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TESE DE DOUTORADO

Os fundamentos da transformação digital nas operações de lavra: pessoas, processos e tecnologia

Autor: **WALTER SCHMIDT FELSCH JUNIOR**
Orientador: **Prof. Dr. HERNANI MOTA DE LIMA**
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Área de concentração:
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DOCTORAL THESIS

The fundamentals of digital transformation in mining operations: People, processes, and technology

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Walter Schmidt Felsch Junior

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RESUMO

A mineração está em constante evolução em seus processos produtivos. Com o advento das tecnologias de sistemas embarcados, transmissão remota de dados e processamento computacional, novas ferramentas, processos e atribuições de pessoas surgiram na indústria mineral. No entanto, o uso de novos produtos associados a tecnologia demandam uma série de ajustes e adaptações no âmbito de processos e pessoas. As competências e qualificações pessoais não são frequentemente atualizadas ao mesmo ritmo que as evoluções tecnológicas. Além disso, a literatura não define soluções para medir a influência do fator humano nos processos das operações de mina a céu aberto. Para lidar com a gestão operacional na mineração devem ser considerados três fatores principais: pessoas, processos e tecnologia. A interação entre estes três fatores deve atingir um ponto ótimo para evitar a alienação, a frustração e o caos tecnológico. Esta tese fornece novos métodos que visam aprimorar a capacitação de pessoas nos centros de controle operacionais, inserir processos automatizados para análise de dados em tempo real, introduzir trabalhos técnicos referentes a sistemas de telemetria e GPS de alta precisão, e destaca os benefícios da implementação de caminhões autônomos na mineração. O estudo que envolve a capacitação de pessoas culminou no aumento da capacidade produtiva da frota de transporte em 19%. A prática de análise dados em tempo real e estruturação de processos resultou no aumento da produtividade de carregamento em 4,71%, além de reduzir em 6,8% as filas no carregamento. A utilização de dados de telemetria associado a um processo bem definido de ações e responsabilidades de pessoas gerou a redução dos custos operacionais de 3,3%. O controle de drenagem realizado por pontos de GPS de alta precisão se mostrou mais eficaz comparado com a metodologia tradicional e possui um alto potencial para melhorias na segurança e redução de ineficiências operacionais. A simulação da operação com o cenário autônomo constatou aumentos na produtividade e utilização das frotas de carga e transporte e evidenciou que a preparação da mina para o recebimento da tecnologia pode gerar resultados expressivos.

Palavras-chave: Transformação digital; Operações de Lavra; Gestão operacional; Pessoas; Processos; Tecnologia.

ABSTRACT

In the field of mining, production processes are constantly evolving. With the advent of embedded systems technologies, remote data transmission, and computer processing, new tools, processes, and operational roles have emerged in the mining industry. However, the usage of new products associated with these technologies requires a series of adjustments and adaptations at the level of processes and people. Personal skills and qualifications are often not updated at the same pace as technological developments are made, and the literature does not contain solutions for measuring the influence of human factors on the processes of open-pit mine operations. When dealing with operational management in mining, three main factors must be considered: people, processes, and technology. The interaction between these three factors must be optimal in order to avoid alienation, frustration, and technological chaos. This thesis presents new methods that focus on improving the training of people in operational control centers, implementing automated processes for real-time data analysis, introducing technical equipment such as telemetry systems and high-precision GPS, and the benefits of implementing autonomous trucks in mining. A study involving the training of people achieved an increase in the productive capacity of a transportation fleet by 19%. The analysis of real-time data and structuring processes enabled an increase in loading productivity of 4.71%, in addition to reducing loading queues by 6.8%. The use of telemetry data together with a well-defined process for specifying the actions and responsibilities of people generated a reduction in the operating costs of 3.3%. Drainage control using high-precision GPS points proved to be more effective than the traditional methodology, and showed strong potential in terms of improving safety and reducing operational inefficiencies. A simulation of operation under autonomous conditions found increases in the productivity and utilization of the loading and transportation fleets, and showed that preparing the mine to receive these technologies can generate significant results.

Keywords: Digital transformation; Operational management; People; Processes; Technology.

