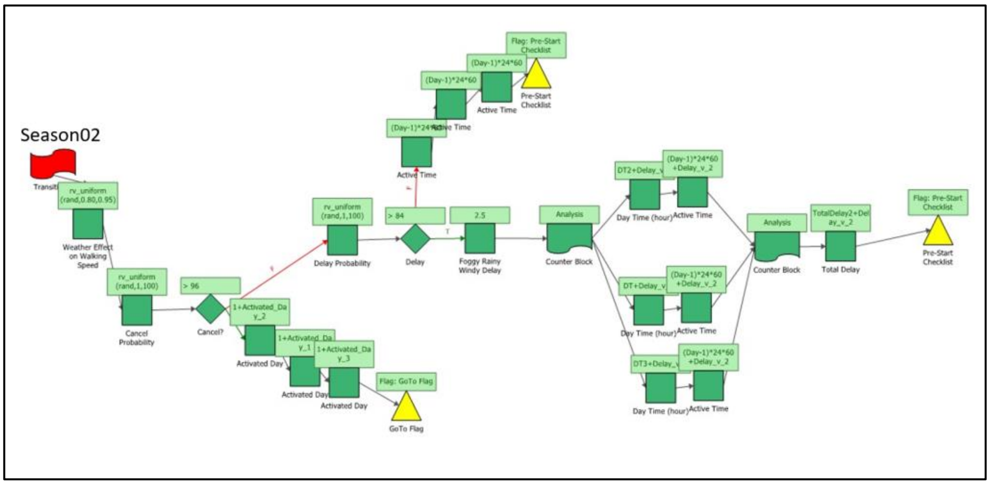


Figure 4.4 Season02 Module (ID01-02)

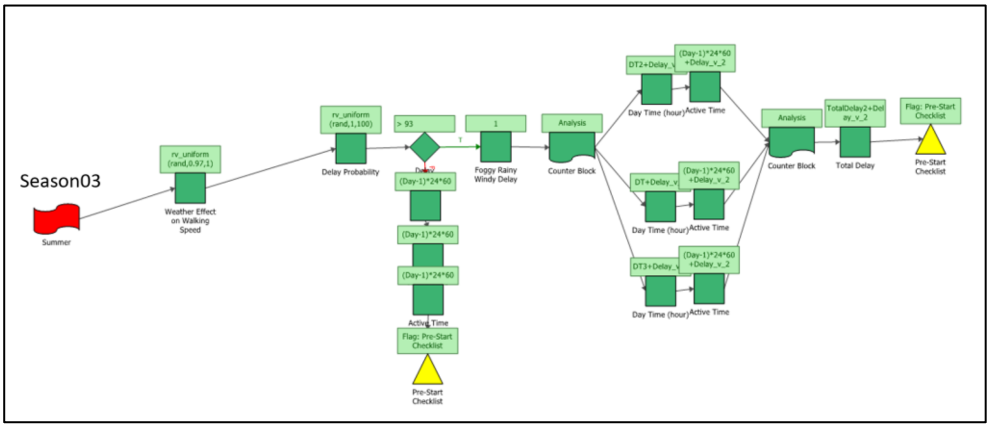


Figure 4.5 Season03 Module (ID01-03)

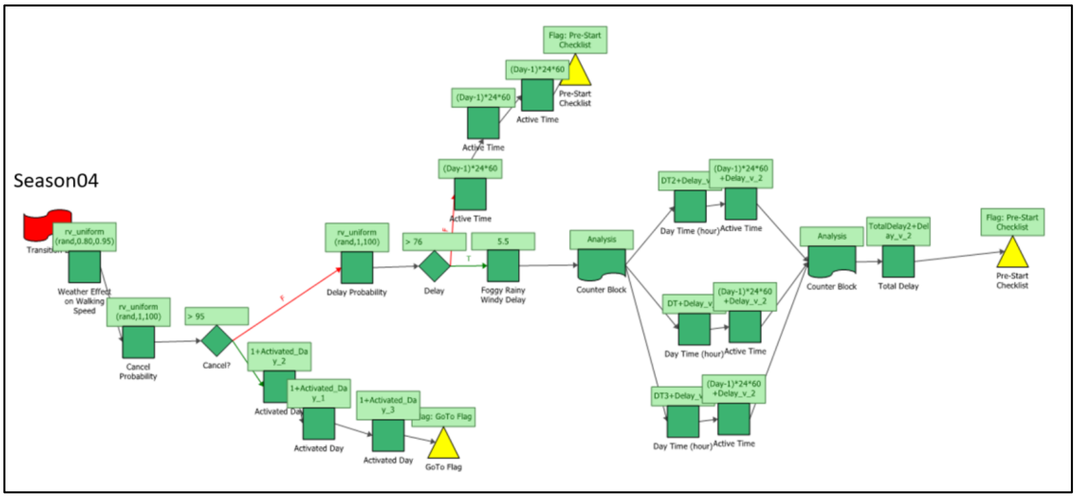


Figure 4.6 Season04 Module (ID01-04)

After deciding on the effect of seasonal conditions on drilling operations, which can be either the postponement of daily activities, continuity of operations in unfavorable conditions, or continuity of operations in favorable weather conditions, the simulation is followed by the Pre-Start Checklist Evaluation Module. Before initiating any drilling operation, the pre-start checklist evaluation module should be activated (Figure 4.7) In this specialized module, operators are tasked with systematically reviewing checklist items for each drill rig. There are 14 checklist items, as discussed in Table 3.2 under Section 3.3. After each checklist item is confirmed as satisfactory, the checklist distribution function is called into action. The time expended on completing the checklist is then accurately calculated and subsequently incorporated into the daytime metric. Furthermore, it is presupposed that an additional pre-checklist completion time increment will be added to the daytime. This additional time accounts for the operators' estimated time to complete the controls on the pre-start checklist. The checklist module will be activated at the beginning of each day. If multiple checklist items fail, the total downtime will be calculated as the sum of the delay times for each failed item. If these failed items are associated with components mentioned in the corrective maintenance module, the lifetime finish points for the affected drilling components will be regenerated. It was assumed that only the checklist items CL03, CL08, and CL10 impact the delay time. If multiple CL items fail, the delay time will be determined by the maximum delay resulting from those CL items. This delay will then be added to both the Day Time and Active Time for the specified driller.

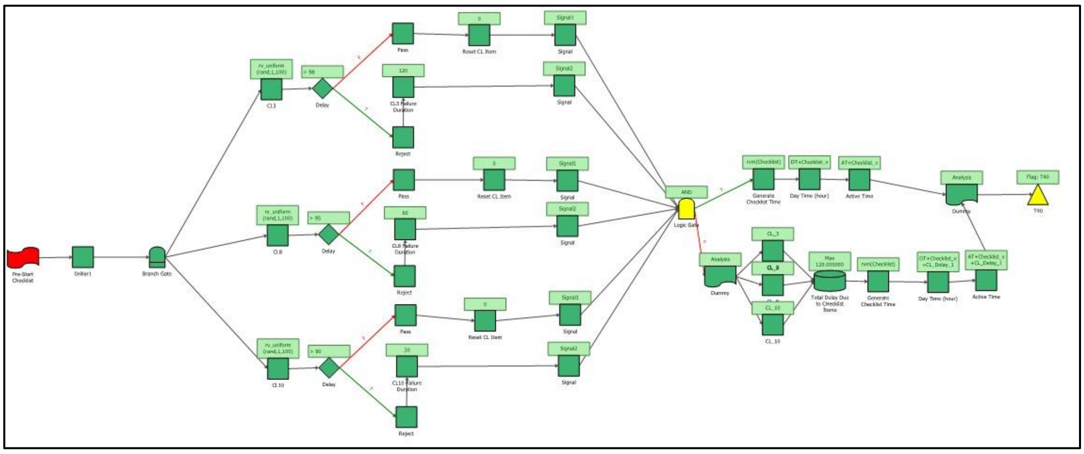


Figure 4.7 Pre-Checklist Item Evaluation Module (ID03)

The operations module is initiated after completing the checklist module (Figure 4.8). This module is significant as it comprehensively details the drilling procedure. If all items on the checklist are verified, the drilling operations can be commenced. The initial move time, which represents the time required for the drill rig to reach the starting position of the assigned first hole, is determined using the $FM(t)$ function. Subsequently, a specific speed for the drill is assigned by using $W.Speed(t)$ function. Using the assigned speed, the duration between the drill's initial position and the very first hole's location is calculated. Once this duration is determined, the drill rig is positioned. In this phase, the drill's boom is oriented to a vertical angle, precisely 90 degrees relative to the drilling surface. The time required for this positioning varies based on the surface inclination. Highly inclined surfaces necessitate longer setup times. This positioning duration is ascertained using the $Positioning(t)$ function, and the resulting time is stored for later evaluations.

After the drill rig is properly positioned, drilling begins at a variable penetration rate influenced by the type of driller and the presence of clay in the active drillhole. This study considered the impact of clay on drilling operations. While geological models offer a preliminary idea of potential clay content at the drilling site, they may not fully reflect the conditions drillers actually experience. In this context, it was assumed that about 20% of all the blastholes contained clay. However, this number serves as a rough guide and should be interpreted carefully. To gain a more accurate insight, additional field data might be collected and compared to these initial assessments.

