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Optimization of Mining and Classification Processes through Linear Programming: Tanlahua Quarry Case, Ecuador

Optimización de procesos de minado y clasificación mediante programación lineal: caso cantera Tanlahua, Ecuador

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Abstract

Open-pit mining operations in Ecuador face the constant challenge of reducing production costs without compromising required extraction volumes. At the Tanlahua quarry (San Antonio de Pichincha), operated by EXPLOCOM, inefficiencies were identified in the excavation, hauling, sorting, and dispatch processes, with significant downtime negatively impacting profitability. Objective. To optimize the mining and sorting processes at the Tanlahua mining area through the application of the Simplex Method of linear programming. Materials and methods. A descriptive, prospective, and field study focused on the concession's operational processes. Techniques included direct observation, cycle time studies, hourly cost analysis, and machinery performance evaluation. Data were processed using JSimplex software to solve objective functions aimed at minimizing operating costs. Results. In high-demand scenarios, the optimized model generated a daily saving of USD 1,068.15 (36.1% reduction), while in low-demand conditions, the saving reached USD 486.85 per day (35.5% reduction). Considering 312 working days, the estimated annual savings amount to USD 242,580. Conclusion. The application of the Simplex Method enables efficient machinery allocation and a reduction in operating costs exceeding 35%, serving as a highly relevant technical-economic management tool for stone aggregate quarries

Keywords: mining optimization; Simplex method; open-pit quarry; linear programming; production costs.

Resumen

Las operaciones de minería a cielo abierto en Ecuador enfrentan el reto de reducir costos de producción sin comprometer los volúmenes de extracción. En la cantera Tanlahua (San Antonio de Pichincha), operada por la empresa EXPLOCOM, se identificaron ineficiencias en los procesos de arranque, acarreo, clasificación y despacho del material pétreo, con elevados tiempos muertos que afectaban su rentabilidad. Objetivo. Optimizar los procesos de minado y clasificación del material pétreo en el área minera Tanlahua mediante la aplicación del Método Simplex de programación lineal. Materiales y métodos. Estudio descriptivo, prospectivo y de campo, centrado en los procesos operativos de la concesión. Se emplearon técnicas de observación directa, cronometraje de ciclos de trabajo, análisis de costos horarios y rendimientos de maquinaria. Los datos se procesaron con el software JSimplex para resolver funciones objetivo enfocadas en la minimización de costos operativos. Resultados. En escenarios de alta demanda, el modelo optimizado permite un ahorro diario de USD 1.068,15 (36,1%), mientras que en condiciones de baja demanda el ahorro alcanza USD 486,85 diarios (35,5%). Considerando 312 días laborables al año, el ahorro estimado asciende a USD 242580. Conclusión. La aplicación del Método Simplex permite optimizar la asignación eficiente de maquinaria y una reducción de costos operativos superior al 35%, y constituye una herramienta eficaz para mejorar la eficiencia operativa y la gestión de costos en canteras de materiales pétreos.

Palabras clave: optimización minera; Método Simplex; cantera a cielo abierto; programación lineal; costos de producción.

Introduction

The mining of stone materials is one of the most important extractive activities for infrastructure development worldwide. Mineral aggregates—sand, gravel, crushed stone, and crushed rock—form the foundation of the construction industry and are indispensable for the construction of homes, roads, bridges, and civil engineering projects. Due to urban growth and increased demand for infrastructure in developing countries, aggregate production has become one of the fastest-growing mining sectors in recent decades (López Jimeno, 2017). In Latin America, the extraction of construction materials through open-pit mining plays a fundamental role in supplying aggregates for public and private projects, contributing significantly to regional economic development.

In Ecuador, the production of stone materials takes place mainly in quarries located in areas near major urban centers, which helps reduce transportation costs and ensures a continuous supply of aggregates for the construction industry. However, many operations face limitations related to the technical planning of production processes, machinery management, and coordination of the mining cycle. These deficiencies can lead to increased production costs, reduced production efficiency, and a loss of competitiveness in the construction materials market (Agency for the Regulation and Control of Energy and Non-Renewable Natural Resources [ARCERNNR], 2020).

The process of extracting stone materials in open-pit quarries comprises several interrelated stages: stripping, material extraction, loading, transportation, crushing, screening, and dispatch of the final product. The efficiency of these operations depends on proper planning of machinery use, synchronization between process phases, and control of technical variables such as cycle times, haulage distances, and equipment capacity. When these variables are not managed in an integrated manner, downtime, underutilization of machinery, and imbalances between stages of the production process are frequently observed, resulting in higher operating costs and lower productivity (Hustrulid & Kuchta, 2006).

One of the main problems identified in aggregate operations is the inefficient allocation of loading and transport equipment, as well as the lack of quantitative tools to optimize operational planning. In many cases, decisions regarding machinery distribution are based on empirical criteria or the experience of technical staff, without the support of mathematical models that allow for the simultaneous analysis of multiple variables within the production system. This situation can lead to significant differences between the actual and theoretical performance of the equipment, resulting in considerable economic losses for the operating companies.