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1. INTRODUCTION

Mining is a strategic activity that is important for the economic and social growth of communities, regions, and countries. In recent years, this activity has faced major challenges, such as scarcity of mineral resources, changes in energy matrices, new environmental and social demands, degradation of ore quality, and broad changes in global competitiveness. However, with the advent of embedded systems technologies, remote data transmission, and computer processing, new possibilities have emerged in the mineral industry, especially in regard to the management of mining operations.

In this context, digital transformation (DT) in mining has become an essential approach to ensure the safe, sustainable, viable, and profitable evolution of the sector.

DT can be described as a process that aims to improve an entity by triggering significant changes in its properties through a combination of information, computing, communication, and connectivity technologies (Vial, 2019; Saarikko, 2020). The focus in this case is on the use of technology in the service of science, business, and society. Thus, through the use of DT, it is possible to mitigate and solve traditional mining problems with greater practicality, speed, and effectiveness.

Among main benefits of DT, its capacity to make communication faster and more assertive is particularly significant. It also has direct effects on the integration of sectors (e.g., mine to port), and can make teams more attuned and collaborative. Another key aspect is the automation of processes and systems, which can support improvements in decision making through the systematic analysis of performance indicators.

However, in order to realize the potential value of DT, continuous analytical efforts are required, which can be translated into comprehensive projects with a focus on safety, sustainability, and productivity. To achieve significant breakthroughs, the process requires digital innovation, for example:

- Software systems to help identify possibilities for asset optimization.
- Devices for remote monitoring and control of activities.

- Processes for the automation of repetitive tasks.
- People with the analytical skills and abilities needed to interact with the software, devices, and processes, and who have a knowledge of business strategies.

In addition, DT has provided mining operations with comprehensive data that can be used to effectively improve occupational safety hazards, reduce carbon emissions, increase productivity, and reduce operating costs. Through the use of appropriate analytical tools, mining operators can improve their ability to focus on opportunities for improvement, prioritize their efforts, and achieve positive results.

Developing interpersonal skills in individuals is crucial for the success of integrating people, processes, and technology in driving digital transformation in the mining industry. Here are some strategies for developing these skills:

- Training and Development: Invest in training programs that focus on developing interpersonal skills such as communication, teamwork, conflict resolution, and empathy.
- Leadership and Mentoring: Promote effective leadership that values interpersonal skills. Establish mentoring programs where experienced employees can guide younger ones, sharing their interpersonal skills.
- Clear and Open Communication: Create a culture of open communication where employees feel comfortable sharing ideas, concerns, and feedback. Hold regular meetings to keep everyone informed about the goals of digital transformation and progress.
- Conflict Resolution: Teach people to deal effectively with conflicts by promoting constructive dialogue and negotiation.
- Adaptability and Continuous Learning: Encourage adaptability and a willingness to learn continuously, as digital transformation in mining can bring frequent changes.
- Assessment and Feedback: Conduct performance evaluations that include an

assessment of interpersonal skills and provide constructive feedback.

- Fostering a Trusting Environment: Build a trust-based work environment where people feel secure to take risks and innovate.
- Continuous Evaluation and Improvement: Regularly assess the effectiveness of interpersonal skills within teams and make improvements as needed.

Developing interpersonal skills in individuals is an ongoing process that requires leadership commitment and an organizational culture that values these skills. When people can communicate effectively, work well in teams, and adapt to changes, it will significantly contribute to the success of digital transformation in the mining industry.

The current scenario, however, suggests weaknesses in the mining companies' digital strategies that can reduce their market competitiveness. In research conducted by the International Data Corporation (IDC), 45% of the mining companies assessed had a low level of maturity in terms of data excellence (Ernst & Young, 2021). The main reasons for this low maturity were the manual use of data, manual data collection methods, a lack of definition of specific procedures and standards for activities, and a low level of knowledge about DT and its use.

In the mining industry, which is increasingly undergoing automation, the volumes of data are growing at an rapid pace. It is crucial to understand how to use these data to improve the accuracy of the information and to obtain the best insights.

