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SIMULATION-BASED OPTIMIZATION OF MAINTENANCE CREW CONFIGURATION IN MINING SITES

MADEN SAHALARINDA BAKIM-ONARIM EKİBİ YAPILANDIRMASININ SİMÜLASYON TABANLI OPTİMİZASYONU

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ÖZ

Madencilik sektörü, insan kaynağı, kanıtlanmış rezerv ve ekipman filosu gibi kısıtlı kaynakların verimli ve etkileşimli olarak kullanılmasını gerektiren bir üretim sektörüdür. Madencilik şirketleri, maksimum üretkenlik ve verimliliği sağlamak amacıyla, bu kaynaklar arasında hassas bir denge kurmalıdırlar. Bir maden işletmesinin en kritik bölümlerinden birisi, ekipman filosunun operasyonel kalımlılığı ve güvenilirliğinidevam ettirmeye yönelik bakım ve onarım faaliyetlerini gerçekleştiren ve planlayan bakım ve onarım bölümüdür. Bu bölümler, farklı teknik yeterlilik ve branşlarda insan kaynağına ihtiyaç duymaktadırlar. Bir bakım ve onarım bölümü için gerekli farklı niteliklerdeki personel sayısı, ilgili madencilik operasyonunda çalışan ekipmanlar, bunların maruz kaldıkları arıza modları, bu arızaların ortaya çıkış frekansları ve sonrasında gerçekleştirilen onarım süreleri gibi faktörlerden etkilenmektedir. Arıza frekansları, bakım ve onarım süreleri ve arıza modu için görevlendirilen çalışan sayısı gibi belirsizlikler farklı seviyelerde mevcut olup, belirsizliğin arttığı durumlarda çalışan noksanlığına bağlı olarak bakım ve onarım yapılamama durumları da sıklıkla gözlenmektedir. Bir sahada, gereğinden fazla personelin çalıştırılması bakım ve onarım faaliyetlerinin zamanında yapılmasına olanak sağlarken, yüksek fiziki giderlere de neden olmaktadır. Bu durum, bakım-onarım personeli azlığı ve çokluğu durumlarında oluşabilecek üretim kayıpları ve fiziki masraflar arasında bir değiş-tokuş noktası yani optimize edilmesi gerekli bir problemi yaratmaktadır. Mevcut araştırma çalışması, işleyen bir maden alanında farklı ekipman ve arıza modu davranışlarını dikkate alan ve buna göre farklı branşlarda gerekli bakım ve onarım personel sayılarını optimize etmeye çalışan bir simülasyon modelinin oluşturulmasını amaçlamaktadır. Böylelikle; model, maksimum verimlilik ve performansı sağlamak için gerekli personelleri farklı ekipman arıza modlarına tahsis etmeyi hedeflemektedir.

Anahtar Sözcükler: Sürekli-Olay Simülasyonu, Optimizasyon, Bakım ve Onarım, Madencilik, Makine ve Ekipman, İşgücü

ABSTRACT

The mining sector is a production industry that requires the efficient and interactive use of limited resources such as human resources, proven reserves, and equipment fleets. Mining companies must establish a delicate balance among these resources with the aim of achieving maximum productivity and efficiency. One of the most critical departments of a mining operation is the maintenance and repair department responsible for performing and planning maintenance and repair activities to ensure the operational reliability and reliability of the equipment fleet. These departments require human resources with different technical competencies and specialties. The number of personnel with different qualifications required for a maintenance and repair department is influenced by factors such as the equipment used in the relevant mining operation, the failure modes they are exposed to, the frequencies at which these failures occur, and the subsequent repair times. Uncertainties such as failure frequencies, repair times, and the number of employees assigned to failure modes often exist at different levels, and in situations where uncertainty increases, cases of maintenance and repair not being carried out due to a shortage of personnel are frequently observed. Employing an excessive number of personnel in the field allows maintenance and repair activities to be carried out on time but also leads to high physical expenses. This situation creates a trade-off point between production losses and physical expenses that need to be optimized when it comes to the shortage or excess of maintenance and repair personnel. The current research aims to create a simulation model that takes into account different equipment and failure mode behaviors in a working mining area and attempts to optimize the required maintenance and repair personnel numbers in different specialties accordingly. Thus, the model aims to allocate the necessary personnel to different equipment failure modes to achieve maximum efficiency and performance.