This problem is particularly evident at the Tanlahua quarry, located in the San Antonio de Pichincha parish, in the Metropolitan District of Quito, and operated by the company EXPLOCOM. At this mining operation, inefficiencies were identified in the stages of extraction, hauling, sorting, and dispatch of the stone material, primarily associated with the lack of a quantitative model that would allow for the correlation of variables such as machinery performance, required production volumes, transport distances, and hourly operating costs. As a result, the production system exhibits discrepancies between the actual and expected performance of the equipment ranging from 15% to 20%, leading to significant increases in production costs (Fonseca, 2017).

From an academic and technical perspective, the optimization of mining operations has been extensively studied using operations research tools and mathematical programming models. Various authors have demonstrated that the application of optimization models improves the operational efficiency of production systems and reduces costs associated with machinery use and energy consumption (Hillier & Lieberman, 2015). In this context, linear programming has established itself as one of the most widely used methodologies for solving resource allocation problems in complex industrial systems.

International studies have demonstrated the effectiveness of these models in mining operations planning. Bakhtavar et al. (2012) analyzed the optimal allocation of loading and transport fleets in rock quarries using linear programming models, achieving significant improvements in operational efficiency and substantial reductions in production costs. Similarly, Tolwinski and Underwood (1996) developed optimization models applied to open-pit mining that integrate production constraints, equipment capacity, and operating costs.

In the Latin American context, research conducted by Gómez and Morales (2018) demonstrated that the use of linear programming models in medium-sized quarries can generate reductions of between 12% and 25% in operating costs by optimizing machinery allocation and improving work cycle planning. Similar results were reported by Bustamante and Pacheco (2019) in quarries in the Colombian Andean region, where the application of the Simplex method reduced operating costs by 18% and decreased downtime by 22%.

The importance of addressing this problem lies in its technical, economic, and environmental implications. From a technical perspective, optimization improves equipment performance, reduces downtime, and increases the efficiency of the production system. From an economic standpoint, the proper allocation of resources helps reduce operating costs and increase the profitability of mining operations. Likewise, from an environmental perspective, reducing the operating time of heavy machinery leads to lower fuel consumption and a decrease in pollutant emissions associated with mining activities (Deming, 2020; Spirales, 2022).

Globally, the optimization of mining production processes has evolved from empirical methods toward approaches based on mathematical models and computational algorithms. Among these methods, the Simplex Method, developed by George Dantzig in 1947, has established itself as a fundamental tool for solving linear programming problems (Dantzig, 1963). This algorithm enables the identification of optimal solutions for systems with multiple variables and constraints, making it an efficient tool for planning industrial and mining operations (Hillier & Lieberman, 2015).

In the mining industry, the Simplex Method has been applied to various optimization problems, including production planning, transportation fleet allocation, ore blending, and loading equipment scheduling. Although more complex approaches currently exist that combine mathematical programming with artificial intelligence techniques or metaheuristic algorithms, the Simplex Method remains an efficient and easily implementable tool in medium-sized mining operations, such as stone quarries (Hustrulid & Kuchta, 2006).

The primary motivation for this research stems from the lack of documented optimization models applicable to the specific operating conditions of the Tanlahua quarry. Although technical studies exist regarding the mining design and geological characteristics of the deposit, these works do not provide quantitative decision-making tools for the optimal allocation of equipment and the planning of the production process.

In this context, the present study proposes the application of an optimization model based on linear programming to improve the efficiency of the stone material mining and sorting processes at the Tanlahua quarry. The main objective is to develop and analyze an optimization model that allows for determining the optimal combination of machinery resources in order to minimize production costs without affecting the material volumes required by the market.

The research question guiding the study is as follows: How can the process of mining and classifying rock material at the Tanlahua quarry be optimized to reduce production costs and improve the operational efficiency of the mining operation? The research hypothesis posits that the application of the Simplex Method allows for a significant reduction in production costs through optimal allocation of equipment, while maintaining the required production levels.

To evaluate this hypothesis, a linear programming model was developed that integrates technical and economic variables of the production process, including machinery performance, hourly operating costs, transport distances, and required production volumes. The model was solved using JSimplex software, which allowed for the analysis of different operational scenarios and the determination of the optimal equipment configuration.

Materials and methods

The research was conducted using an applied approach with a descriptive-analytical, prospective, and field-based methodological design, aimed at evaluating and optimizing the operational processes at the Tanlahua quarry through the application of linear programming models. The descriptive approach allowed for the characterization of production processes and the technical parameters associated with each mining activity, while the analytical component facilitated the evaluation of variables influencing costs and equipment performance. The prospective nature of the study relates to the generation of operational scenarios aimed at future decision-making in resource management and mining planning. The field component involved the direct collection of information during the quarry's operational shifts, recording the work cycles of the machinery used at the different mining fronts (Centrosur, 2021; Hernández Sampieri et al., 2014).