After determining the clay condition in the drillholes, the operation continues with the assignment of the penetration rate, indicating the speed at which it will penetrate the ground, and it is established using the $PR(t)$ function. With this rate, the total drilling duration and operational hours for each drill can be deduced. In this study, two distinct types of drill rigs are utilized. Different drill rigs incorporate rods of varying lengths for the drilling process. For the SmartRoc T40 rig, for instance, it is assumed that the first rod accomplishes up to 75% of the total drilling depth. Once this depth is achieved, a second rod is attached to the initial one, necessitating additional time. This coupling duration is identified using the $CT(t)$ function. Following this attachment, the remaining depth of the hole is drilled using the second rod. After the completion of a hole, a tally of the total drilled holes is maintained. On the other hand, the FlexiRoc T35 does not require a second rod attachment because its rod length is sufficient enough to drill a single drillhole.

A pause is taken every three holes to clean a pipe responsible for dust collection. Proper maintenance of this pipe is essential as it aids in accurate sample collection from the drilling. If not cleaned adequately, there is a risk of sample contamination from different holes. In this scenario, when cleaning becomes necessary, the dust collector pipe-cleaning function $DCPC_{driller}(t)$ is invoked for the specified drill rig. Following this cleaning process, an assessment is done on the total number of holes drilled in the pattern to determine if the drilling pattern has been completed. If the pattern hasn't been finished, a simple MOD formula is employed to determine the movement between rows of holes.

It is assumed that the drilling patterns take on a rectangular shape. On the shorter side of this rectangle, 15 holes are planned, while the longer side is designed to accommodate 30 holes. The entire pattern comprises around 450 holes in total. If, in the process, the drill rig finishes drilling the holes in the active row and needs to pass to the next row, a walking speed for that drill rig is set. This speed is essential because it helps determine the time the drill rig will take to move between rows. This time is calculated via the assigned walking speed and the actual distance that separates one row from the next. The process is repeated until all the drillholes have been completed.

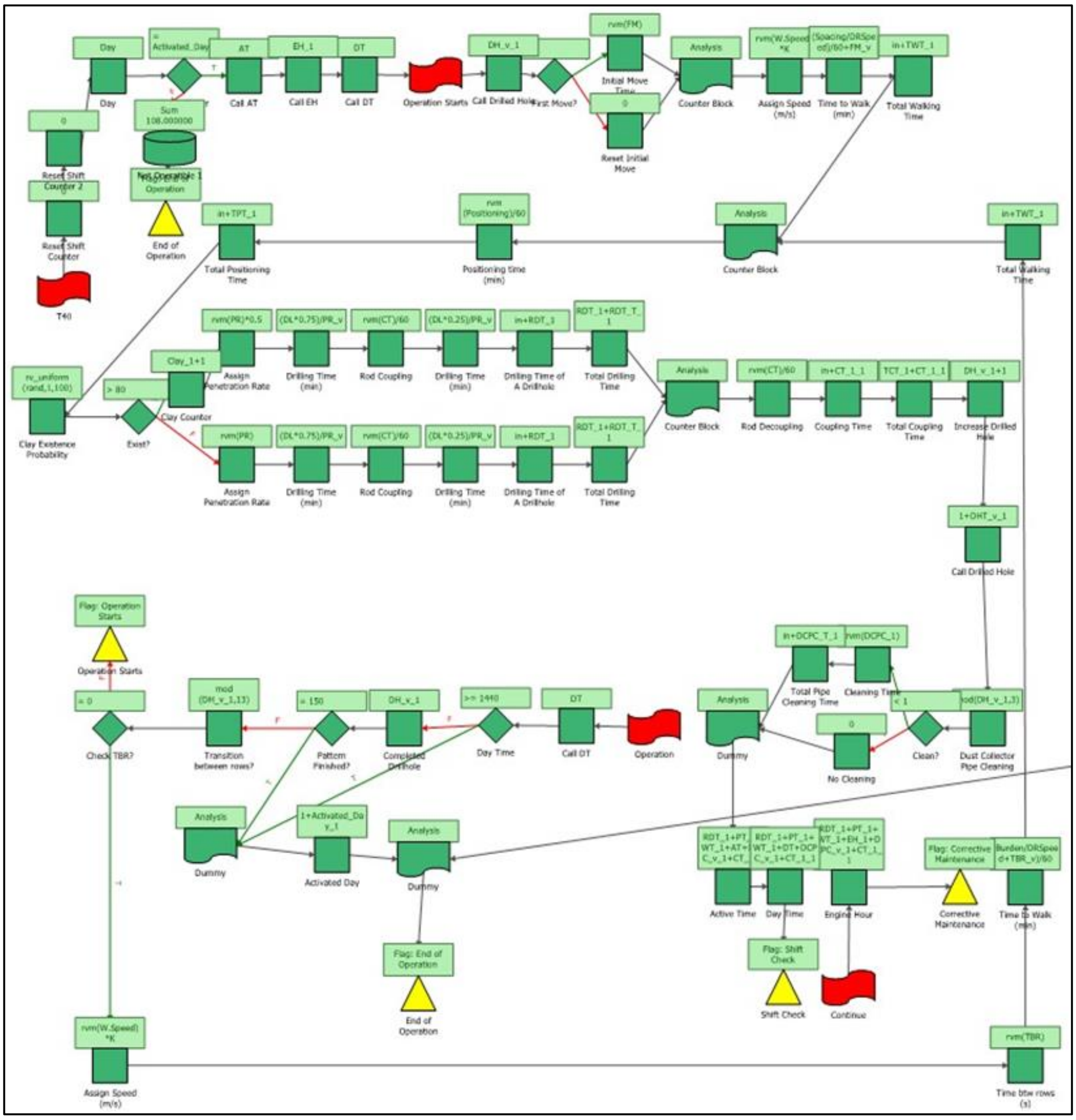


Figure 4.8 The Drilling Operation Module (ID04)

The corrective maintenance module is initiated by examining the lifetime finish point of each component (Figure 4.9). It is assumed that at the very beginning of the simulation model, the lifetime finish point for all components is generated from the $TBF(t)$ function. To determine if a specific component for a particular driller needs repair or replacement, it's essential to first identify the malfunctioning component. The total drilling length must be examined to assess if the first component (bit) requires replacement. If the initially assigned TBF (Time Between Failures) value is less than the total drilling length, corrective maintenance is initiated for that component. The total rock drill hours should be examined if the second component (rod) requires replacement or repair. If the initially assigned TBF (Time Between Failures) value is less than the rock drill hours for the specified driller, corrective maintenance is initiated for that component. If the third component (shank) requires replacement or repair, the total rock drill hours should be reviewed, similar to the procedure for rod failure. If the initially assigned TBF (Time Between Failures) value is less than the rock drill hours for the specified driller, corrective maintenance is initiated for that component. If the fourth component (rock drill) needs replacement or repair, the total rock drill hours warrant examination, following the same procedure as for rod and shank failures. When the initially assigned TBF (Time Between Failures) value is less than the rock drill hours allocated to the specified driller, corrective maintenance for that component is triggered. The total engine hours should be reviewed if the fifth component (hydraulic) require replacement or repair. When the initially assigned TBF (Time Between Failures) value is less than the engine hours designated to the specified driller, corrective maintenance for that component is initiated. Similarly, for the sixth and final component (mechanic) requiring replacement or repair, the total engine hours are examined, like the hydraulic component. Corrective maintenance for that component is undertaken if the initially assigned TBF (Time Between Failures) value is less than the engine hours designated to the specified driller. If a corrective maintenance decision is taken for any component, a repair time is derived from the corresponding $TTR(t)$ function. There are six major components that are prone to fail during operations.

The assigned time-to-repair values are also stored cumulatively for each driller to be used in availability estimations. A new lifetime finish point for the maintained component is assigned just after the maintenance activity. Therefore, this initial assignment will take the value summing the previous lifetime finish value, random time-to-repair from $TTR(t)$, and new random time-between-failure from $TBF(t)$. This lifetime finish point will be also extended for the periods where the components are inactive due to corrective maintenance activities of other driller components, administrative halts, and non-operational time due to completion of the daily pattern drilling. During any corrective maintenance downtime, the drill rig will be non-operational. If there's enough time left to complete the drill pattern, the remaining drill holes are redistributed among the other drillers. However, a backup drill rig must be deployed to substitute the failed driller if time isn't insufficient. In this way, all drillholes are ensured to be drilled before blasting operations. In addition, this module operates in conjunction with the other modules. For instance, when the drilling of each hole is completed, this module operates automatically and monitors the remaining lifetime of the components. Alternatively, this module operates alongside checklist items. If any downtime occurs due to a component as indicated in the checklist, and if that component is any of the six failure modes mentioned above, the lifetime of that component is extended by calculating the next failure interval by using the $TTR(t)$ function. When each blasthole is completed, the corrective maintenance module becomes active and instantly checks whether corrective maintenance is required for the specified driller components. If no corrective maintenance is required, the operation reverts to the operation module and first assesses whether the drillholes are complete. If drilling is still underway, the system checks for a transition between rows. In case a transition occurs, the time spent during this movement is added to the driller's total walking time. If there is no transition between rows, the operation resumes at its previous point and proceeds to the next drillhole.