Keywords: Continuous Event Simulation, Optimization, Maintenance Crew, Mining, Workforce

INTRODUCTION

With mass production and globalization improvements, machines have become crucial in various manufacturing sectors. Consequently, a strong correlation between production operations and maintenance has become essential for the overall success of companies. Equipment malfunctions can directly or indirectly disrupt production, resulting in significant financial losses. Therefore, it has become imperative for production companies to establish a competent and well-organized maintenance department with a skilled workforce possessing diverse competencies to ensure uninterrupted production. In the mining sector, which heavily relies on machinery, mining companies must also establish efficient maintenance departments in their operational areas. Mining equipment varies in complexity and is used in surface mines, underground mines, and mineral processing facilities, facing multiple failure modes that demand different maintenance actions. Maintenance workshops comprise units and employees with diverse qualifications in mining areas. Additionally, the maintenance policies in mining are diverse and complex, with maintenance work representing a substantial share of the operating cost. The relationship between maintenance and operating costs in the mining industry has been extensively discussed in various studies and literature. The findings reveal several important observations; for instance, equipment maintenance cost in mining constitutes a significant portion, ranging from 20% to 35%, of the total operating cost (Unger and Conway, 1994). In specific regions like Chile and Indonesia, maintenance costs for surface mines surpass 60% of the operating cost (Wong et al., 2000). In addition, maintenance costs dominate a substantial portion of the equipment operating cost across the mining industry, ranging from 40% to 50% (Kumar and Forsman, 1992). Moreover, a Finnish company shared that maintenance costs in their mines account for approximately 30% of the production cost (Harjunpaa, 1992). Lastly, unplanned maintenance activities have been shown to lead to a 10% production loss in Australian underground coal mines (Clark, 1990). These observations underscore the significant impact of maintenance costs on the overall operational expenses in the mining sector and highlight the importance of effective maintenance strategies to ensure efficient and uninterrupted production.

The literature highlights that maintenance is unavoidable in machinery-based production industries and can significantly impact operating costs, leading to both direct expenses and indirect consequences like production loss. Therefore, when devising maintenance policies, it is crucial to develop a balance between the physical cost of maintenance work and the value of production loss per unit. The composition of the maintenance crew, referring to the number of individuals with different qualifications, is a critical factor in making maintenance-related decisions. Finding the right balance in the maintenance crew is essential as both over-employment and under-employment can affect the cost dynamics, including direct and indirect expenses.

This study aims to develop a continuous simulation algorithm to determine the optimal maintenance crew in terms of quantity and qualification. The objective is to minimize the overall cost, considering the stochastic nature of equipment failures experienced at a mining site.

Problem Statement

Maintenance plays a crucial role in production areas, as it enhances and sustains the reliability and functionality of systems. However, maintenance activities can lead to production loss if the maintenance department lacks the necessary workforce. Additionally, maintenance actions can be expensive and limited by available resources. Hence, balancing system breakdown costs and maintenance expenses is essential. Neglecting maintenance can result in excessive failures, leading to downtime and system deterioration. To ensure sustained production and improved operational profitability, it is crucial to establish an optimal maintenance policy that minimizes both direct and indirect cost items related to employee expenses. In machine-intensive sectors such as mining, where production relies on multiple well-coordinated heavy-duty machines, maintenance costs can be substantial and significantly contribute to the total operating cost. The maintenance cost included in the operating cost budget can differ significantly across industries. For the manufacturing industry, it typically ranges from 3% to 15%, while for metallurgical processes, it falls between 15% and 20%. However, in the highly mechanized mining industry, the accounted maintenance cost can be as high as 50% (Ben-Daya et al., 2016). Furthermore, in numerous industries, the challenge of allocating limited resources to a specific set of tasks is a common occurrence. At this point, optimizing labor resource allocation and configuration is essential to enhance systems' service levels while minimizing direct and indirect costs. In the case of a highly machine-intensive industry like mining, determining the optimal human resource configuration for maintenance activities becomes very crucial.

Objective & Scope of the Study

The current study aims to develop a simulation algorithm capable of optimizing the maintenance crew configuration in an operation involving multiple types of equipment with random failure modes. The primary goal is to minimize the cumulative cost associated with the maintenance crew, encompassing both direct and indirect cost items. Direct crew-induced costs include various elements such as salary, insurance, food service, shuttle service, rent help, and family help. Indirect costs, on the other hand, encompass production losses resulting from scheduled maintenance downtime and potential unavailability of the maintenance crew. In addition to the main objective, the study aims to achieve several sub-objectives. First, an industrial research component is conducted to investigate the factors determining maintenance crew configuration, specifically in the mining industry. Understanding these factors is crucial for optimizing the crew structure effectively.