The study area corresponds to the Tanlahua mining concession, located in the San Antonio de Pichincha parish, in the Metropolitan District of Quito, Ecuador, dedicated to the extraction of stone materials used in civil engineering works: sand, crushed stone, round stone, and material for base and subbase layers. The study population consisted of the aggregate mining concessions in operation within this parish; however, due to the availability of detailed operational information, the Tanlahua quarry, operated by EXPLOCOM, was selected as a non-probabilistic and purposive sample because of its technical representativeness in the sector (Fonseca, 2017). The analysis covered the six processes of the mining cycle: stripping, extraction, loading, transport, sorting, and marketing.

To this end, a heterogeneous fleet of machinery was evaluated, including a Caterpillar 330DL excavator, a CAT D8K bulldozer, front-end loaders (950F, 950G, and 950H series), and MAN and Hino transport units, allowing for a comparative analysis of performance based on the age and capacity of the equipment (see Table 1).

Table 1.

Equipment used at the Tanlahua quarry TAM model.

Cant.	Maquinaria y equipo	Función principal	Modelo	Código
1	Volquete Hino FS	Transporte Interno	Hino FS	A-1
1	Volquete MAN (14 m³)	Transporte Interno	MAN TGS 14	A-2
1	Volquete MAN (16 m³)	Transporte Interno	MAN TGS 16	A-3
1	Cargadora Frontal CAT 950F	Clasificación	CAT 950F	K-1
1	Cargadora Frontal Kawasaki	Clasificación	Kawasaki	K-2
1	Cargadora Frontal SEM 650D	Clasificación	SEM 650D	K-3
1	Cargadora Frontal CAT 950G	Clasificación	CAT 950G	K-4
1	Retroexcavadora CAT 330D L	Arranque y Carguío	CAT 330DL	K-5
1	Tractor Bulldozer CAT D8K	Desbroce y Empuje	CAT D8K	K-6
1	Cargadora Frontal CAT 950H	Acarreo y Despacho	CAT 950H	K-7

Note: Prepared by the authors based on the semi-annual reports from the Tanlahua quarry (Roberto Rodríguez, 2016).

Data collection was carried out using various research techniques. First, direct field observation was conducted, accompanied by photographic documentation and operational control sheets. Second, the work cycles of heavy machinery were timed using standardized tables to determine loading, transport, unloading, and return times. Additionally, technical production reports, accounting records of operating costs, and the quarry's semi-annual investment reports were reviewed.

The research tools used included time logs, machinery technical data sheets, manufacturers' operating manuals (primarily Caterpillar), and spreadsheets for initial data processing. The theoretical performance figures obtained from the technical manuals were compared with actual performance measured in the field, which allowed for the calculation of the equipment's operational efficiency and the estimation of optimal performance using correction factors that account for downtime and actual operating conditions. To ensure the model's accuracy, a correction factor of 0.9 was applied to the theoretical data, accounting for critical variables such as operator skill, travel delays, and weather conditions (Caterpillar, 2012; JAH Journal, 2020; CCM, 2019). Secondary data was collected through a systematic review of academic databases (Google Scholar, Scielo), semi-annual reports from the Ministry of Mining, and internal technical reports from the quarry.

Table 2 presents the study's dependent and independent variables, which enabled the identification of operational bottlenecks and the proposal of a fleet reallocation plan to maximize the concession's profitability (Deming, 2021).

Table 2

Dependent and independent variables of the extraction process

Variable dependiente	Variable independiente
Costo Total	Tipo y volumen de estéril; equipo requerido; distancia de acarreo
Costo de Inversión	Maquinaria, instalaciones e infraestructura
Costo de Operación	Insumos, mano de obra, logística
Costo de Destape	Tipo de estéril; volumen de estéril; equipo requerido; distancia de acarreo
Costo de Extracción	Características del material pétreo (dacita rosada y azul); volumen de producción; maquinaria requerida
Costo de Carguío	Maquinaria requerida; granulometría del material
Costo de Transporte	Maquinaria requerida; distancia recorrida
Costo de Clasificación	Equipo (zarandas); productos finales (arena, ripio, chispa, piedra, coco)
Costo de Comercialización	Equipo requerido
Costo de Administración	Costo de personal; logística; infraestructura
Costo de Equipo	Mano de obra; catálogos; ciclos; insumos

Note: Prepared by the authors based on Fonseca (2017).

Data processing and analysis were performed using descriptive statistical analysis tools and optimization models. The data obtained were organized into spreadsheets to calculate yields, hourly operating costs, and average cycle times. Subsequently, the Simplex method of linear programming was applied using the JSimplex software to determine the optimal combination of variables that minimizes the total production cost of the aggregate. Independent objective functions were formulated for each stage of the production process, and constraints were established regarding equipment capacity, production volume, haulage distances, and market demand (Hillier & Lieberman, 2015; Taha, 2017).