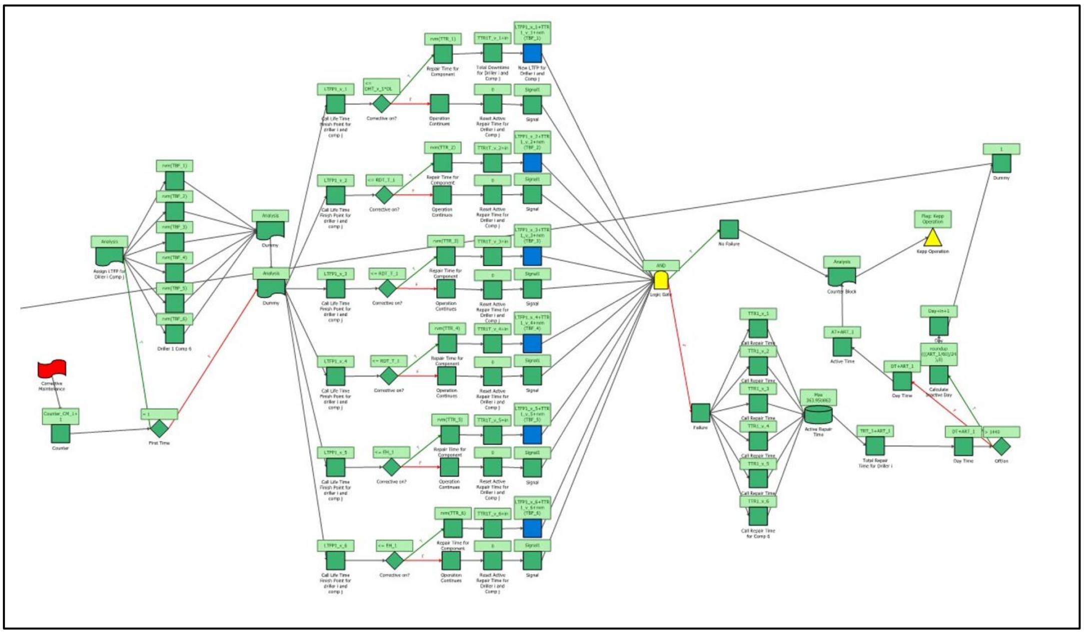


Figure 4.9 Corrective Maintenance Module(ID05)

Preventive Maintenance Monitoring Module in case of a positive decision on performing the drilling operation (Figure 4.10). In this module, the model evaluated the Engine Hours of the drillers to initiate any scheduled preventive maintenance. The accumulation of engine hours corresponds to the period the driller remains active, signifying that the engine is running, regardless of whether actual drilling occurs. Upon completion of a drilling operation, this module evaluates the engine hours for each drill rig (driller).

Based on the cumulative up-to-date engine hours, scheduled preventive maintenance procedures are determined as follows:

0-250 Hours: No preventive maintenance is required.

Every 250 Hours: A singular maintenance operation is conducted, focusing on replacing engine oil. This essential task ensures the driller engine's optimal performance and typically concludes within an hour.

Every 500 Hours: Maintenance extends to not only replacing the engine oil but also substituting the hydraulic oil. Even with this added procedure, the entire maintenance session is usually completed in about an hour.

Every 1000 Hours: The preventive maintenance every 1000 hours involves changing both engine and hydraulic oils and a comprehensive replacement of all the rig's filters. Typically, this process takes around two hours.

Every 2000 Hours: The maintenance protocol at this stage is comprehensive, encompassing all tasks undertaken during the 1000-hour service, augmented by several intricate procedures. This maintenance session is notably extensive, generally necessitating a full day (or roughly 24 hours) for completion.

Every 6000 Hours: The rig undergoes a maintenance regimen analogous to the one executed at the 2000-hour mark. It also typically spans 24 hours.

In addition to any decision for preventive maintenance for any driller, the number of maintenance services performed at the 250, 500, 1000, 2000, and 6000-hour intervals are also stored for each driller. The engine hours of each driller are set to zero initially at the beginning of each simulation. If any preventive maintenance decision is given, the lifetime finish points of the maintained components are extended due to the positive impact of preventive maintenance on those components. Moreover, if a driller is detected to experience any preventive maintenance, all the preventive maintenance work packages are assumed to be completed before the drilling operation the next day. Therefore, preventive maintenance has no negative contribution to the operational availability of drillers since they are assumed to be performed between the completion of the daily operation and the start of the operation the next day. Still, it can create some additional financial burden. The feasibility of preventive maintenance activities is out of scope under the current study.

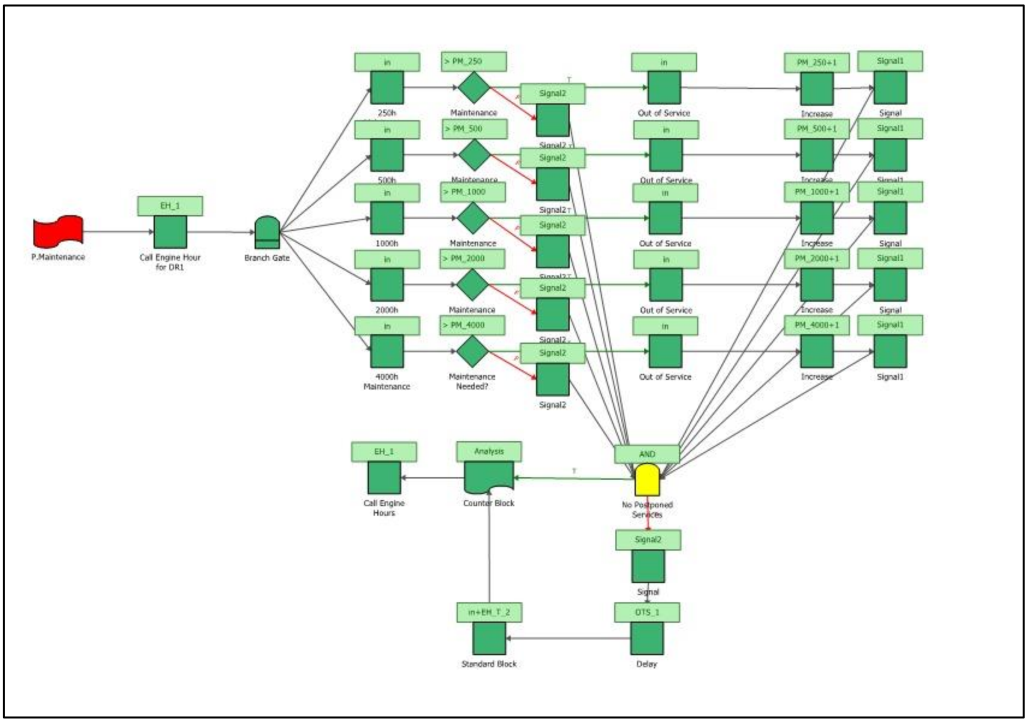


Figure 4.10 Preventive Maintenance Monitoring Module (ID02)

Last, the result storage and monitoring module stores and visualizes the simulation metrics, such as the availability and utilization of the drill rigs, total downtimes, the number of corrective and preventive maintenance instances, and delays due to weather and environmental conditions (Figure 4.11).

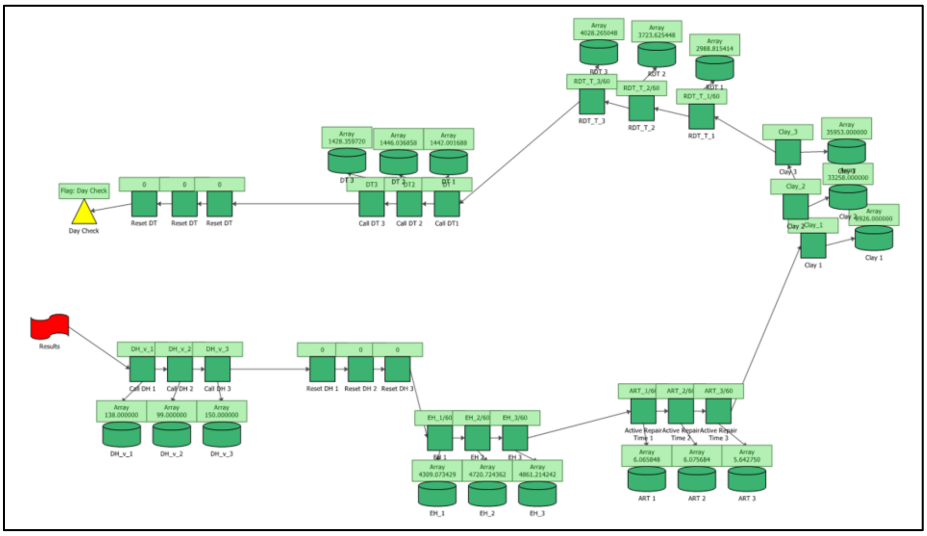


Figure 4.11 Result Storage and Monitoring Module (ID06)

4.4 Input Dataset used for the Simulation Implementation

As discussed in Section 4.2, two types of datasets, which are the sets of constant values (parameters) and probability distribution functions, are required to implement the developed simulation algorithm. At this point, the parametric values of the probability distribution functions were determined using expert opinions from the operators and artisans with long-term experience in operating and maintaining the drillers. Accordingly, two extreme points and the most expected values are asked to build up expert data (triangular) distributions. Extreme points refer to the minimum and maximum points experienced before, while the most expected is the point that should be stated in the case of a single value determination as the most frequently experienced value. The parameters and the probability distribution functions used as input can be viewed in Table 4.9 while the variables are tabulated in Table 4.10.