Besides, the study seeks to establish the dependencies between production loss and the maintenance workforce. By understanding how these two factors are related, the researchers can better design a maintenance crew configuration that minimizes production losses. To facilitate the objectives, the research endeavors to develop a maintenance crew simulation algorithm within a continuous event simulation environment. This algorithm will enable the evaluation and optimization of the crew configuration under various scenarios. Moreover, the study involves implementing the developed model using an operational dataset after pre-processing data groups. This practical implementation using real-world data will enhance the reliability and relevance of the results. Lastly, the researchers focus on verifying and validating the developed simulation algorithm to ensure its accuracy and effectiveness in optimizing the maintenance crew configuration. In the application part, the study utilizes the historical maintenance dataset of a five-excavator fleet operating in a surface coal mine. The failures are categorized into two common types: mechanical and electrical.

LITERATURE REVIEW

Maintenance can be defined as the auxiliary activities to ensure that a system, which may have varying complexity and functions, remains in a satisfactory state by conducting regular checks, replacements and repairs on its components. As a result, a maintenance policy involves a combination of actions with distinct objectives to enable a component to function effectively throughout the system's entire service life. The primary purpose of maintenance actions is to enhance the functionality and dependability of systems. Nevertheless, improving reliability can be expensive in certain situations and is constrained by technical and financial limitations. Consequently, there exists a delicate balance between the economic impact of maintenance activities and the potential deterioration of the system. To ensure optimal results, a maintenance policy must be designed to maintain the system's reliability above the desired level, taking into account its role and value in production. However, it is essential to avoid implementing excessively high-rated preventive work packages, as they may lead to additional investment costs and increased system unavailability due to preventive downtimes.

For a mining company, three critical assets are crucial: human resources, ore reserves for exploitation, and an equipment fleet. Among these, human resources employed in operational areas hold particular significance. The number and qualifications of personnel must be determined based on the divisional capacity requirements in mining areas. Notably, the maintenance facility is observed to be the most labor-intensive aspect, as it requires a considerable number of individuals with diverse qualifications to ensure the optimal performance of the equipment fleet. Several studies have focused on mining equipment maintenance and management decision-making processes for the mining sector.

Barberá et al. (2014) utilized the GAMM method to analyze two slurry pumps in a mining plant in Chile, suggesting improvements for pump maintenance. Ali and Reza (2014) developed a new approach using statistical models to determine loading equipment's overhaul and maintenance cost in surface mining. Morad et al. (2014) investigated maintenance policies for operating trucks in Sungun Copper Mine to minimize failure downtimes. Kovacevic et al. (2016) described a two-step method to analyze factors influencing human errors during mining machines' maintenance activity. Nikulin et al. (2016) presented a computer-aided application to evaluate the operational and maintenance strategy for complex processes with equipment. Gölbaşı and Demirel (2017) developed a simulation algorithm to optimize inspection intervals and minimize maintenance costs for mining machines. Jonsson et al. (2018) discussed analyzing digitalized condition-based maintenance data in an iron ore mine. Angeles and Kumral (2020) proposed a maintenance management approach to improve equipment availability and reliability in a mining truck fleet. These studies contribute valuable insights and practical tools for effectively maintaining mining systems regarding cost minimization and availability maximization.

In addition, various simulation studies in the mining industry have been conducted to evaluate uncertainties at the operational level, optimize processes, and address various aspects of mining operations. For instance, Hashemi and Sattarvand (2014) developed a model using discrete-event simulation to analyze interactions between loading and hauling systems in mines, resulting in improved dispatching systems and reduced truck queueing time. Upadhyay and Nasab (2018) presented a simulation and optimization framework to enhance short-term production planning and decision-making in mining operations, considering uncertainties and dependencies between various factors. Golbasi and Demirel (2017) introduced an inspection interval optimizer using a stochastic, continuous, and dynamic simulation structure to determine the best cost-wise decisions in equipment maintenance policies.

Other studies explored optimization in truck dispatching and allocation to shovels (Moradi et al., 2019), truck allocation considering uncertainties in dispatching operations (Moradi et al., 2019), and the effectof human factors on mining equipment reliability (Ozdemir and Kumral, 2018). Additionally, Ozdemir and Kumral (2019) proposed a two-stage dispatching system to maximize the utilization of truck-shovel systems, leading to increased material quantity. Golbasi and Turan (2020) introduced a maintenance policy optimizer to determine optimal maintenance work packages based on equipment uptime and downtime characteristics. Bernardi et al. (2020) compared materials handling systems in a mine to optimize handling systems and minimize operating costs using discrete event simulation. Golbasi and Kina (2022) developed a fuel consumption simulator to evaluate fuel usage in haul trucks operating under stochastic conditions.