There is therefore a widespread need for new processes and skilled workers when developing smart business applications for decision making. However, when a workforce is trained in the technological management of mining operations, personal skills and qualifications are not often updated at the same rate as technological changes take place. The current scenario indicates that there are difficulties in keeping mining professionals up to date and enabling them to understand the new functions and tools that can add value to the business. A lack of structuring and procedures for training has a strong negative effect on the search for greater operational efficiency. In addition, the technical literature does not cover the influence of human factors and production processes on the operational results of open-pit mines.

Digital transformation in mining represents a significant advancement in how operations are conducted in this crucial sector for the global economy. One of the critical pillars of this transformation is the pursuit of more assertive communications. The effective communication is essential to ensure that information flows efficiently throughout the mining value chain, from extraction to mineral marketing. The implementation of advanced technologies, such as IoT (Internet of Things) systems and 5G networks, enables real-time collection of operational, geological, and environmental data, allowing for more informed and agile decision-making.

This more assertive communication plays a fundamental role in the integration of people, processes, and technology in mining. Field teams can communicate instantly with experts in control centers, enabling a faster response to unplanned events and optimizing operational efficiency. Furthermore, communication also plays a crucial role in managing the cultural changes necessary for digital transformation in mining. Clear and transparent communication helps mitigate resistance and promotes the adoption of new technologies and practices.

To achieve optimal operational management in mining, the three key aspects of people, processes, and technology must be considered. The interaction between these three factors must be carefully managed in order to avoid alienation, frustration, and technological chaos (Figure 1). As technology advances, processes become more complex, and trained professionals with specific skills are therefore required to leverage these technologies and achieve optimal operational management.

These three fundamental pillars of operational management—people, processes, and technology—must be developed and balanced to achieve efficiency, reduce costs, and improve customer service. If any of these are lacking, it can lead to inefficiency, increased costs, poor customer service, and unusable systems.

