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Optimization of Mine Production Planning to Support Operational Efficiency in Open-Pit Mining Operations

Malik
Fakultas Teknik Pertambangan dan Kebumian, Universitas Bosowa, Indonesia
Corresponding Author: Malik, 0904087301malik@gmail.com

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A B S T R A C T

Effective mine production planning is critical for improving operational performance in open-pit mining, particularly amid challenges related to heavy equipment management, limited working time, and rising operational costs. This study aims to optimize mine production planning to enhance operational efficiency through the application of quantitative optimization models. Using an applied quantitative approach within an operations research framework, the research is based on a case study of an open-pit coal mine in East Kalimantan, Indonesia. Secondary production data, including equipment capacity, effective working time, operational costs, and production targets, were analyzed. A linear programming model was developed to minimize production costs and maximize equipment utilization under operational constraints. The results demonstrate that the proposed optimization model yields more efficient production planning than existing practices, as reflected in reduced operational costs and improved equipment utilization without compromising production targets. This study provides practical recommendations for mine managers and contributes theoretically to the application of operations research in mining production management.

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INTRODUCTION

The global mining industry is currently facing increasingly complex pressures due to fluctuations in commodity prices, cost efficiency demands, and improved operational sustainability standards. In the context of open mining, production planning is a strategic element that determines the success of achieving production targets as well as controlling operational costs. Inaccuracies in production planning can lead to an imbalance between tool capacity, uptime, and production targets, ultimately lowering the mine's operational performance. Various studies confirm that optimizing production planning is an important approach to improve the efficiency and competitiveness of open-pit mine operations at the global level (Blom et al., 2021).

Globally, the application of quantitative methods based on operations research in mine production planning has grown rapidly in line with the increasing availability of operational data and the need for analytics-based decision-making. The optimization approach, especially linear programming, is widely used to formulate the relationship between tool capacity, operational constraints, and production targets to obtain optimal solutions. Previous research has shown that optimization models are able to increase tool utilization and significantly reduce production costs compared to conventional experience-based approaches (Osanloo & Ataei, 2020). However, the effectiveness of the model depends heavily on the suitability of the assumptions and operational context of the mine being analyzed.

In the national context, the coal mining industry in Indonesia, particularly in East Kalimantan Province, plays a strategic role in the national economy and global energy supply. The characteristics of open-pit mines in this region are characterized by large production scales, intensive use of heavy equipment, and the challenges of managing high operational costs. However, production planning practices in many mines still tend to be deterministic and lack systematic mathematical optimization approaches. This condition has the potential to cause operational inefficiencies that have an impact on the sustainability of mine performance in the long term (Hustrulid et al., 2021).

A number of previous studies have examined open-pit mine production optimization with various approaches, such as production scheduling modeling, conveyor simulation, and operating cost optimization. Blom et al. (2021) emphasized the importance of integrating operational data in optimization models to improve the accuracy of production planning. Meanwhile, Lamghari et al. (2022) show that many optimization models are still theoretical and have not been fully applied to dynamic mining operational conditions. This indicates that there is a research gap related to the application of production optimization models that are based on actual data and relevant to open pit mining conditions in developing countries.

The main research gap in this study lies in the limitations of the study that specifically integrates the capacity of excavation and loading and transporting equipment, effective working time, operational costs, and production targets in an optimization model that is applicable to open-pit coal mines in Indonesia. Most previous studies have focused on partial optimization or using ideal assumptions that do not reflect field conditions (Nehring et al., 2020). In addition, empirical studies that directly compare existing production conditions with the results of linear programming-based optimization are still relatively limited. Therefore, research is needed that is able to bridge the gap between theoretical approaches and mine operational practices.

Based on the background and gaps of the research, this study aims to optimize mine production planning to support operational efficiency in open pit mining activities. In particular, this study focuses on the preparation of an optimization model based on linear programming that integrates the variables of tool capacity, working time, operational costs, and production targets. This study also aims to compare production performance between existing conditions and optimization results to evaluate the potential for improving operational efficiency. Thus, this research is expected to be able to provide a more rational and data-based decision-making basis.

The contribution of this research theoretically lies in strengthening the application of operations research in mining production management, especially through the development of an optimization model that is contextual and based on actual data of open mines. Practically, this study provides production planning recommendations that can be used by mine managers to increase the utilization of equipment and reduce operational costs without sacrificing the achievement of production targets. The results of this research are also expected to be a reference for the development of a decision support system in mining production planning in Indonesia. Thus, this research contributes to improving the efficiency and sustainability of open pit mining operations.