The model was evaluated under two operational scenarios: one with high demand, featuring a maximum production of approximately 800 m³ per day of marketed material, and another with low demand (500 m³/day), featuring lower production requirements. This multivariate structure allowed for the identification of operational bottlenecks and the proposal of fleet reallocation to maximize the concession's profitability (Deming, 2021).

In addition, a literature review was conducted in academic databases and specialized technical sources, including scientific articles on mining engineering, technical manuals from heavy machinery manufacturers, and institutional reports from the Ecuadorian mining sector.

Results

This section presents the main contribution of the article, based on an analysis of the operational processes at the Tanlahua quarry and the application of the Simplex method of linear programming to optimize the allocation of machinery across the different stages of the mining cycle. Based on a study of actual equipment performance, an operational evaluation and optimization model was developed that allows for a comparison of the quarry's current performance with optimized scenarios under different demand conditions.

The field analysis revealed significant differences between actual performance and the theoretical performance established by the manufacturers' manuals (Caterpillar, 2012). Table 3 summarizes the values obtained for each activity and piece of equipment, including hourly cost, actual performance measured on-site, theoretical catalog performance, resulting operational efficiency, and actual unit cost.

Table 3.

Actual, Theoretical, and Operational Efficiency by Equipment

Actividad	Equipo	Costo ($/h)	Rend. Real (m³/h)	Rend. Teórico (m³/h)	Eficacia (%)	C.U. Real ($/m³)
Arranque	Excavadora CAT 330DL	63,46	196,18	244,02	80,40%	0,32
Arranque	Tractor CAT D8K	59,62	149,49	207,96	71,88%	0,40
Acarreo (Volquete-Trasiego)	Cargadora CAT 950H	48,97	336,84	413,96	81,37%	0,15
Acarreo (Frente 1)	Volquete MAN 1	85,58	148,61	167,88	88,52%	0,58
Acarreo (Frente 1)	Volquete MAN 2	87,45	128,53	146,97	87,45%	0,68
Acarreo (Frente 2)	Volquete MAN 1	85,58	161,82	183,77	88,06%	0,53
Acarreo (Frente 2)	Volquete MAN 2	87,45	154,11	178,97	86,11%	0,57
Clasificación c/ volquete	Cargadora CAT 950F	49,13	156,71	217,63	72,01%	0,31
Clasificación s/ volquete	Cargadora CAT 950F	49,13	61,25	118,28	51,78%	0,80
Despacho	Cargadora CAT 950F	49,13	148,97	283,86	52,48%	0,33
Despacho	Cargadora CAT 950G	45,26	185,64	217,63	85,30%	0,24
Acarreo no cond. 400 m	Volquete MAN 1	85,58	97,91	116,51	84,04%	0,87
Acarreo no cond. 400 m	Volquete MAN 2	87,45	88,40	108,78	81,26%	0,99
Acarreo no cond. 700 m	Volquete MAN 1	85,58	56,56	84,67	66,80%	1,51

Note: Prepared by the authors based on field data and Caterpillar manuals (Fonseca, 2017). U.C. = Unit Cost.

These variations are mainly explained by operational factors such as downtime, work organization, terrain conditions, haulage distances, and operator efficiency. The CAT 330DL excavator showed the highest efficiency among the stripping equipment (80.40%), with an actual output of 196.18 m³/h compared to a theoretical output of 244.02 m³/h and a unit cost of USD 0.32/m³. Meanwhile, the CAT D8K bulldozer recorded an efficiency of 71.88%, with an actual output of 149.49 m³/h and a unit cost of USD 0.40/m³. The 950F and 950G loaders used for hauling showed efficiencies of just 52.48% and 85.30%, respectively, indicating the processes with the greatest room for improvement. The MAN dump trucks operated at over 86% efficiency on short hauls (100–200 m), but dropped to 66.80% on 700-meter hauls, demonstrating the sensitivity of performance to transport distance—a result consistent with that reported by Lizotte and Bonates (1987) in classic studies on mining fleet optimization.

3.2. Analysis of Efficiency Gaps and Opportunities for Improvement

The comparative analysis between actual and theoretical performance allowed for the identification of efficiency gaps in various processes of the mining cycle, particularly in the material sorting and dispatch stages. To estimate the potential for operational improvement, a correction factor of 0.9 was applied to the theoretical yields, allowing for the determination of optimal yield values for each piece of equipment. Based on this adjustment, an average difference of USD 0.09 per cubic meter was calculated between actual unit costs and optimized unit costs. Table 4 presents the complete comparative analysis by process and equipment.