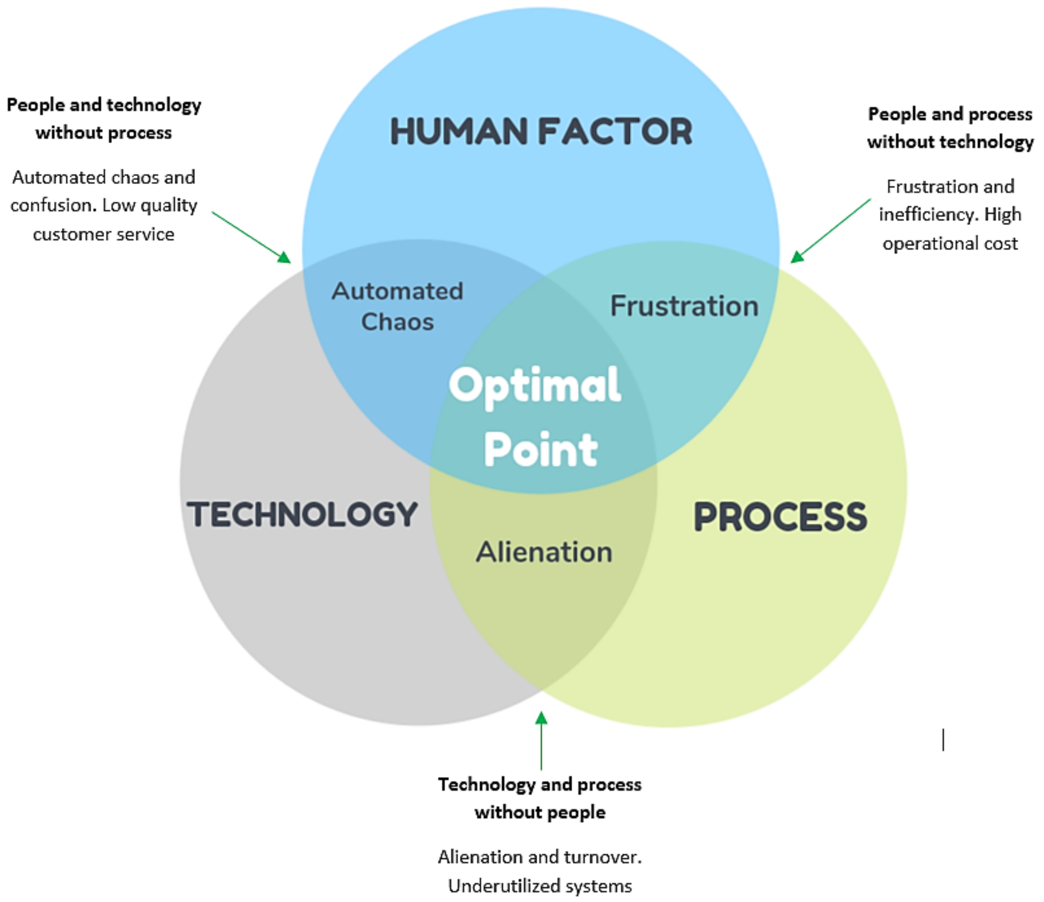

Figure 1 - Main factors associated with operational management in mining

Source: Author's elaboration

In addition to people, processes, and technology, there are several other key factors that contribute to the successful implementation of new technologies in mining, including connectivity, planning, and analytics (Hilson & Murck, 2000; Sishi & Telukdarie, 2017; Kubrin & Kopylov, 2019; Lööw, 2021). Connectivity is essential for real-time engagement and data sharing between all of the stakeholders in the mining value chain, whereas planning is critical for automation, rule definition, and the assignment of responsibility for new technologies, and analytics can help to improve decision making and create a data-driven culture.

However, it is not sufficient simply to implement new technologies; to capture the value they create, it is necessary to associate them with a set of best management practices that cover the fundamentals of strategy, logistics, organization, and culture.

Some specific examples of how these practices can be applied to the mining industry include:

- Strategy: The mining company's overall strategy should be aligned with the goals of implementing new technologies. This will help to ensure that the technologies are used in a way that supports the company's long-term objectives.
- Logistics: The mining company must have a plan for how to deploy and manage new technologies. This includes ensuring that the technologies are compatible with the company's existing infrastructure, and that adequate training is available to employees on how to use them.
- Organization: The mining company's organizational structure must be flexible enough to accommodate the changes brought about by new technologies. This may involve creating new roles and responsibilities or adjusting existing processes.
- Culture: The mining company's culture must be supportive of innovation and change. This means creating an environment where employees are encouraged to experiment and learn from their mistakes.

By following these best management practices, mining companies can maximize the value of new technologies and achieve their long-term goals.

The ability to innovate is influenced by organizational culture, and deficiencies in this regard are one of the main barriers to the success of companies in the digital age (McKinsey, 2016). Technology plays a vital role in managing mining operations, automating tasks, and generating valuable insights. There are numerous tools that can add value to operations, such as fleet management systems (FMSs), onboard telemetry, high-precision GPS, and collision avoidance systems, among others. These technologies are essential for the implementation of autonomous equipment in mining, together with robust telecommunications networks. In addition, well-defined processes and trained personnel are essential for the success of projects.

The widespread use of autonomous equipment is now a reality in the mining industry, and mechanisms are needed to reduce the barrier to entry for companies of all sizes. However, there is limited research on these trends and their impact on operations.

An FMS is an essential requirement for the operation of autonomous technology. This formed the central theme of the author’s Master's dissertation (Felsch Jr., 2014), and there have been several studies and practical experiments that have demonstrated the benefits of the use of an FMS, for example by Ercelebi and Bascetin (2019), Mohtasham et al. (2021), Nobahar et al. (2022), and Felsch et al. (2022).

The technological evolution of an FMS can be divided into three milestones: static allocation, dynamic allocation, and full automation with an autonomous fleet. Figure 2 shows the main pillars of the FMS infrastructure, which include communication, onboard telemetry, and high-precision positioning.