These studies have provided valuable insights and practical tools for effectively maintaining mining systems regarding cost minimization and availability maximization, improving mining operations, optimizing maintenance policies, and enhancing decision-making processes. However, optimization of human resource configuration in mining activities has not been observed in the literature.

MODEL DEVELOPMENT

The algorithm's objective is to determine the optimal maintenance crew configuration for a mining area, ensuring the most cost-effective operation by striking a balance between physical expenses and production losses resulting from over or under-employment of skilled workers. The maintenance crew incurs various physical cost items, including wages, employment insurance, food service, transportation, and accommodation. Over-employment in different maintenance branches can lead to a significant increase in direct costs. Conversely, under-employment in a maintenance branch can cause notable production losses as related failure types may not receive timely attention, impacting machinery availability. It is crucial to avoid overlapping maintenance activities for similar failure modes that require similar technical competency, as failure to evaluate failure mode characterization and crew member occupancy rates jointly can disrupt machinery availability.

Given that mining areas utilize numerous equipment with varying numbers and operational requirements, any misjudgment in maintenance behavior can lead to catastrophic situations, reduce equipment utilization, and result in additional unavailability periods that harm short-term production plans. The algorithm logic is illustrated in Figure 1 briefly.

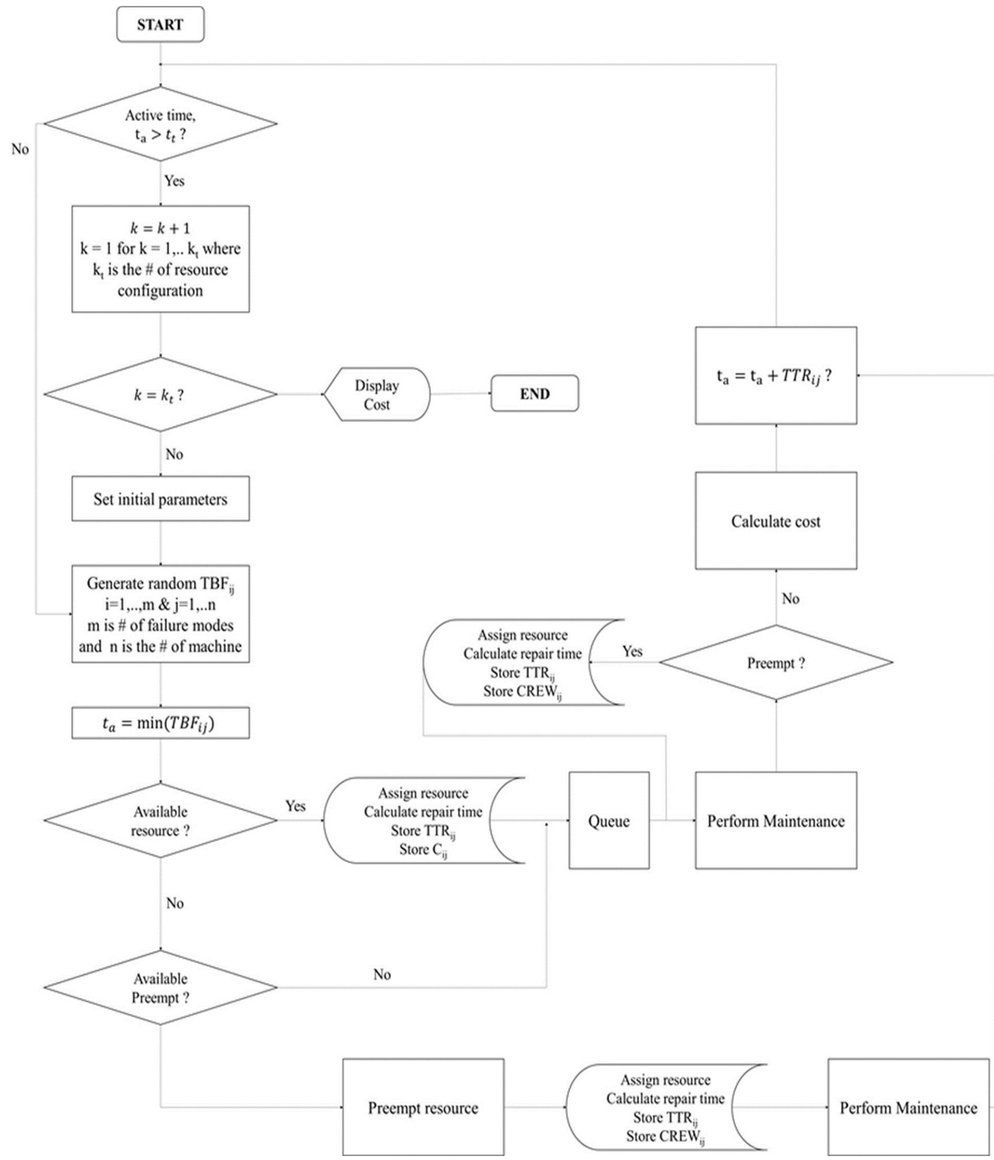

Figure 1. Simulation Model Algorithm

The model was tested on a fleet of five excavators, each with distinct failure occurrence and maintenance characteristics. Failures were categorized into mechanical and electrical types, which determinedthe crew groups. Through 200 simulations, the interactions within the system were evaluated by varying the total number of