Table 4.9 Parameters and Probability Distribution Functions (PDF)

PDFs		Parameters	
Abbreviation	**Value**	**Abbreviation**	**Value**
$TBF_{component}(t)$	$TBF_1(t)$: tri, dist(400, 2000,4000)	Burden	3
	$TBF_2(t)$: tri, dist(3860,6750,9000)	Spacing	3.25
	$TBF_3(t)$: tri, dist(8210,11730,21900)	Drillhole Length	5.5
	$TBF_4(t)$: tri, dist(9000,16200,30000)	BHN	450
	$TBF_5(t)$: tri, dist(2970,6930,13860)	LB	60
	$TBF_6(t)$: tri, dist(3465,6930,13860)	NOD	5 (2 spares)
$TTR_{component}(t)$	$TTR_1(t)$: tri, dist(7,10,20)	ST	365
	$TTR_2(t)$: tri, dist(5,10,30)	Shift	3
	$TTR_3(t)$: tri, dist(45,60,150)		
	$TTR_4(t)$: tri, dist(450,990,6930)		
	$TTR_5(t)$: tri, dist(120,450,2700)		
	$TTR_6(t)$: tri, dist(660,990,6390)		
TBR(t)	TBR(t): tri, dist(20,30,45)		
PR(t)	PR(t): tri, dist(0.55,1.2,1.6)		
Positioning(t)	Positioning(t): tri, dist (7,9,20)		
FM(t)	FM(t): tri, dist(8,12,25)		
$DCPC_{driller}(t)$	$DCPC_1(t)$: tri, dist(1,1.5,6)		
	$DCPC_2(t)$: tri, dist(1,1.5,6)		
	$DCPC_3(t)$: tri, dist(1,1.5,6)		
	$DCPC_4(t)$: tri, dist(1,1.5,6)		
	$DCPC_5(t)$: tri, dist(1,1.5,6)		
	$DCPC_6(t)$: tri, dist(1,1.5,6)		
CT(t)	CT(t): tri, dist(10,12,15)		
Checklist(t)	Checklist(t): tri, dist(15,20,30)		
W. Speed(t)	W. Speed(t): tri, dist(0.47,0.7,1)		

Table 4.10 Variables Used in Algorithm and Their Initial Values

Variables	
Abbreviation	**Initial Value**
$ART\_DR_{driller}$	0
AT	0
CT	0
Day	0
$DCPC_{driller}$	0
DT	0
$EH_{driller}$	0
$EHT_{driller}$	0
$LTFP_{driller;\ component}$	0
$PM250_{driller}$	0
$PM500_{driller}$	0
$PM2000_{driller}$	0
$PM6000_{driller}$	0
$PT_{driller}$	0
$RDH_{driller}$	0
$TTR_{driller;\ component}$	0
$TWT_{driller}$	0

4.5 Implementation Results

Various types of data are stored during the simulation to evaluate key performance indicators (KPIs) of drilling operation: Average penetration rate of each driller, the ratio between cumulative time to penetrate and cumulative engine hour of each driller, the average penetration rate of each driller according to weather and ground conditions, total expected time spent per drillhole, utilization and availability values of drillers, total corrective maintenance time per annum, and total preventive maintenance time per annum. In the comprehensive analysis conducted with the advanced algorithm developed using the ReliaSoft RENO software, the ensuing results are delineated below. After obtaining these outcomes, they were further refined and processed using the Minitab software. The methodology followed in this intricate procedure is detailed in the subsequent sections. The algorithm has been applied to an authentic drilling operation in an open-pit mine in a practical setting. This operation encompasses a range of variables: it involves three distinct drillers, employs two different types of drilling machines, navigates through two unique geological formations, operates under four varying weather conditions, and addresses maintenance needs for six different driller components. This intricate interplay of factors provides a whole representation of the drilling dynamics in the mining operation.

Firstly, a boxplot test was applied for each set of outcomes. Outliers can be easily spotted in a boxplot as data points that fall outside of the whiskers. Sample pre-processing of the outcome values will be shown for Driller 1- EH (Engine Hour). Accordingly, the boxplot test graph for Driller 1 – EH (Engine Hours) can be seen in Figure 4.12.

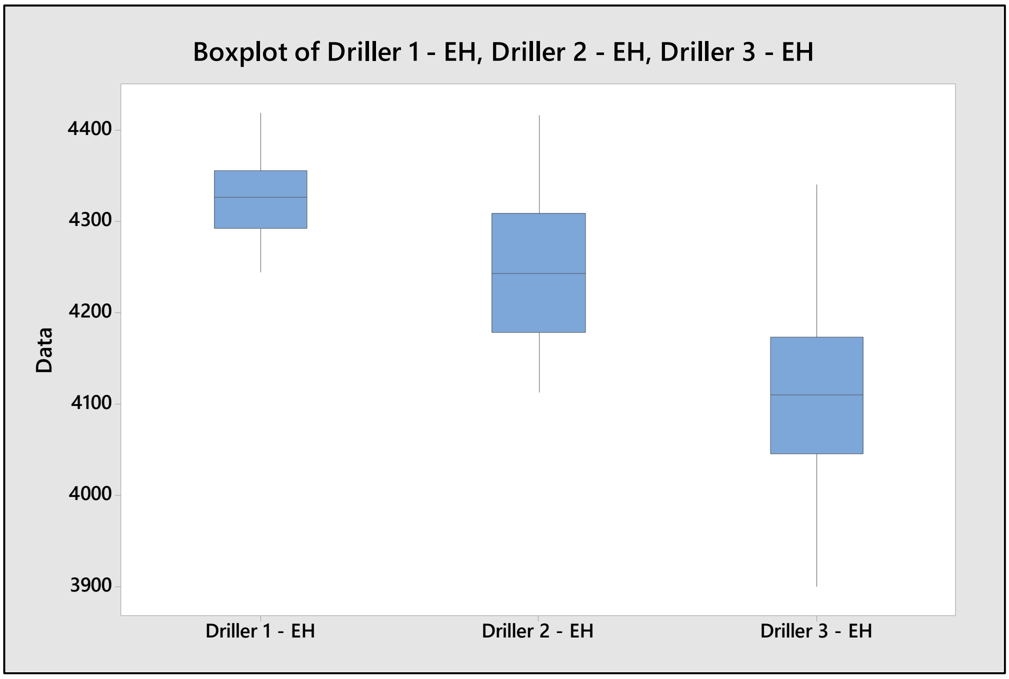


Figure 4.12 Boxplot Test for the EH (Engine Hour) Results

Second, a run chart was used to detect whether the Driller 1 – EH data is sensitive to the variation in time. The run chart for the given data can be seen in Figure 4.13. The figure shows that the approximate p-values for clustering and trends are above 0.05. This value suggests that the data are randomly distributed without any time affect.

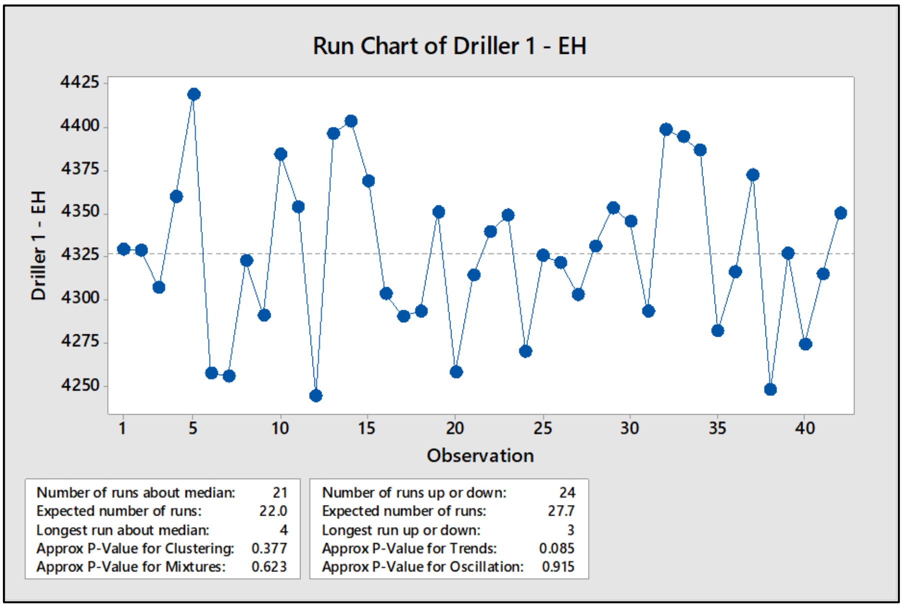


Figure 4.13 Run Chart Test for Driller 1 – EH Results

Last, a goodness of fit test was performed to determine the best-fit distribution for the related outcome dataset. The highest P-values, which should be higher than 0.05 for a 95% confidence interval, point to the best-fit distribution. Here, the goodness of fit determination with the Anderson-Darling (AD) test can be examined in Table 4.11. Here, lognormal and normal distributions are determined as the best-fit for the Driller 1 – EH outcome data. Accordingly, the lognormal probability plot and the histogram can also be investigated in Figure 4.14 and Figure 4.15, respectively.