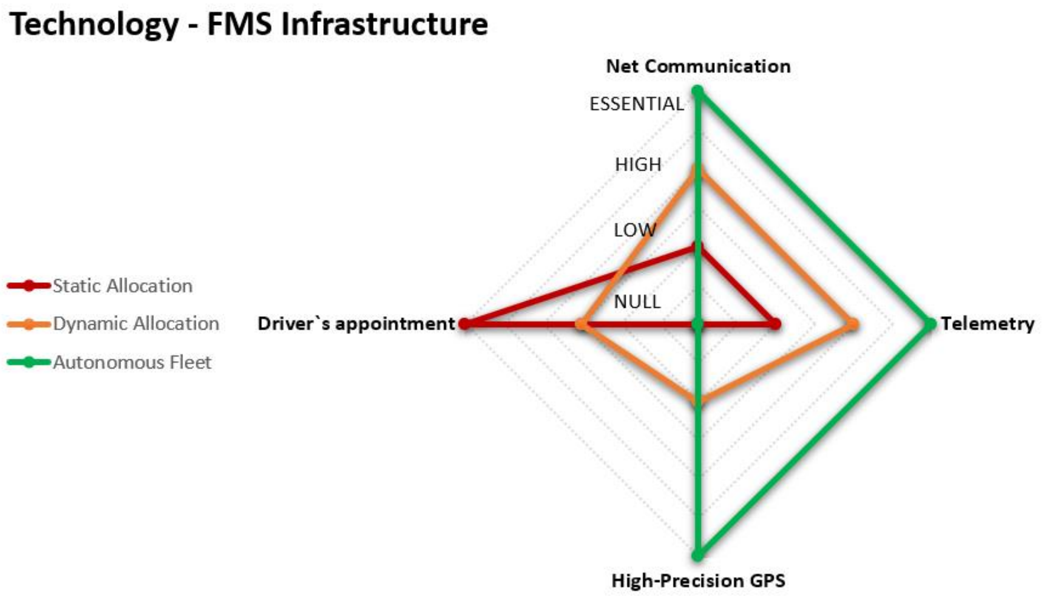

Figure 2 - Main pillars influencing the FMS infrastructure

Source: Author’s elaboration

In view of the current status of this field, it is essential that academic research and technical work be conducted to enable a better understanding of the impact of DT on mining operations and the development of solutions that can contribute to the advancement of the sector.

The role of technology in mine operational management is becoming more prominent with the advancement of new branches of knowledge, such as Artificial Intelligence, Machine Learning, and blockchain. However, this research will not evaluate them or develop tools based on their concepts.

This thesis proposes an innovative approach that aims to improve the structuring of work processes, increase the technical knowledge of the technologies involved in mining operational management, and enable the introduction of routine human capital training activities.

This work identifies three key fundamental aspects affecting the dissemination and integration of DT in mining operations: people, processes, and technology. Each of these has its own features and importance, as explored in later sections of this thesis that present case studies and discuss technical approaches for training people, the integration of processes for real-time data analysis, telemetry systems, the use of high-precision GPS, and a simulation study that highlights the benefits of implementing autonomous trucks in mining.

Each of these discussions is based around scientific articles published or submitted to international journals and conferences with a high impact factor. These solutions can be considered joint activities that illustrate the various possibilities for improving the mining industry and to enable it to meet major economic, social, and environmental challenges.

1.1. OBJECTIVES

The objectives of this research are to:

- Develop a methodology for training people working in mine control centers.
- Build a cyber-physical system for the automation of real-time data analysis for loading equipment.
- Evaluate the benefits and features of implementing a telemetry system.
- Develop a methodology for drainage control in loading squares.
- Simulate the gains arising from the implementation of autonomous trucks in mining.

The following research questions will be addressed in this thesis:

1. What are the key challenges and opportunities associated with training people working in mine control centers?
2. How can a cyber-physical system be used to automate real-time data analysis for loading equipment?
3. What are the benefits and features of implementing a telemetry system?
4. How can a methodology for drainage control be developed at loading squares?
5. What are the gains related to the implementation of autonomous trucks in mining?

1.2. METHODOLOGY

This research relies on several methods and approaches, including a literature review, case studies, and surveys. A literature review is carried out to identify the key challenges and opportunities associated with the research objectives, and case studies are used to explore the ways in which these objectives have been addressed in different mining operations. Surveys are used to collect data from mining professionals about their views on the research objectives.

1.2.1 Expected Outcomes

The outcomes of this research are expected to:

- Empower people to perform activities in the mining control room more efficiently.
- Increase the productivity of loading operations through the automation of real-time data analysis.
- Increase the safety of mining operations and equipment performance with data from telemetry systems.
- Enable the automation of drainage control in loading squares.
- Quantify the operational benefits of using autonomous trucks in mining by considering the mine adjustments needed to receive the technology and its implementation.