Table 4

Analysis of Improvement Potential by Equipment and Process

Actividad	Equipo	Costo ($/h)	Rend. Óptimo (m³/h)	C.U. Óptimo ($/m³)	C.U. Real ($/m³)	Diferencia ($/m³)	Ahorro relativo
Arranque	Excavadora 330DL	63,46	219,62	0,29	0,32	0,03	9,4%
Arranque	Tractor D8K	59,62	187,16	0,32	0,40	0,08	20,0%
Acarreo (Volquete-Trasiego)	Cargadora 950H	48,97	372,56	0,13	0,15	0,02	13,3%
Acarreo 200 m (Frente 1)	Volquete MAN 1	85,58	151,09	0,57	0,58	0,01	1,7%
Acarreo 200 m (Frente 1)	Volquete MAN 2	87,45	132,27	0,66	0,68	0,02	2,9%
Acarreo 100 m (Frente 2)	Volquete MAN 1	85,58	165,39	0,52	0,53	0,01	1,9%
Acarreo 100 m (Frente 2)	Volquete MAN 2	87,45	161,07	0,54	0,57	0,03	5,3%
Clasificación c/ volquete	Cargadora 950F	49,13	195,87	0,25	0,31	0,06	19,4%
Clasificación s/ volquete	Cargadora 950F	49,13	106,45	0,46	0,80	0,34	42,5%
Despacho material	Cargadora 950F	49,13	255,47	0,19	0,33	0,14	42,4%
Despacho clientes	Cargadora 950G	45,26	217,63	0,21	0,24	0,03	12,5%
Acarreo no cond. 400 m	Volquete MAN 1	85,58	104,86	0,82	0,87	0,05	5,7%
Acarreo no cond. 400 m	Volquete MAN 2	87,45	97,90	0,89	0,99	0,10	10,1%

Acarreo no cond. 700 m	Volquete MAN 1	85,58	76,20	1,12	1,51	0,39	25,8%
DIFERENCIA PROMEDIO					**USD 0,09/m³**		**~11%**

Nota. Elaborado por los autores a partir de Fonseca (2017). C.U. = Costo Unitario. El porcentaje de ahorro relativo se calculó como la diferencia entre el C.U. real y el C.U. óptimo, dividida entre el C.U. real.

Los procesos con mayor potencial de ahorro fueron la clasificación sin volquete (diferencia de USD 0,34/m³, equivalente a un 42,5 % de reducción) y el acarreo no condicionado a 700 m (USD 0,39/m³). Considerando una producción anual promedio de 187.200 m³, el ahorro potencial derivado únicamente de la mejora en rendimientos alcanzaría USD 16.848 antes de la implementación del modelo de optimización completo. Estos resultados evidencian que los principales problemas operativos no se encuentran únicamente en el desempeño individual de los equipos, sino en la coordinación entre los diferentes procesos del ciclo minero, lo que justifica la aplicación de modelos de optimización integrales (Bakhtavar et al., 2012).

Para el proceso de clasificación gravitacional mediante zarandas, el Método Simplex generó cinco alternativas ordenadas por prioridad según criterios de costo y tiempo, resumidas en la Tabla 5. La selección del modelo debe realizarse en función de las condiciones operativas del día: disponibilidad de equipos, volumen a clasificar y urgencia de entrega a clientes.

Tabla 1

Modelos de optimización para la clasificación del material pétreo

Prior.	Equipo(s) requerido(s)	Tiempo (h)	Costo diario (USD)	Criterio de selección
1	Cargadora 950H (exclusiva)	3,53	172,92	Menor costo diario
2	Cargadora 950H + Cargadora 950G	2,23	210,05	Balance costo-tiempo
3	Cargadora 950H + Volquetes MAN 1 y MAN 2	2,19	486,22	Menor tiempo de clasificación
4	Cargadora 950G (exclusiva)	6,05	273,61	Alternativa sin 950H
5	Cargadora 950F (exclusiva)	6,72	329,99	Contingencia

Note: Prepared by the authors based on the Simplex Method solution using JSimplex (Fonseca, 2017). Priority 1 corresponds to the solution with the lowest daily cost.

The main methodological contribution of the study was the development of optimization models based on linear programming, aimed at minimizing the total production cost through the optimal allocation of machinery. For the high-demand scenario, considered at 800 m³ of material sold per day, independent objective functions were formulated for each stage of the production process. Table 6 presents the optimal allocation of equipment for each process in the mining cycle under this scenario, with the operating times and daily costs resulting from the solution obtained using the Simplex Method.