Table 4.11 Anderson-Darling Test for Driller 1- EH Results

Distribution	AD	P
Normal	0.205	0.863
Box-Cox Transformation	0.205	0.863
Lognormal	0.203	0.868
3-Parameter Lognormal	0.218	*
Exponential	18.867	<0.003
2-Parameter Exponential	3.33	<0.010
Weibull	0.583	0.133
3-Parameter Weibull	0.236	>0.500
Smallest Extreme Value	0.606	0.112
Largest Extreme Value	0.486	0.225
Gamma	0.22	>0.250
3-Parameter Gamma	0.256	*
Logistic	0.248	>0.250
Loglogistic	0.247	>0.250
3-Parameter Loglogistic	0.246	*

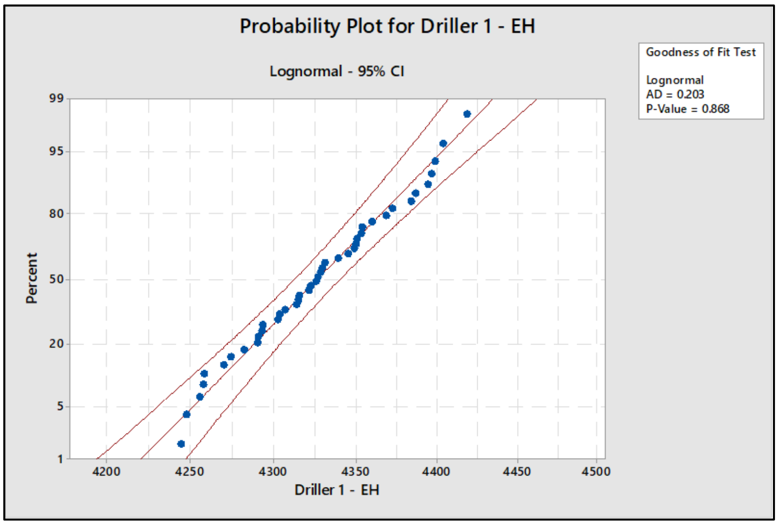


Figure 4.14 Probability Plot of Driller 1 – EH Results

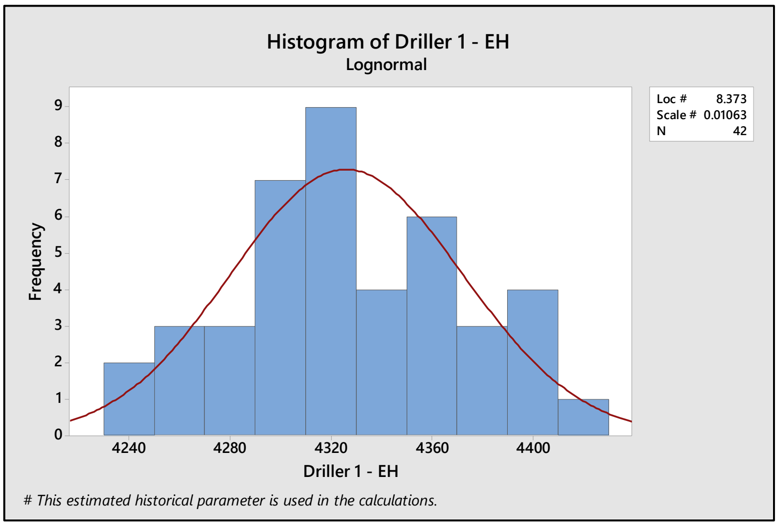


Figure 4.15 Histogram of Driller 1 – EH Results

The histograms and the fitted distribution lines for all monitored outcomes of the three drillers can be seen in Figures 4.16 to 4.22. The resultant parametric values of these best-fit distributions are given in Table 4.12. Since normal or quasi-normal distributions are observed for all outcome datasets, their descriptive statistics in terms of mean and standard deviation are also listed in Table 4.13.

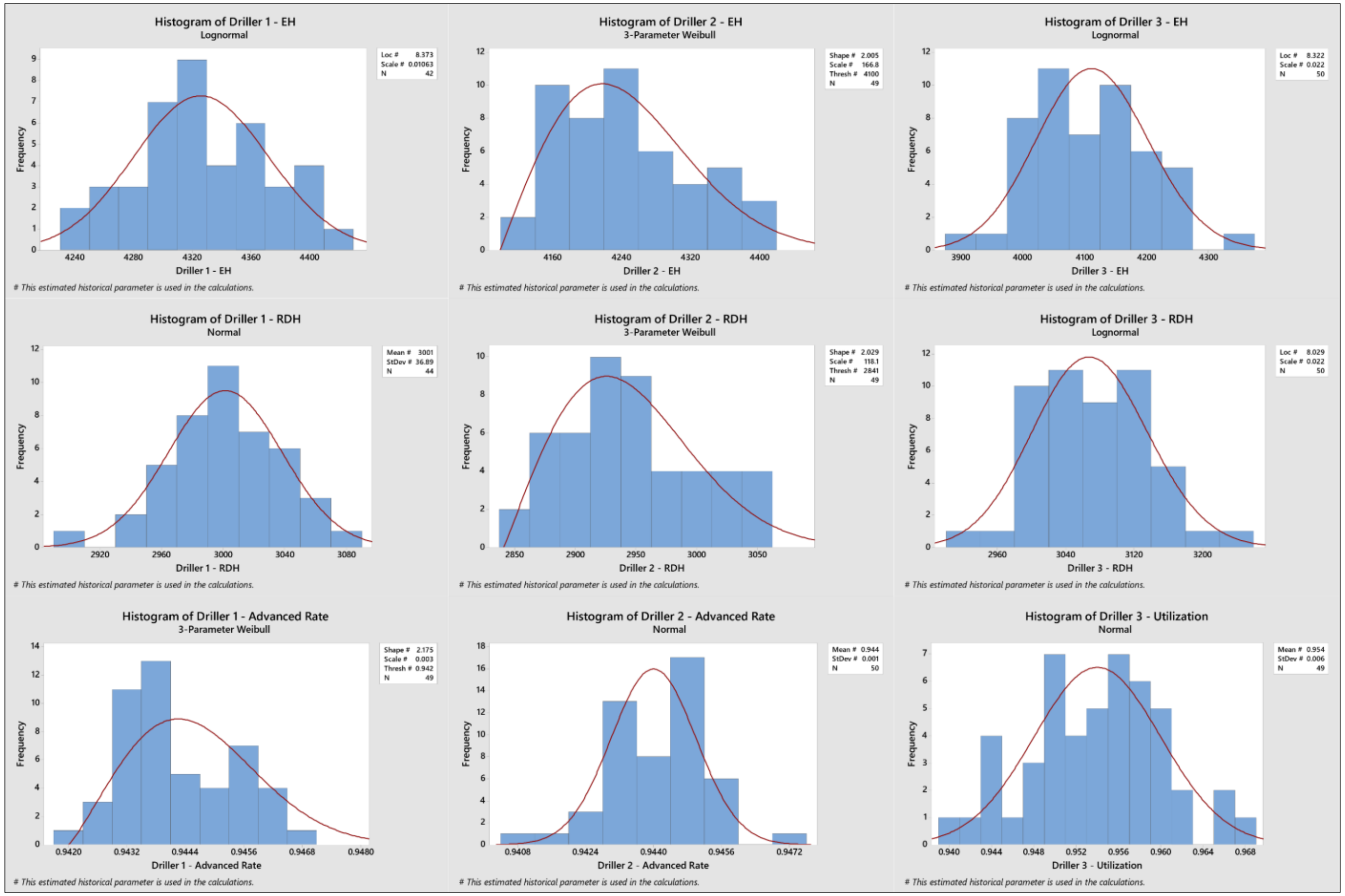


Figure 4.16 Histograms of the EH, RDH, and Advance Rate Results for the Drillers

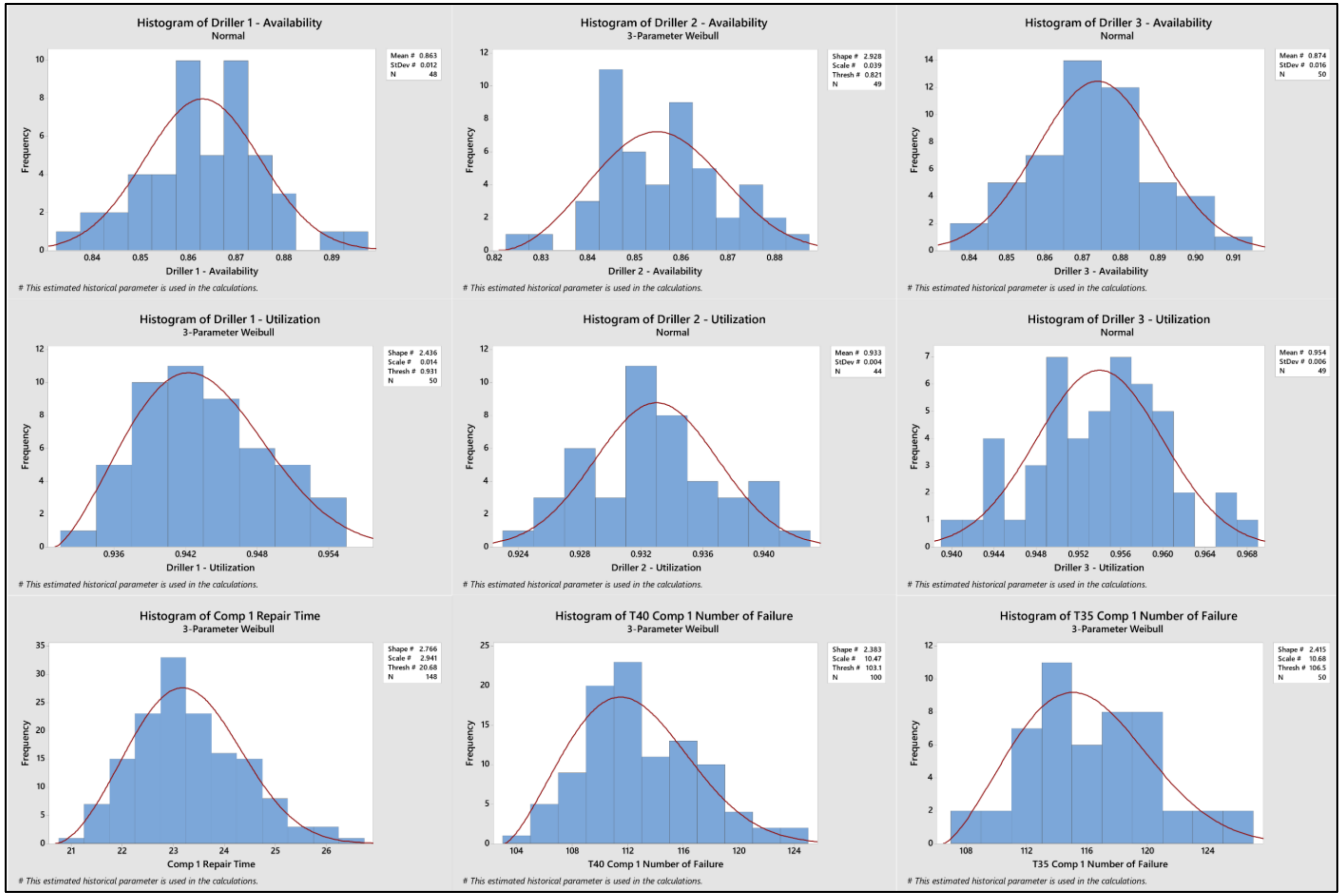


Figure 4.17 Histograms of the Availability, Utilization, and Component-1 Maintenance Results for the Drillers