1.2.2 Significance

This research is important because it will provide the mining industry with the information and tools it needs to address the challenges and opportunities associated with the research objectives. The findings of this research will help mining companies to improve efficiency, reduce costs, and increase safety.

1.3. STRUCTURE OF THE THESIS

Based on the objectives outlined above, the thesis is organized as follows:

- Chapter 1: Presentation of the problem and discussion of objectives.
- Chapter 2: Literature review, methodology, details of the case study, results, and research analysis of the human factors associated with operational management technology in the mining sector.
- Chapter 3: Literature review, methodology, practical applications, results, and research analysis of a cyber-physical system aimed at increasing productivity in the mining industry.
- Chapter 4: Literature review, methodology, results, and research analysis of the use of telemetry systems to manage operational processes.
- Chapter 5: Literature review, methodology, results, and research analysis related to the use of high precision GPS.
- Chapter 6: Literature review, methodology, results, and research analysis of the simulation of the use of autonomous trucks.
- Chapter 7: Final considerations and the contribution to DT in the mining industry.
- Chapter 8: Summary of the conclusions of the studies presented here.
- Chapter 9: Suggestions for further research.

A list of the references for all of the studies making up this thesis is also presented.

2. AN INNOVATIVE APPROACH OF HUMAN FACTOR ASSOCIATED WITH MINING OPERATIONAL MANAGEMENT TECHNOLOGY

2.1. INTRODUCTION

The human factor has been of great relevance to mining activities since the beginning of civilization. In its early days, mining was slow and dangerous, with complete dependence on human factors for its development. However, over time, technology has provided safer and more productive methods for carrying out this activity. Human beings continue to play a fundamental role in mining activities but with different attributions, seeking greater adaptability with new processes and modern operational management systems.

The concepts associated with Industry 4.0 and digital transformation in mining (Young and Rogers, 2019; Barnewold and Lottermoser, 2020; Sganzerla et al., 2016) aim at introducing greater innovation into mining operations. These concepts are aligned with the activities of professionals in the search for improved safety in operations and production volumes in addition to reducing costs and operational inefficiencies. In addition, modern mining has changed the way in which people work and the work environment is established. The investment in human capital can be a plausible driver of sustainable business models (Umar et al., 2022). Thus, understanding the roles that people play in systems is essential to achieving technology security and productivity (Beer and Mulder, 2020). The operational management team is considered to be a key component in the implementation of technological systems in mining operations (Bellamy and Pravica, 2011).

Based on a survey of 80 specialists representing a group of mining companies in Australia (Heather, 2018) 82% of interviewees said they were having difficulties hiring people with qualified skills for available positions, especially in operational management. As a result, as technological advances occur, companies tend to face a shortage of professionals with the desired profile.

A study conducted by the World Economic Forum (2016) predicts an increasing demand for cognitive abilities, system skills and complex problem-solving skills in the near future. Hence, organizations must develop and implement appropriate training and education programs and develop digital skills as well as entirely new skills to reinforce the employability and personal development of their employees (Schlaepfer, 2017).

Companies must evaluate the current requirements in the search for qualifications. Then, they need to develop mechanisms that ensure that future professionals are prepared for advances and innovations in modern mining, such as the increasing use of automation and real-time data analysis (AusIMM Bulletin, 2020). However, there is great difficulty in offering adequate training and personal development opportunities for technical staff as well as for newly hired professionals.

Besides, companies' difficulty in determining how to integrate technological systems and human work is explained by several points. For instance, there is a lack of a strategic business vision and technical knowledge regarding the necessary skills to carry out management activities and data analysis. Moreover, technology implementations rarely fail because the technology did not work but because people lack the necessary expertise or find it extremely difficult to use it (Cotteleer and Murphy, 2018)

There are significant challenges related to managing and training people in companies, which are not only attributed to technology (Westerman et al., 2011). For instance, problems may arise in the implementation phase and in organizational challenges (e.g., a lack of skills, cultural issues and a lack of IT vision and coordination). Currently, there are problems of technological integration, particularly in work design, and a lack of training for operational management in mining (Chirgwin, 2021; Lynas and Horberry, 2011).