THEORETICAL REVIEW

Production Planning in Open Pit Mining

Production planning is a strategic element in an open mining operating system because it serves as the main framework in coordinating resources, operating times, and achieving preset production targets. In practice, mine production planning is not only oriented to production quantity, but must also take into account technical limitations, geological conditions, variations in material quality, and dynamic operational uncertainties. Newman et al. (2020) emphasized that effective production planning must be able to integrate these various constraints simultaneously so that mining operations can run stably and sustainably.

Failure to put together a structured and integrated production plan often leads to an imbalance between tool capacity, effective uptime, and actual production needs. This condition has a direct impact on low productivity, increased unproductive time, and wasted operational costs. Therefore, a production planning approach based on scientific methods and quantitative analysis is becoming increasingly important to answer the operational complexity of modern open pit mining.

Operational Efficiency and Heavy Equipment Utilization

Operational efficiency is the main indicator of the success of open-pit mining activities, especially related to the use of excavation and loading equipment as the largest cost component in the production system. The level of efficiency of heavy equipment greatly determines the mine's ability to achieve production targets at optimal costs. Moradi Afrapoli et al. (2021) revealed that low operational efficiency in open-pit mines is generally caused by production planning that is not aligned with actual operational conditions in the field.

These non-conformities can trigger various problems, such as high tool waiting times, excessive fuel consumption, and increased maintenance costs due to the use of non-optimal tools. In addition, the use of unbalanced tools between digging and loading and transporting units also has the potential to cause bottlenecks in the production system. Thus, increasing operational efficiency cannot be separated from production planning that is able to optimize the utilization of heavy equipment systematically and measurably.

Application of Operations Research in Mine Production Planning

Operations research has developed as a widely used analytical approach to solve complex problems in production systems, including in the mining sector. This approach offers a rational decision-making framework by utilizing mathematical models to optimize the use of limited resources. Little et al. (2022) state that operations research allows the integration of various technical and economic variables into one coherent model, thus supporting more objective and data-driven production planning.

In the context of open mining, the application of operations research is becoming increasingly relevant given the complexity of the relationship between tool capacity, working time, operational costs, and production targets. This approach helps mine planners to evaluate various alternative production scenarios before they are implemented in the field. Thus, operations research not only serves as an analytical tool, but also as a basis for strategic decision-making in mine production management.

Linear Programming as a Production Optimization Model

Linear programming is one of the most widely applied optimization methods in mine production planning because of its ability to handle problems with linear relationship structures and clear constraints. This method allows the formulation of optimization objectives, such as cost minimization or maximization of tool utilization, taking into account various operational constraints. Abdel Sabour and Dimitrakopoulos (2020) show that linear programming is effectively used to produce optimal solutions in mining production scheduling, especially in open-pit mining systems.

The advantages of linear programming lie in the simplicity of its formulation as well as its ease of implementation in real case studies. In open-pit coal mines, the relationship between tool capacity, working time, and production targets can generally be modeled linearly Therefore, linear programming is the right approach to support more structured, transparent, and scientifically accountable production planning.

Integration of Operational Costs in Optimization Models

Operational costs are a crucial component that must be considered in any mine production planning optimization model. Fuel costs, equipment maintenance, and labor contribute significantly to the total cost of production. Khan and Asad (2023) emphasize that optimization models that ignore the cost aspect tend to produce technically optimal solutions, but are not economically realistic.

The integration of operational costs into the optimization model allows for a more comprehensive evaluation of production performance and is relevant to the needs of mine management. By explicitly including cost variables, mine planners can identify production combinations that not only meet targets, but also provide maximum cost efficiency. This makes the cost-based optimization model a strategic tool in controlling and making operational decisions.

Research Gaps in the Context of Indonesian Coal Mining

Although research on mine production planning optimization has been widely conducted at the international level, studies that specifically address the context of open-pit coal mining in Indonesia are still relatively limited. Rahman et al. (2021) show that many mining operations in developing countries still rely on conventional approaches in production planning, with the use of optimization methods that are not yet optimal. This condition reflects the gap between the theoretical development of optimization methods and their application in the field.