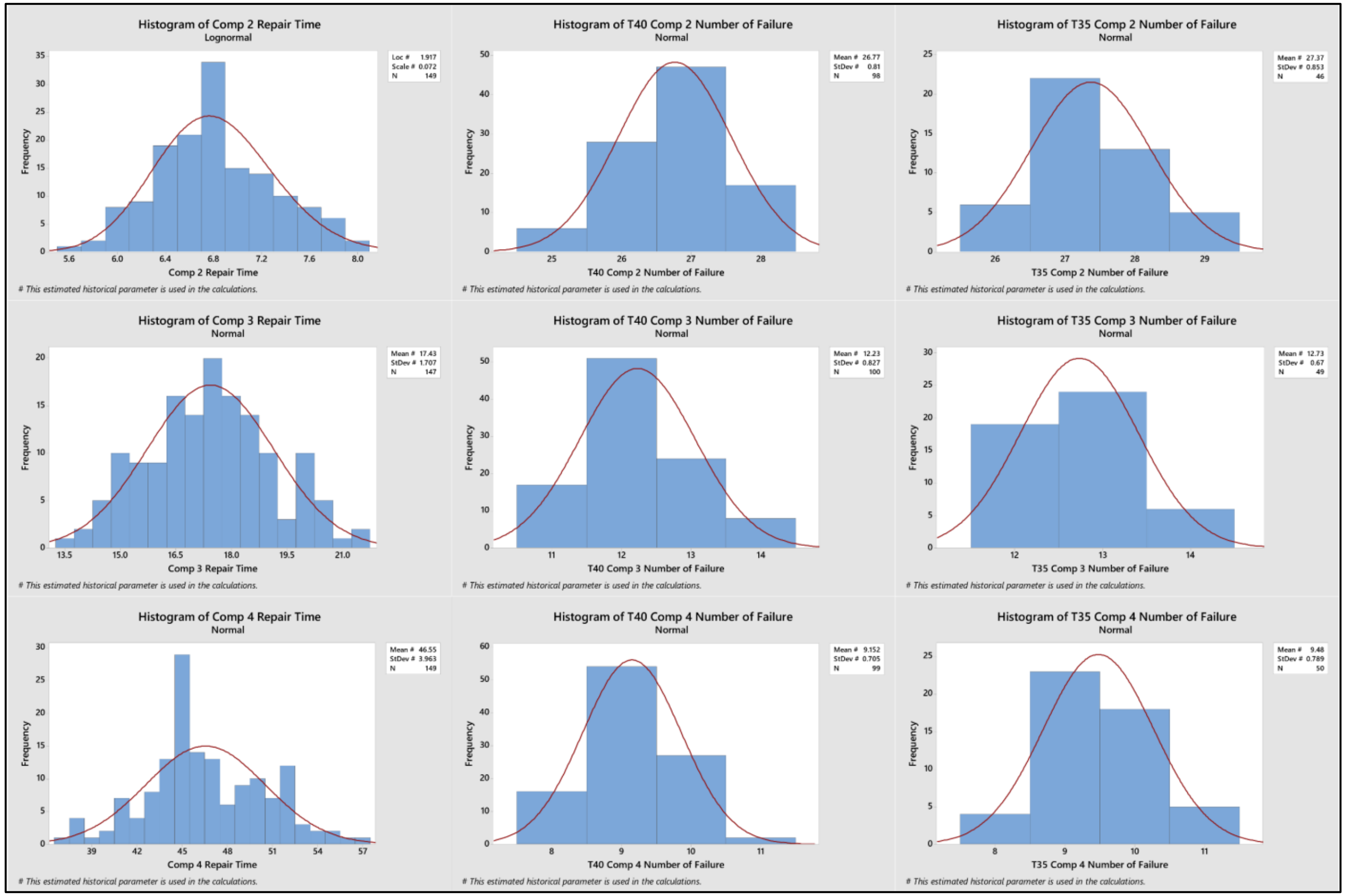


Figure 4.18 Histograms of the Component 2, Component 3, and Component 4 Maintenance Results

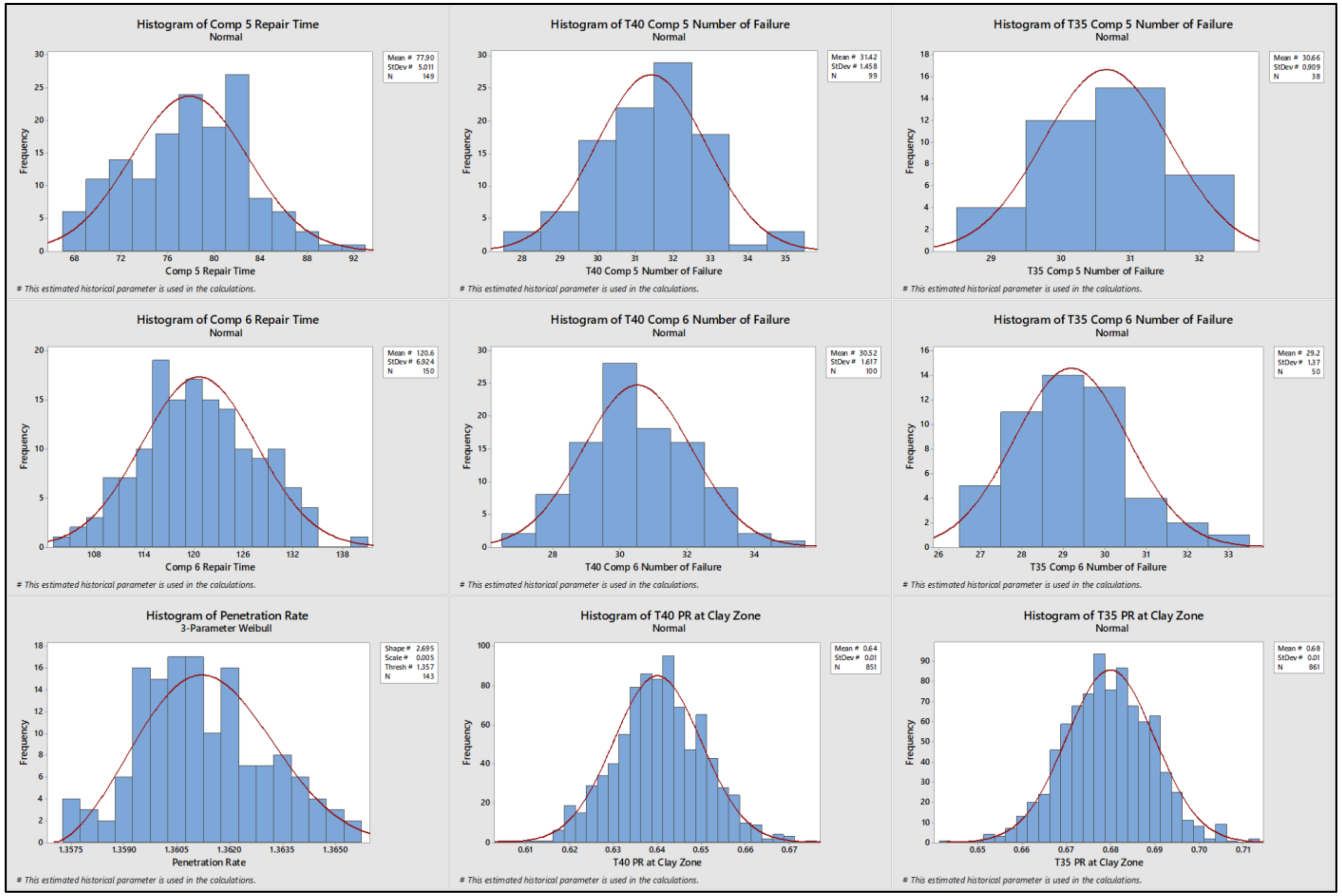


Figure 4.19 Histograms of the Component 5 & 6 Maintenance and Penetration Rate Results