Furthermore, the interaction between humankind and technology must be seen in a broader context related to the objectives and resources of mining. However, combining human skills and substantial information requires technological solutions that reduce the conflict among personnel and systems. To achieve that, it is necessary to create ways to increase staff members' intellectual and practical capabilities to achieve more effective systems (Emmanouilidis et al., 2019). Thus, a robust training methodology, associated with efficient operational management with targets and goals, can become a real revolution in mining.

Based on all the above, this article proposes a comprehensive view of the importance of the human factor in mine operational management as well as exposing the weaknesses and potential gains related to efficient management with properly trained and motivated people. To illustrate the work, the article presents a real case study that explores the technical and financial benefits that qualified professionals can provide to companies.

2.2. FACTORS ASSOCIATED WITH OPERATIONAL MANAGEMENT

2.2.1 Technology Associated with the Management of Mining Operations

With the advent of technology, mainly referring to industrial automation remote data transmission and computational processing, operational control centers (OCCs) emerged in the mineral industry (Rogers et al., 2019). They should be considered as the core of information that refers to mining operations. This environment, also known as the "control room," concentrates all management and operational logistics information, such as distribution and activities assigned to equipment, information on mining plans, the vital condition of assets, ore quality and fatigue control of operators, among others. Thus, for the efficient management of these activities, it is necessary to use specialist systems, known in mining as fleet management systems (FMSs).

Operational management in mining operations has undergone an impressive evolution over time. One of the biggest technological factors responsible for this development is FMSs, but these systems need a robust infrastructure, which provides reliable data to enable the best decision-making action (Lynas and Horberry, 2011). Its main structure is based on the telecommunications network for transmitting data generated in the field to the OCC.

FMSs are widely used in mining companies for improving fleet control and gaining associated cost savings (Mohtasham et al., 2021; Nobahar et al., 2022; Ercelebi and Bascetin, 2019; Mena et al., 2013; Felsch et al., 2022). In addition, former studies conducted by mining experts indicate that the loading and haulage costs are the highest in the mining phase, ranging between 50% and 60% of the total operating cost of open-pit mines (Trueman, 2001; Mohutsiwai and Musingwini, 2015). Another highly relevant factor is the potential of this technology for reducing carbon dioxide emissions into the atmosphere (Huo et al., 2023; Rodovalho et al., 2020)

Information regarding mine equipment, mining fronts, crushers, waste dumps, conditions to access roads and ore quality, among others, is available from FMS databases with real-time access. Then, all these factors integrated with the technical capacity of employees generate the best decisions in a short period of time, and these decisions reflect safety, environmental and financial benefits for companies.

The professionals responsible for operating FMSs are called fleet controllers (FCs), and they are the link between mine managers and equipment operators in modern mining. Among the tasks assigned to FCs is the responsibility for allocating resources for the execution of the mining plan in the most optimized, safe, efficient and economical way possible. Thus, interaction with the FMS is fundamental for the execution of FC activities. Merging most systems' functionalities and engaging in assertive communication with team leaders and drivers are also indispensable requirements for the success of OCC activities.

Moreover, FC experts influence the equipment performance and desired production volume significantly. Hence, they must have a deep understanding of the end-to-end operation as well as the financial impacts resulting from their decisions. People and processes without the use of technology generally lead to frustration and inefficiency as technology generally increases process reliability and directs the workforce, reducing the operating costs.

2.2.2 Processes

The first step in developing the necessary skills for operational management in mining is to define the activities and responsibilities of employees. Accordingly, it is necessary to understand the required attributions of and tasks involved in the productive process and to create appropriate work procedures. For instance, the lack of structured processes and shared responsibilities has a great impact in terms of operational inefficiency and work overload.

Furthermore, the implementation of technological systems is considered to be a fundamental factor for raising operational performance levels (Lynas and Horberry, 2011). The success of operational management is conditioned by the interactions that people have with systems, which characterize the human factor in the process. In addition, among its main functions are the maximization of equipment operation and production time, the reduction of the number of trucks needed for haulage and compliance with the processing plants’ quality standards.