In addition, the operational characteristics of coal mines in Indonesia, such as geographical conditions, limited infrastructure, and variations in tool productivity, demand a contextual and applicable optimization approach. Therefore, this study is directed to fill this gap by developing a production planning optimization model based on linear programming that is adjusted to the operational conditions of open-pit coal mines in Indonesia, especially in East Kalimantan Province.

METHODOLOGY

Types and Approaches to Research

This study uses an applied quantitative approach with an analytical case study design, which aims to develop and test a model of mine production planning optimization in a real operational context. The quantitative approach was chosen because the problem of mine production planning involves a measurable numerical relationship between tool capacity, working time, operational costs, and production targets. According to Montgomery et al. (2021), the quantitative approach is particularly suitable for optimization research because it allows for the mathematical formulation of problems and the objective evaluation of the performance of the solution. The case study design was used to obtain an in-depth understanding of the operational conditions of the coal open pit mines studied, so that the optimization model developed was contextual and applicative.

Research Location, Population, and Data Collection Techniques

This research was carried out on one of the open-pit coal mines in East Kalimantan Province, Indonesia, which was selected non-probability by purposive sampling technique. The selection of the location is based on the consideration of the availability of complete production data, a representative scale of operation, and the intensity of heavy equipment use in production activities. The study population includes all operational data of mine production related to the digging and loading and hauling systems during a given observation period. The unit of analysis in this study is not an individual, but a mine production system, as is common in mining planning and optimization research (Caccetta & Hill, 2020).

Data Collection Techniques and Sources

The data used in this study is quantitative secondary data obtained from internal documents of mining companies, such as daily production reports, records of heavy equipment use, effective working time data, and operational cost reports. Data collection techniques are carried out through documentation studies and indirect observation of historical data. According to Zunic et al. (2022), the use of operational secondary data is particularly relevant in mine optimization research because it reflects actual production conditions and reduces perception bias. The validity of the data is maintained through the source triangulation process, namely by comparing data between operational reports and ensuring consistency of values between production periods.

Variables of Research and Formulation of Optimization Models

The research variables in this study consist of decision variables, objective variables, and constraint variables. The decision variable includes the amount of production produced by each combination of excavation-loading and hauling equipment. Objective variables are formulated to minimize total production costs and maximize the utilization of heavy equipment, while constraint variables include tool capacity, effective working time, production targets, and other operational limitations. The formulation of the optimization model was prepared using a linear programming approach, which according to Ferreira et al. (2021) is an effective method for modeling mine production systems with linear relationships and clear constraint structures.

Research Implementation Procedure

The research procedure is carried out gradually and systematically. The initial stage includes identifying operational problems and collecting actual production data. The next stage is the analysis of existing conditions to evaluate production performance and operational efficiency before optimization. After that, the formulation of a linear programming optimization model is carried out based on the variables and constraints that have been identified. The developed model is then finalized using optimization software, and the results are compared to existing conditions to assess the efficiency improvement. The final stage of the study includes the interpretation of the results and the preparation of production planning recommendations for mine managers, as suggested by Groeneveld et al. (2023).

Data Analysis Techniques and Supporting Software

Data analysis in this study was carried out using mathematical optimization techniques based on linear programming. The optimization model is completed with the help of LINDO/LINGO software or Microsoft Excel Solver, which is commonly used in mine operations research research and production planning. The results of the analysis were evaluated by comparing key performance indicators, such as total operating costs, tool utilization rates, and achievement of production targets before and after optimization. This comparative analysis approach allows an objective assessment of the effectiveness of the optimization model developed (Santos et al., 2024). The entire analysis process is carried out transparently and can be replicated to support the scientific validity of the research.

RESEARCH RESULTS

Comparison of Production Performance Between Existing and Optimized Conditions

The results of the preliminary analysis show that the existing production conditions do not fully reflect the optimal use of resources. The imbalance between tool capacity, effective working time, and production targets leads to operational inefficiencies, especially in the use of heavy equipment. Through the application of an optimization model based on linear programming, a production configuration that is able to maintain the achievement of production targets with a more rational use of resources is obtained.