mechanical and electrical crew members in each run. Each simulation covered an observationperiod of 4,383 hours. The results indicated that the optimized crew configuration, consisting of 4 members in the electrical and 4 members in the mechanical divisions, minimized the cumulative direct and indirect costs. The fleet's general evaluation, including five excavators, can also be seen and Figure 2.

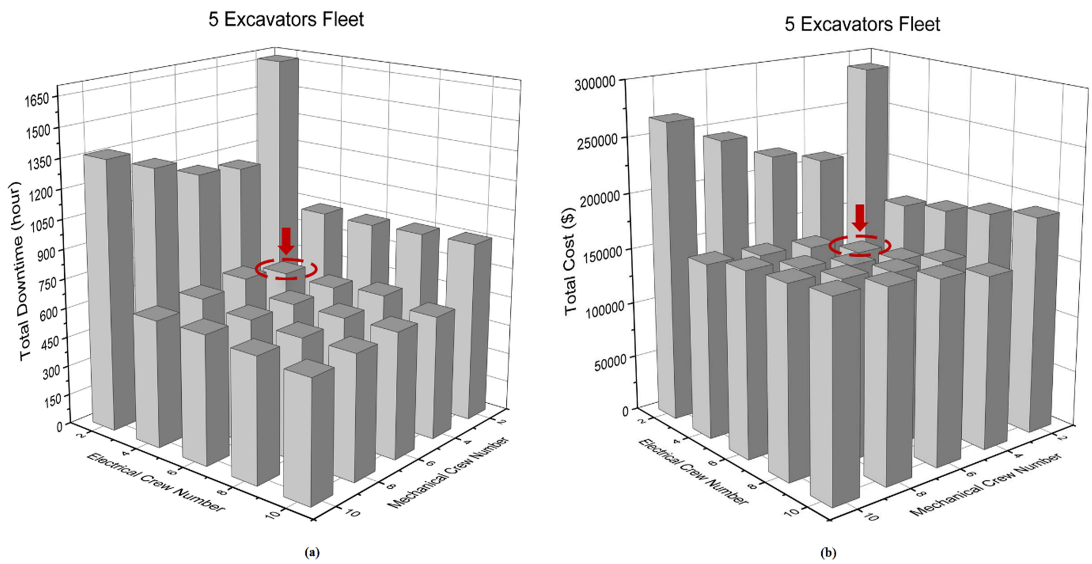

Figure 2. Total Downtime (B) and Total Cost (A) for 5 Excavators for Each Crew Policy

CONCLUSIONS

In a machine-based production company, the maintenance department consists of various divisions with different crew configurations, depending on the company's production profile, complexity, and types of machines involved in production phases. In mining areas, operations can be either surface or underground, depending on the mining method, and specific heavy-duty machinery with varying production rates is required based on the mining type and production capacity. A mining company typically possesses a large fleet of machines, including loading, hauling, drilling, and auxiliary equipment. Each machine may experiencedifferent failure modes with varying occurrence frequency and consequences, resulting in different downtimeprofiles.

Given that the maintenance crew is a limited resource with specific numbers of people in each division, it is crucial to determine the optimal configuration of the maintenance crew, considering the trade-off betweenthe total financial consequences of different crew configurations. To address this, the study develops a multi- scenario continuous-event simulation model to identify the optimal capacity and qualification of the maintenance crew for a functional mining operation. The developed model is implemented for the maintenance crew requirement of a fleet covering five excavators experiencing random failures with varying maintenance requirements and durations. The overall cost is minimized for a crew configuration with 4 and 4 people in theelectrical and mechanical departments.

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