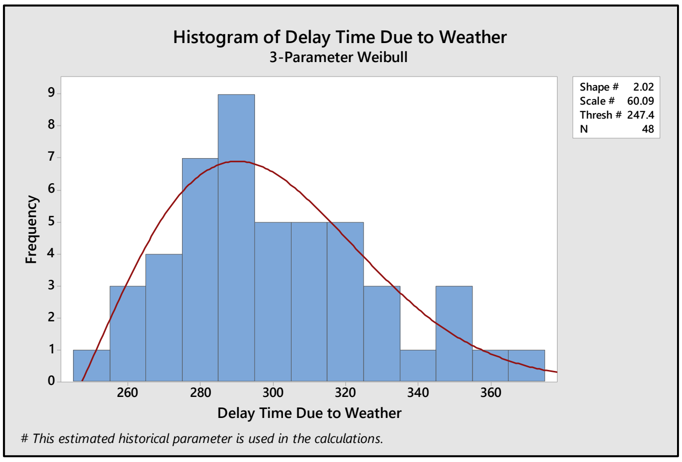


Figure 4.20 Histogram of the Delay Times due to Unfavorable Weather

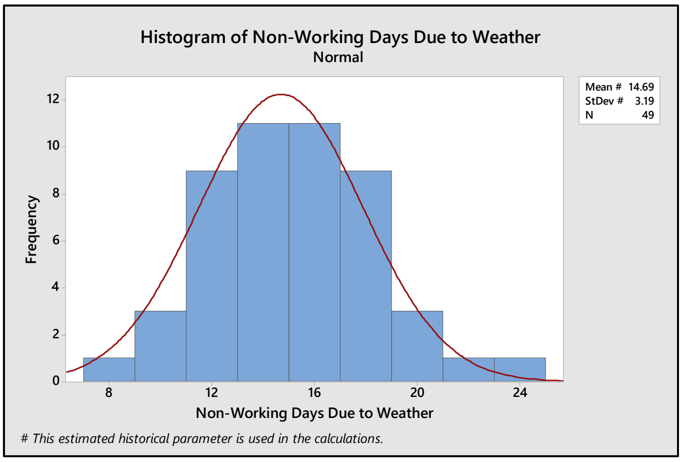


Figure 4.21 Histogram of the Non-Working Days due to Unfavorable Weather

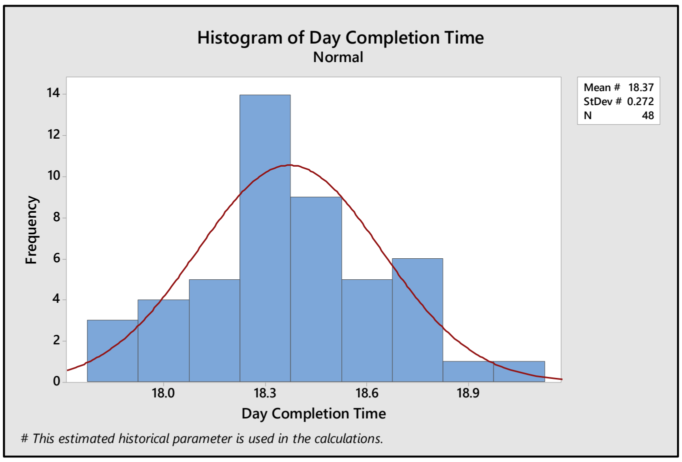


Figure 4.22 Histogram of the Completion Times

Table 4.12 Best-Fit Distribution Parameters of the Monitored KPI Values

Variable	Distribution	Location	Shape	Scale	Threshold
Driller 1 - EH	Lognormal	8.373		0.011	
Driller 2 - EH	3-Parameter Weibull		2.005	166.751	4099.855
Driller 3 - EH	Lognormal	8.322		0.022	
Driller 1 - RDH	Normal	3001.346		36.893	
Driller 2 - RDH	3-Parameter Weibull		2.029	118.121	2841.257
Driller 3 - RDH	Lognormal	8.029		0.022	
Driller 1 - Advanced Rate	3-Parameter Weibull		2.175	0.003	0.942
Driller 2 - Advanced Rate	Normal	0.944		0.001	
Driller 3 - Advanced Rate	Normal	1.016		0.001	
Penetration Rate	3-Parameter Weibull		2.695	0.005	1.357
Driller 1 - Availability	Normal	0.863		0.012	
Driller 2 - Availability	3-Parameter Weibull		2.928	0.039	0.821
Driller 3 - Availability	Normal	0.874		0.016	
Driller 1 - Utilization	3-Parameter Weibull		2.436	0.014	0.931
Driller 2 - Utilization	Normal	0.933		0.004	
Driller 3 - Utilization	Normal	0.954		0.006	
Comp 1 Repair Time	3-Parameter Weibull		2.766	2.941	20.680
T40 Comp 1 # of Failure	3-Parameter Weibull		2.383	10.474	103.134
T35 Comp 1 # of Failure	3-Parameter Weibull		2.415	10.684	106.484
Comp 2 Repair Time	Lognormal	1.917		0.072	
T40 Comp 2 # of Failure	Normal	26.765		0.810	
T35 Comp 2 # of Failure	Normal	27.370		0.853	
Comp 3 Repair Time	Normal	17.434		1.707	
T40 Comp 3 # of Failure	Normal	12.230		0.827	
T35 Comp 3 # of Failure	Normal	12.735		0.670	
Comp 4 Repair Time	Normal	46.547		3.963	
T40 Comp 4 # of Failure	Normal	9.152		0.705	
T35 Comp 4 # of Failure	Normal	9.480		0.789	
Comp 5 Repair Time	Normal	77.899		5.011	
T40 Comp 5 # of Failure	Normal	31.424		1.458	
T35 Comp 5 # of Failure	Normal	30.658		0.909	
Comp 6 Repair Time	Normal	120.608		6.924	
T40 Comp 6 # of Failure	Normal	30.520		1.617	
T35 Comp 6 # of Failure	Normal	29.200		1.370	
T40 PR at Clay Zone	Normal	0.640		0.010	
T35 PR at Clay Zone	Normal	0.680		0.010	
Delay Time Due to Weather	3-Parameter Weibull		2.020	60.095	247.356
Non-Working Days Due to Weather	Normal	14.694		3.190	
Day Completion Time	Normal	18.372		0.272	

Table 4.13 Descriptive Statistics of the Monitored KPI Values

Variable	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Driller 1 - EH (h)	42	4326.700	46.000	4244.300	4292.400	4326.200	4355.200	4418.500
Driller 2 - EH (h)	49	4247.600	77.900	4111.700	4178.200	4242.800	4308.400	4415.900
Driller 3 - EH (h)	50	4113.700	89.100	3899.500	4045.400	4109.800	4173.300	4339.900
Driller 1 - RDH (h)	44	3001.300	36.900	2909.400	2977.800	3001.300	3027.300	3089.200
Driller 2 - RDH (h)	49	2945.900	54.600	2850.300	2894.700	2943.800	2989.500	3060.200
Driller 3 - RDH (h)	50	3070.000	66.900	2911.400	3020.200	3068.900	3116.900	3241.400
Driller 1 - Advanced Rate (m/min)	49	0.944	0.001	0.942	0.943	0.944	0.945	0.947
Driller 2 - Advanced Rate (m/min)	50	0.944	0.001	0.941	0.943	0.944	0.945	0.947
Driller 3 - Advanced Rate (m/min)	49	1.016	0.001	1.013	1.015	1.016	1.017	1.019
Penetration Rate (m/min)	143	1.361	0.002	1.357	1.360	1.361	1.362	1.366
Driller 1 - Availability	48	0.863	0.012	0.833	0.855	0.863	0.871	0.893
Driller 2 - Availability	49	0.856	0.013	0.827	0.845	0.855	0.863	0.885
Driller 3 - Availability	50	0.874	0.016	0.838	0.862	0.873	0.885	0.912
Driller 1 - Utilization	50	0.944	0.005	0.933	0.939	0.943	0.948	0.955
Driller 2 - Utilization	44	0.933	0.004	0.924	0.930	0.932	0.935	0.941
Driller 3 - Utilization	49	0.954	0.006	0.941	0.950	0.954	0.958	0.968
Comp 1 Repair Time (h)	148	23.296	1.027	20.921	22.472	23.197	23.952	26.049
T40 Comp 1 # of Failure	100	112.420	4.160	104.000	110.000	112.000	115.750	123.000
T35 Comp 1 # of Failure	50	115.960	4.220	108.000	113.000	116.000	119.000	126.000
Comp 2 Repair Time (h)	149	6.818	0.490	5.573	6.474	6.820	7.121	8.020
T40 Comp 2 # of Failure	98	26.765	0.810	25.000	26.000	27.000	27.000	28.000
T35 Comp 2 # of Failure	46	27.370	0.853	26.000	27.000	27.000	28.000	29.000
Comp 3 Repair Time (h)	147	17.434	1.707	13.439	16.303	17.432	18.574	21.614
T40 Comp 3 # of Failure	100	12.230	0.827	11.000	12.000	12.000	13.000	14.000
T35 Comp 3 # of Failure	49	12.735	0.670	12.000	12.000	13.000	13.000	14.000
Comp 4 Repair Time (h)	149	46.547	3.963	37.477	44.213	45.911	49.588	56.676
T40 Comp 4 # of Failure	99	9.152	0.705	8.000	9.000	9.000	10.000	11.000
T35 Comp 4 # of Failure	50	9.480	0.789	8.000	9.000	9.000	10.000	11.000
Comp 5 Repair Time (h)	149	77.899	5.011	67.219	74.174	77.962	81.430	91.076
T40 Comp 5 # of Failure	99	31.424	1.457	28.000	30.000	32.000	32.000	35.000
T35 Comp 5 # of Failure	38	30.658	0.909	29.000	30.000	31.000	31.000	32.000
Comp 6 Repair Time (h)	150	120.610	6.920	103.610	115.700	120.350	125.480	139.600
T40 Comp 6 # of Failure	100	30.520	1.617	27.000	29.000	30.000	32.000	35.000
T35 Comp 6 # of Failure	50	29.200	1.370	27.000	28.000	29.000	30.000	33.000
T40 PR at Clay Zone (m/min)	851	0.640	0.010	0.620	0.640	0.650	0.650	0.670
T35 PR at Clay Zone (m/min)	861	0.680	0.010	0.660	0.670	0.680	0.680	0.700
Delay Time Due to Weather (h)	48	300.640	27.820	252.000	282.000	295.500	321.130	373.500
Non-Working Days Due to Weather	49	14.694	3.190	8.000	12.000	15.000	17.000	23.000
Drilling Completion Time (h)	48	18.372	0.272	17.860	18.205	18.353	18.568	19.006

Engine Hours (EH) represent the total hours the driller engines are running, while Rock Drill Hours (RDH) represent the hours the drillers are actively drilling into rock. On this basis, the ratio of RDH to EH for each driller can give insights into the efficiency of active drilling vs. total operation. According to the simulation results, this ratio is determined 69% for SmartRoc T40 and 74% for FlexiRoc T35. The Driller 3 (FlexiRoc T35) spends more of its operational time actively drilling into rock than the other two drillers (SmartRoc T40). In essence, the engine is not just running; it's being used productively to drill. If operational costs or fuel consumption are tied to engine hours (EH), then a higher RDH/EH ratio might indicate that for every hour the engine is running, more value is derived in terms of active drilling. It could suggest a better return on investment or cost efficiency for that particular driller compared to others with a lower ratio.