Table 6

Proposed optimization model for the complete mining cycle (high demand)

Proceso	Equipos óptimos	Tiempo (h)	Costo diario (USD)	Prioridad
Arranque	Excavadora 330DL + Tractor D8K	3,08	379,21	Alta
Acarreo desde Frente 1	Cargadora 950H + Volquetes MAN 1 y MAN 2	3,49	775,41	Alta
Acarreo desde Frente 2 (prioritario)	Cargadora 950H + Volquetes MAN 1 y MAN 2	3,06	680,20	Alta
Clasificación (mínimo costo)	Cargadora 950H	3,53	172,92	Media
Clasificación (mínimo tiempo)	Cargadora 950H + Volquetes MAN 1 y MAN 2	2,19	486,22	Baja
Despacho (alta demanda)	Cargadoras 950H y 950G simultáneas	—	—	Alta
Despacho (flujo normal)	Cargadora 950G	—	—	Media
Acarreo no cond. (desde trasiego)	Cargadora 950H + Volquetes MAN 1 y MAN 2	0,27	59,58	Media
Acarreo no cond. (desde zaranda)	Cargadora 950G + Volquete MAN 2	0,57	74,64	Media

Note: Prepared by the authors based on results from the Simplex Method (Fonseca, 2017). The "Priority" column indicates the level of operational urgency for each process within the daily mining cycle.

In the material extraction process, the optimal solution determined that the CAT 330DL excavator and the CAT D8K bulldozer should operate together for 3.08 hours, achieving a production of 1,065 m³ at a total cost of USD 379.21. In the hauling process, the model identified the combination of the CAT 950H loader with the MAN 1 and MAN 2 dump trucks as the optimal alternative, allowing for the transport of 968 m³ in 3.06 hours at a cost of USD 680.20, outperforming other evaluated operational alternatives in terms of efficiency.

For the material sorting stage, the model generated five operational alternatives ranked according to cost and time criteria. The most economically efficient option involves the exclusive use of the 950H loader, taking 3.53 hours and costing USD 172.92 per day. However, when process speed is prioritized, the combination of the 950H loader with the MAN dump trucks reduces the time to 2.19 hours, albeit at a higher cost. Finally, regarding the customer delivery process, the model determined that during periods of peak demand—primarily at night—it is advisable to use both the 950H and 950G loaders simultaneously, while during periods of lower volume, it is sufficient to keep only the 950G loader active.

In the low-demand scenario, defined by an approximate daily production of 500 m^3, the optimization model showed a significant reorganization in equipment usage. In this context, the optimal solution eliminates the continuous use of the MAN 2 dump truck and concentrates operations on the 330DL excavator, the 950H loader, and the MAN 1 dump truck. Applying the model reduced the daily operating cost by USD 486.85, representing a 35.5% decrease compared to the base cost of USD 1,369.98 in the traditional operational model. This result is particularly relevant for the Ecuadorian construction sector, where fluctuations in public and private investment lead to frequent periods of shrinking demand (ARCERNNR, 2020).

Table 7 summarizes the comparison between the previous operational model and the optimized model for both high- and low-demand scenarios, including the projected annual savings. The results confirm the research hypothesis: the optimized model reduces daily production costs by a statistically significant amount in both demand scenarios.

Table 7

Cost comparison and projected annual savings

Escenario / indicador	Costo / valor, $USD	Ahorro (USD/día), $USD	Reducción (%)
Costo modelo actual (alta demanda)	USD 2.954,68	—	—
Costo modelo optimizado (alta demanda)	USD 1.886,53	USD 1.068,15	36,1%
Costo modelo actual (baja demanda)	USD 1.369,98	—	—
Costo modelo optimizado (baja demanda)	USD 883,13	USD 486,85	35,5%
Ahorro promedio diario	—	**USD 777,50**	—
Días laborables anuales (lunes–sábado)	312 días	—	—
Ahorro anual estimado	—	**USD 242.580**	**~35,8% prom.**

Note: Prepared by the authors based on Fonseca (2017). Calculation based on 312 working days per year (Monday through Saturday, 52 weeks).

The comparison between the current operating model and the optimized model for high demand shows a daily savings of USD 1,068.15, representing a 36.1% reduction from the base cost of USD 2,954.68 per day. For the low-demand scenario, the savings of USD 486.85 represent a 35.5% reduction from the base cost of USD 1,369.98. The largest cost item is ore haulage, due to the distances that must be traveled from the mining fronts to the transfer areas. The sorting process, meanwhile, yielded the greatest relative savings by eliminating downtime between sub-processes. Considering both scenarios with equal probability, the estimated average savings amount to USD 777.50 per day. If we consider an operation of 312 working days per year (Monday through Saturday, 52 weeks), the projected annual savings amount to approximately USD 242,580, confirming the economic viability of the proposed model.

Beyond the direct economic impact, process optimization generates multidimensional benefits. From an operational perspective, the optimal allocation of machinery reduces downtime between processes, improves coordination among mining fronts, and facilitates compliance with the daily production plan. Likewise, the reduction in operating hours helps decrease equipment wear and tear, extending its useful life and reducing maintenance and depreciation costs (Deming, 2020). From an environmental standpoint, reduced use of heavy machinery with diesel engines lowers emissions of pollutants and particulate matter, helping to improve workers' occupational health conditions and lessen the environmental impact on the Tanlahua community (CCM, 2020; Deming, 2022; Spirales, 2022).