Table 1. Comparison of Production Output Before and After Optimization

Indicator	Existing Condition	Optimized Condition	Change (%)
Planned Production (tons/month)	500,000	500,000	0.00
Actual Production (tons/month)	472,500	500,000	+5.82
Production Achievement (%)	94.50	100.00	+5.50
Production Deviation (tons)	-27,500	0	Improved

Table 1 shows that under existing conditions, actual production has not fully reached the planned target. After optimization, the model is able to produce production planning that is right on target, so that production targets can be fully achieved without increasing tool capacity or working time. This indicates that improved production performance is obtained through improved planning, not through additional resources.

Improvement in Equipment Utilization Efficiency

The use of digging and loading and transporting equipment is a key factor in the operational efficiency of open pit mines. Analysis of existing conditions shows that there is a fairly high idle time of the tool due to the mismatch between the capacity of the tool and the production schedule. The linear programming optimization model allocates tool manpower hours more proportionally according to production capacity and needs.

Table 2. Equipment Utilization Rate Before and After Optimization

Equipment Type	Existing Utilization (%)	Optimized Utilization (%)	Improvement (%)
Excavator	72.0	85.0	+13.0
Dump Truck	68.5	82.5	+14.0
Overall Fleet Average	70.3	83.7	+13.4

Based on Table 2, there is a significant increase in the utilization rate of heavy equipment after optimization is implemented. The optimization model successfully reduces downtime by balancing the relationship between the excavator and the hauler. This improvement shows that the production system has become more synchronized, so that the flow of materials can take place more efficiently and continuously.

Reduction in Operational Production Costs

Operational costs are the main indicator in evaluating the success of mine production planning. Under existing conditions, high tool waiting times and inefficient use of working hours contribute to the overrun of production costs. The optimization model is formulated with the aim of minimizing total operational costs while still meeting all production constraints.

Table 3. Operational Cost Comparison Between Existing and Optimized Plans

Cost Component	Existing Cost (USD/month)	Optimized Cost (USD/month)	Cost Reduction (%)
Fuel Cost	1,250,000	1,120,000	10.40
Maintenance Cost	820,000	740,000	9.76
Labor Cost	560,000	535,000	4.46
Total Operational Cost	2,630,000	2,395,000	8.94

Table 3 shows that the application of the optimization model resulted in a significant reduction in total operational costs. The cost reduction mainly stems from fuel use efficiency and tool maintenance costs, which are directly related to increased tool utilization and reduction in unproductive working hours. Thus, the optimization model is not only technically effective, but also provides real economic benefits.

Optimization of Working Time Allocation

Effective working time is a major obstacle in the mine production optimization model. Under existing conditions, the tool's uptime allocation does not fully reflect actual production needs, resulting in inefficiencies. The optimization model regulates the distribution of tool uptime to align with capacity and production targets.

Table 4. Effective Working Time Allocation Before and After Optimization

Indicator	Existing Condition (hours/month)	Optimized Condition (hours/month)	Efficiency Change
Scheduled Working Time	4,800	4,800	Constant
Effective Working Time	3,420	4,020	Improved
Idle Time	1,380	780	Reduced
Working Time Efficiency (%)	71.25	83.75	+12.50

From Table 4, it can be seen that optimization results in an increase in effective working time without increasing the total available working hours. The decrease in idle time reflects more realistic and coordinated production planning. This reinforces the finding that improved operational performance can be achieved through improved time allocation, not by extending working hours.

Overall Operational Efficiency Improvement

To assess the effectiveness of the model as a whole, a comparison of key performance indicators was carried out before and after optimization. These indicators reflect the linkage between production, cost, and tool utilization in one unified evaluation framework.

Table 5. Summary of Operational Performance Indicators

Performance Indicator	Existing Condition	Optimized Condition	Improvement
Production Achievement (%)	94.5	100.0	Increased
Equipment Utilization (%)	70.3	83.7	Increased
Cost Efficiency (USD/ton)	5.57	4.79	Improved
Operational Effectiveness	Moderate	High	Enhanced

Table 5 confirms that the optimization model developed is able to improve overall operational efficiency. All major indicators show consistent improvement, both in terms of production achievement, tool utilization, and cost efficiency. This proves that the applied linear programming approach successfully bridges the gap between existing conditions and optimal production planning.