Higher engine hours might correlate with higher availability. An available machine might be used more frequently, leading to higher engine hours. However, even though Driller 3 has lower EH when compared to other drillers, its availability is 1% and 2% higher than Driller – 1 and Driller – 2, respectively. It means that Driller 3, with higher availability and utilization but lower EH, is likely more efficient. It completes tasks in less time compared to other drillers, thus requiring fewer engine hours.

While availability indicates how often a machine is ready for use, utilization indicates how effectively a driller is used when it's in an operational condition. A high correlation between these two would mean that machines that are available more often are also used more effectively. Driller 3 has both the highest availability and the highest utilization. It means that this driller is available more often and used more intensively when it's in operation.

Driller 3 has the highest Rock Drill Hours (RDH). If it also has more component failures, it could indicate that its components might be wearing out faster due to the extended drilling hours. This condition could suggest a direct relationship; the prolonged drilling activity might accelerate wear on its components, leading to more frequent breakdowns or malfunctions.

For Components 1 to 4, Driller 3 (FlexiRoc T35) tends to have slightly higher average failures than Driller 1 and Driller 2 (SmartRoc T40). However, for Components 5 and 6, T40 has a slightly higher average number of failures than T35. The differences in the average number of failures between SmartRoc T40 and FlexiRoc T35 across components are relatively small because both types have similar reliability or sensitivity to failure. Component 1 has the highest number of failures for both SmartRoc T40 and FlexiRoc T35 because it is directly related to ground and drilled lengths. The wear of the bit is greater compared to the rod, shank, and other components.

The average delay time due to weather is detected to be quite crucial at approximately 300 hours (or 12.5 days). It indicates that weather significantly impacts operations, causing more than two weeks of delays on average. The range between the minimum and maximum values for both delay time and non-working days indicates variability in the impact of weather. Season 03 experienced relatively minor disruptions, while other seasons experienced more extended delays. The significant number of non-working days and delay hours underscores the importance of considering weather in operational planning and scheduling. It might also emphasize the value of having contingency plans or mitigation strategies for weather-related disruptions.

The average PR for Diller 3 (FlexiRoc T35) in the clay zone is higher (0.680 m/min) than for the other drillers, SmartRoc T40 (0.640 m/min). This condition suggests that FlexiRoc T35 is more efficient or faster when drilling in clay compared to SmartRoc T40. When drilling specifically in clay, choosing FlexiRoc T35 might offer better performance in terms of penetration rate. However, other factors like wear and tear, cost, and equipment availability should also be considered carefully. In conclusion, while FlexiRoc T35 appears more efficient than SmartRoc T40 when drilling in clay, both have a considerably slower penetration rate in clayed ground compared to rock.

This situation underscores the importance of understanding material-specific performance when planning drilling operations.

In this study, all crew members are assumed to be experienced professionals. However, it's important to emphasize that the level of crew competency is a pivotal factor in drilling operations. Skilled and experienced crews tend to operate machinery more efficiently, adhere to maintenance schedules, and troubleshoot issues promptly. This proficiency enhances the reliability of both the machinery and its individual components. Moreover, a competent crew plays a critical role in optimizing the performance of the driller, ensuring that the equipment is used effectively and safely. While this study assumes a high level of crew competency, the influence of this variable on machinery reliability and driller performance remains important in real-world operations.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The significance of drilling in mining operations cannot be underestimated. Drilling encompasses the entire mining process, beginning with exploration and concluding with the end of mine operations. The importance of drilling lies in its ability to extract valuable resources from the earth while ensuring the safety and effectiveness of mining operations. The versatility of drilling, with its various applications such as exploration, production, and pre-split drilling, underscores its importance. From obtaining crushed and core samples in exploration, which elucidates waste and ore material content and geomechanical properties, to creating voids for blasting, drilling performance is crucial. Notably, the efficiency of the subsequent blasting operations and production rates is heavily contingent upon the precision and adherence to design parameters in drilling.

The varied nature of pre-blasting requirements in mining operations, governed by rock material attributes and the required drill size, necessitates diverse drilling equipment. Consequently, a myriad of uncertainties emanates at the pre-blasting drilling stages. These uncertainties, which can be categorized into geological, equipment-based, environmental, and human factors, have profound implications on the overall productivity and profitability of mining activities.

To contextualize, geological uncertainties encompass factors such as geologic structures, groundwater conditions, and rock mineralogy, while equipment uncertainties deal with the capacity and performance of drilling equipment. Simultaneously, environmental uncertainties include the ever-shifting dynamics of weather, topography, and extreme temperature conditions, and the human element brings in variability in drilling crew competencies.

Given these multi-faceted challenges, the study aimed to provide a comprehensive solution by developing a discrete event simulation algorithm optimized for drill rigs (drillers). The strength of this model lies in its capacity to incorporate the stochastic nature of failures, catering to the changing conditions that influence drill rig behavior. The model stands equipped to evaluate operating drillers in terms of location, time, type of drill rig, crew experience, or machine failures,

The practical application of the model on a fleet consisting of three distinct drill rigs plus two spares, factoring in diverse failure modes and weather conditions, solidified its relevance. The model offered a comprehensive understanding by systematically categorizing six failure types and considering four primary weather conditions. The results from the year-long simulation underscore the algorithm's ability to clarify the complexities of drilling performance.

In analyzing the KPIs vital to drilling performance, several determinants emerge. Geological structures play a crucial role. For instance, distinct penetration rates in clay zones versus rock terrains highlight the challenges and adaptability required in diverse geological settings. The penetration rate is reduced by 51% in the clay zone compared to the rock zone. The effectiveness of a maintenance policy is mirrored in the machinery's reliability and operational hours. By using durable and best-fit components, downtime duration and maintenance costs might be reduced. Moreover, maintenance and component replacements are vital to ensure consistent performance and efficiency. Specifically, the frequency of these maintenance activities is dictated by the wear and tear of various components. For instance, given their direct interaction with the geological formations, drill bits require a change every three days. The second frequently observed wear problem becomes available in the rods, necessitating a replacement every two weeks. The shank, another pivotal component, demands attention once a month, either in the form of a replacement or a repair. The rock drill, integral to the drilling process, undergoes a replacement or repair approximately every 5-6 weeks. Additionally, interventions are needed every two weeks to address issues stemming from mechanical and hydraulic components. This schedule underscores the demands of drilling operations and the importance of timely maintenance. Furthermore, the role of human expertise cannot be underestimated. A proficient crew can significantly increase machinery performance, ensuring KPIs are consistently met or surpassed. Yet, external factors, such as weather, present unpredictable challenges. With weather-related disruptions causing an average delay of 300 hours, the importance of resilience and flexibility in operations is evident. These factors collectively emphasize that achieving peak drilling performance is a blend of understanding geological structures, adhering to dynamic maintenance policies, leveraging crew expertise, and adapting to external challenges.

In conclusion, this research has tried to bridge the gap between the inherent uncertainties and downtimes in drilling operations and the quest for optimal productivity. By developing an advanced algorithm that accounts for different variables in drilling, the study covers the way for more resilient and efficient drilling practices in future mining operations.

5.2 Recommendations

A detailed simulation model was developed, taking into account the daily drilling pattern layouts, variations in formation within each pattern that could alter the drill rigs's penetration rate, the design and dependability of the drilling equipment, and factors causing operation downtimes such as delay due to weather conditions, and drill rigs' component failure frequency. While Drill Navigation and Monitoring Systems capture real-time or historical data, a simulation can be designed to predict future scenarios. It allows engineers to test various scenarios, which can't be done using only past or current data. In addition, simulations can help optimize operations. The most efficient and effective operational strategies can be identified by running various scenarios, which might not be evident from only real-time monitoring. Testing changes or new strategies in the real world could be costly. Simulations allow for cost-effective testing and validation before implementation in the actual operations. Based on this study, the following suggestions are put forward to enhance and refine the model for subsequent research endeavors.

i. This study assumed all equipment was identical, and the same failure model was utilized for each drill rig. Equipment-based component lifetimes and repair times can be applied separately for each drill rig's condition.
ii. Cost data was not utilized in the conducted research. By employing cost data, drilling plans can be prepared cost-efficiently.
iii. When a production forecast is provided, it's possible to schedule more precise drilling plans by factoring in weather forecasts, geological uncertainties, crew expertise, and equipment conditions.
iv. In future studies, the spare part inventory can be taken into consideration. Insufficiency in the spare part can adversely impact operation times, leading to increased downtimes.
v. The accuracy of the study can be enhanced by using actual data instead of just using expert opinions and assumptions.
vi. Decisions requiring financial considerations, such as the drill rig fleet size and spare equipment, can be calculated in the future studies using cost data.

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