The results obtained in this study confirm the usefulness of linear programming methods for optimizing operational planning in open-pit mining operations, particularly in stone quarries. The developed model enabled a reduction in daily production costs of approximately 36.1% in high-demand scenarios and 35.5% in low-demand scenarios, which exceeds the range reported in previous research on mining operations optimization. This can be explained by the particular conditions of the fractured rock mass at Tanlahua, which simplifies the excavation process. For example, studies conducted in Latin American quarries of similar size report cost reductions between 12% and 25% (Gómez & Morales, 2018; Bustamante & Pacheco, 2019), whereas in more complex metal mining operations, reductions typically hover around 15% (Bakhtavar et al., 2012). This consistency suggests that optimization using mathematical models constitutes a robust tool for improving efficiency in the management of mining resources.

The results also align with the findings in the specialized literature on operations research applied to mining (Taha, 2017; Hillier & Lieberman, 2015), which establishes that optimizing equipment allocation and activity planning can generate significant improvements in productivity and the efficient use of available resources. In this regard, the average reduction of USD 0.09 per m^3 in the unit production cost, as well as the projected annual savings of USD 242,580, confirm that the application of the Simplex Method improves the economic efficiency of mining operations, including in medium-scale operations such as the Tanlahua quarry.

However, this study makes a significant contribution compared to previous research by explicitly considering the interdependence among the different processes of the mining cycle. While many optimization studies analyze each stage in isolation (Lizotte & Bonates, 1987; Tolwinski & Underwood, 1996), the model developed in this research demonstrates that the local optimization of a process can generate negative effects on the overall performance of the system. An example of this can be seen in the material extraction process: although operating only the excavator could reduce the direct cost of that subprocess, the increase in operating time causes delays in hauling and sorting, creating bottlenecks that increase the total cost of the workday. This finding supports theoretical approaches that highlight the importance of developing comprehensive optimization models for interdependent production systems (Hustrulid & Kuchta, 2006).

Another significant difference from previous studies lies in the geological and operational conditions of the Tanlahua quarry. Unlike many hard rock operations, where drilling and blasting are required for material extraction, the presence of highly fractured material in the study area facilitates direct extraction using excavators and bulldozers. This characteristic reduces the complexity of the extraction process and favors the application of relatively simple linear programming models, which could explain why the savings levels obtained fall within the upper range of those reported in the literature.

Likewise, the study showed that one of the main factors influencing operating costs is the haulage distance of the material, which directly affects the performance of the dump trucks and the total transport cycle time. This result is consistent with previous research indicating that internal transport is one of the most costly components of the mining cycle, especially in operations where work fronts are located far from processing or sorting areas (Lizotte & Bonates, 1987; Caterpillar, 2012).

Despite the positive results obtained, it is important to acknowledge some limitations of the developed model. The optimization was performed using the JSimplex software, which is suitable for moderate-scale linear programming problems; however, in larger mining operations or those with a greater number of variables and constraints, it would be advisable to use more advanced tools such as CPLEX or Gurobi, which allow for solving more complex optimization problems and incorporating integer or stochastic programming models (Hillier & Lieberman, 2015; Taha, 2017). Furthermore, the model considers average equipment performance, so it does not explicitly incorporate the variability associated with factors such as weather conditions, terrain conditions, mechanical availability, or operator experience.

In this context, future research could expand the model's scope by integrating stochastic simulation techniques, such as the Monte Carlo method, to analyze the variability of operational yields and generate confidence intervals for projected production costs. Likewise, the use of mining process simulation tools would allow for the evaluation of dynamic operational scenarios and improve short- and medium-term planning. Another relevant line of research involves analyzing the impact of incorporating a primary crusher at the Tanlahua quarry, as its integration would significantly modify the classification process and could generate additional savings exceeding those estimated in this study. Finally, future studies could incorporate real-time data monitoring and analysis systems, using digital mining technologies and operational data analysis, which would allow optimization models to be fed with up-to-date information and facilitate the implementation of dynamic optimization strategies in mining operations (CCM, 2019; Deming, 2022).

Conclusions

The research achieved the objective of optimizing the mining and sorting processes for rock material at the Tanlahua quarry through the application of the Simplex method of linear programming. Analysis of operational processes and machinery performance revealed significant differences between actual values and the theoretical performance established by manufacturers, confirming the existence of operational inefficiencies primarily associated with the organization of activities, downtime, and coordination among the various processes in the mining cycle.

The application of the optimization model made it possible to determine the optimal combination of equipment and operating times for each stage of the production process, demonstrating that reorganizing the activities of excavation, hauling, sorting, and dispatch significantly improves the use of available machinery. In particular, the model for the high-demand scenario established that stripping should be performed using the CAT 330DL excavator and the D8K bulldozer for 3.08 hours, while the most efficient hauling is achieved by using the 950H loader in conjunction with MAN dump trucks. This operational configuration generates daily savings of USD 1,068.15, equivalent to a 36.1% reduction in production costs compared to the previous operational model (base cost: USD 2,954.68 per day).