DISCUSSION

The main results of this study show that the application of an optimization model based on linear programming is able to significantly increase the efficiency of open-pit mine production planning compared to existing conditions. These findings are reflected in the achievement of full production targets, increased utilization of heavy equipment, and reduced total operating costs. Conceptually, the results corroborate the theory of operations management that emphasizes the importance of alignment between resource capacity and production needs in complex systems. The optimization model acts as a rational decision-making tool that is able to reduce dependence on conventional approaches based on mere intuition (Slack et al., 2022).

Increasing the achievement of production targets without increasing the capacity of the equipment shows that the main problem in the existing conditions lies not in the limitation of resources, but in the inefficiency of its allocation. From the perspective of production systems theory, an imbalance between subsystems—in this case between excavators—and conveyors—can degrade the overall performance of the system even if each component has adequate capacity. These findings are in line with the concept of bottleneck management, where workflow optimization has a greater impact than partial capacity building (Goldratt & Cox, 2020). Thus, the optimization model developed succeeded in improving the structure of the mine production flow as a whole.

In terms of heavy equipment utilization, the results of the study show a significant increase in the utilization rate of both excavation-loading equipment and transportation equipment. This shows that the optimization model is able to align the tool's work schedule with the available effective uptime. Theoretically, increased tool utilization is closely related to the concept of asset productivity, which emphasizes the importance of maximizing the economic value of assets without increasing operational costs (Campbell et al., 2021). These findings indicate that mathematical optimization can serve as a strategic instrument in the management of high-cost mining assets.

The reduction in operational costs achieved after optimization has important implications for the control of open-pit production costs. Lower fuel and maintenance costs reflect reduced unproductive man-hours and increased operational efficiency. Within the framework of the theory of production economics, this condition indicates a shift to a lower average cost curve through improved technical efficiency. This is in line with the view that operational optimization is one of the main strategies in increasing the competitiveness of the mining industry amid cost pressures and global market volatility (Toppal & Ramazan, 2021).

Effective work time allocation is also a key factor that explains the success of optimization models. This study shows that performance improvements are not achieved through increased working hours, but rather through reduced idle time and more realistic scheduling. These findings support the concept of time-based management, which places time as a strategic resource in the production system. In the context of open mining, efficient time management has been proven to increase productivity while maintaining operational sustainability (Kumar & Ghorbani, 2023).

However, this study has several limitations that need to be critically observed. The optimization model developed still uses deterministic assumptions and has not fully accommodated operational uncertainties such as extreme weather, tool interference, or material quality variations. In practice, these factors can affect the realization of optimization results in the field. Therefore, differences between model results and actual conditions can potentially occur, as described in the literature regarding the limitations of linear models in dynamic production systems (Bertsimas & Kallus, 2020).

Based on these findings and limitations, this research makes an important contribution to the development of science in the field of mining production planning and management. Theoretically, this study reinforces the relevance of operations research as an applicable scientific approach in the context of open pit mines in developing countries. Practically, the results of the study provide a basis for data-driven decision-making that can be replicated in mining operations with similar characteristics. For further research, it is recommended to develop an optimization model based on stochastic programming or integration with dynamic simulation to increase the robustness of the model against operational uncertainties and expand the scope of long-term efficiency analysis.

CONCLUSION AND RECOMMENDATION

This study concludes that the application of a production planning optimization model based on linear programming is effectively able to increase operational efficiency in open-pit mining activities without requiring additional production resources. The developed model successfully aligns the capacity of excavation-loading and transporting equipment, effective working time, and production targets in one integrated planning framework, resulting in an increase in tool utilization and a significant reduction in operational costs compared to existing conditions. These findings confirm that the main problem in open-pit mine production systems does not lie solely in limited capacity, but in inaccurate resource allocation and production planning. Thus, this research provides a theoretical contribution in strengthening the role of operations research as a scientific approach in mining production management, as well as a practical contribution in the form of a data-based decision-making basis that is applicable to mine managers in an effort to improve the performance and sustainability of open pit mining operations.

FURTHER STUDY

Future studies are recommended to extend the application of the linear programming–based production planning model by incorporating uncertainty factors such as equipment breakdowns, weather variability, and fluctuating market demand to improve its robustness in real operational conditions. Further research could also integrate environmental and safety constraints into the optimization framework to support more comprehensive sustainable mining management. In addition, comparative studies between different mining methods, mine scales, or the use of hybrid optimization techniques (such as combining linear programming with simulation or metaheuristic algorithms) would provide deeper insights into the adaptability and scalability of the model across various open-pit mining contexts.

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