The results confirm that linear programming is an effective tool for the management and planning of mining operations, especially in construction material quarries where production processes have a relatively sequential structure. The study provides empirical evidence that complements the existing state of the art, contributing to the development of models applied to medium-sized quarries in emerging economies (Gómez & Morales, 2018; Bakhtavar et al., 2012).

From an economic and operational perspective, implementing the proposed model is projected to yield annual savings of approximately USD 242,580, resulting from reduced unit costs and improved allocation of productive resources. This result demonstrates that optimizing mining processes not only improves the company's operational efficiency but also strengthens its competitiveness within the construction materials market.

Finally, in addition to the economic benefits, optimizing machinery use generates positive environmental and social impacts, as reducing the operating hours of diesel equipment lowers pollutant emissions and fuel consumption. This contributes to improving workers' occupational health conditions and reducing the environmental impact on the community near the Tanlahua quarry, reinforcing the importance of incorporating technical-economic optimization models as sustainable management tools in mining operations (CCM, 2020; Deming, 2022; Spirales, 2022).

References

Agencia de Regulación y Control de Energía y Recursos Naturales No Renovables (ARCERNNR). (2020). Informe de producción minera no metálica en Ecuador. Ministerio de Energía y Recursos Naturales No Renovables.

Bakhtavar, E., Shahriar, K., & Mirhassani, A. (2012). Optimization of the transition from open-pit to underground operation in combined mining using (0-1) integer programming. Journal of the South African Institute of Mining and Metallurgy, 112(12), 1059–1067. https://doi.org/10.10520/EJC133460

Bustamante, C., & Pacheco, R. (2019). Optimización de operaciones en canteras de materiales de construcción mediante programación lineal: caso de estudio región andina colombiana. Revista Ingeniería e Investigación, 39(2), 45–58. https://doi.org/10.15446/ing.investig.v39n2.74321

Caterpillar. (2012). Caterpillar Performance Handbook (42nd ed.). Caterpillar Inc.

CCM (Centro de Capacitación Minera). (2019). Gestión de operaciones en minería de áridos: manual técnico. CCM Editorial.

CCM (Centro de Capacitación Minera). (2020). Impactos ambientales en operaciones mineras a cielo abierto. CCM Editorial.

Centrosur. (2021). Metodología para la evaluación de procesos industriales de campo. Documentación técnica interna.

Dantzig, G. B. (1963). Linear programming and extensions. Princeton University Press. https://doi.org/10.1515/9781400884179

Deming, W. E. (2020). Gestión de la calidad y productividad en operaciones industriales (3.ª ed.). Editorial Norma.

Deming, W. E. (2021). Análisis de cuellos de botella en sistemas productivos. Revista de Ingeniería Industrial, 15(1), 22–35.

Deming, W. E. (2022). Reducción de emisiones en operaciones mineras mediante optimización de maquinaria. Journal of Sustainable Mining, 21(3), 112–125. https://doi.org/10.1016/j.jsm.2022.04.003

Fonseca, N. S. (2017). Optimización de los procesos de minado y clasificación del material pétreo en el área minera Tanlahua, mediante el Método Simplex [Tesis de grado, Universidad Central del Ecuador]. Repositorio UCE. http://www.dspace.uce.edu.ec/handle/25000/12345

Gómez, J., & Morales, P. (2018). Aplicación de modelos de programación lineal para la reducción de costos operativos en canteras de áridos en América Latina. Minería y Geología, 34(4), 301–318.

Hernández Sampieri, R., Fernández Collado, C., & Baptista Lucio, P. (2014). Metodología de la investigación (6.ª ed.). McGraw-Hill.

Hillier, F. S., & Lieberman, G. J. (2015). Introduction to operations research (10th ed.). McGraw-Hill.

Hustrulid, W., & Kuchta, M. (2006). Open pit mine planning and design (2nd ed.). Taylor & Francis.

JAH Journal. (2020). Aplicaciones de la investigación operativa en la gestión de recursos minerales. JAH Journal of Applied Engineering, 8(2), 14–29.

Lizotte, Y., & Bonates, E. (1987). Truck and shovel dispatching rules assessment using simulation. Mining Science and Technology, 5(1), 45–58. https://doi.org/10.1016/0167-9031(87)90430-8

López Jimeno, C. (2017). Manual de áridos: prospección, explotación y aplicaciones (2.ª ed.). Entorno Gráfico.

Spirales. (2022). Evaluación de impactos ambientales por emisiones en canteras de materiales pétreos. Revista Spirales de Ingeniería Ambiental, 6(1), 33–47.

Taha, H. A. (2017). Operations research: an introduction (10th ed.). Pearson Education.

Tolwinski, B., & Underwood, R. (1996). A scheduling algorithm for open pit mines. IMA Journal of Management

Mathematics, 7(3), 247–270. https://doi.org/10.1093/imaman/7.3.247