When dealing with modern operational management systems, field instrumentation, interfaces associated with the control system and essentially well-qualified professionals to perform that function are necessary (Li et al., 2011). Consequently, mining companies are evolving toward recognizing and improving an integrated view of their value chain to optimize their performance. This systemic view highlights operational inefficiencies and identifies possibilities for optimizing resources. These inefficiencies are often caused by a lack of technical knowledge or poor process management.

Besides that, anomaly detection is a necessary assignment to ensure performance in industrial systems, avoiding the generation of failures and helping to minimize downtime (Pulido et al., 2019). Therefore, the development of an efficient work methodology is essential to guarantee a safe production process and reduce operating costs more effectively.

Finally, the interaction among people and technology without a solid process may create confusion in the execution of activities and automated chaos that has a direct impact on customers. Then, a well-designed process is critical for directing people to utilize technology fully.

2.2.3 People

The function of people must be evaluated well to incorporate new professional profiles into the modern industry scenario. The human factor associated with operational management performs a wide range of very simple to highly complex tasks. It is also well recognized in the industry that the role of the control room operator is essential, particularly when the process becomes unstable or when identifying failures in systems, processes and people (Li et al., 2011).

Firstly, people are responsible for analyzing operational data in real time, leveraging their technical and operational expertise. Consequently, this well-executed activity will allow them to maximize the value of the technology and reduce the operational costs. That is mainly because the human factor must be treated as a solution, part of a multidisciplinary team of professionals willing to contribute to the mineral sector, rather than as problems and risks for the operational management area (Zimmermann and Renaud, 2019). Restricting people or excluding them from the decision-making process means limiting their capacity to make active contributions to maintaining and improving operational management.

Secondly, the development of human–machine interfaces, effective alarms, training and optimization of organizational factors are key items to help achieve better integration of the human factor with operational management technologies (Felsch et al., 2022). For instance, the introduction of new processes, such as decision automation, on-board telemetry, tire, fuel and geotechnical monitoring, further corroborates in illustrating the potential of people in mining.

Thirdly, one skill of great relevance is the capacity for assertive communication, which is enhanced by training in so-called soft skills (management of issues related to human factors). Additionally, some core competencies, including technical knowledge, initiative, strong computing skills, interpersonal skills and emotional intelligence, are valued.

Table 1, below, lists the main competencies that must be developed in modern mining professionals.

Table 1 - Necessary skills for modern mining professionals

Hard Skills	Understanding mine operation	Understanding the company production process	Mastery of FMS tools	Advanced computer skills	Experience in BI systems
Soft Skills	Assertive communication (oral and written)	Flexibility	Emotional intelligence	Problem solving	Analytical skills
Advanced Skills	Coherence	Leadership	Proactivity	Autonomy	Spontaneity

Source: Author’s elaboration

Finally, technology and processes without a human workforce result in underutilization of analysis systems and tools. In addition, many direct impacts on management emerge from that situation, such as alienation, lack of interest and high turnover.

2.2.3.1 Challenges

Problems faced by companies at different stages of the mining value chain are minimized with the use of digital technology and real-time data analysis. Hence, the key point in this context is having qualified people to perform these actions with assertiveness.

Furthermore, the scarcity of qualified professionals is affecting the evolution of the mineral industry, generating an immediate demand for those types of employees (Chirgwin, 2021). Companies need professionals with a new set of skills, for instance people who can understand, interpret and operate the available technology.

The main challenges to be faced, aiming to achieve greater proximity between people and mine operational management, are the following:

- Understanding the entire value chain regarding the role of people and their importance for automation and the reduction of operating costs.

- Understanding the OCC’s internal demand and determining the number of qualified people to perform activities with excellence.

- Establishing an adequate routine for carrying out training and qualifications.
- Developing competences focused on advanced data analysis to identify different types of problems that, through traditional means, would not be discovered.

The development of a career plan and the involvement of people management are essential in terms of attracting and retaining talents. The high demand for qualified professionals also increases the employee turnover rate since it is simpler to hire a qualified professional than to start the training process.

Meeting the expectations of assertive decision making requires people with experience and a professional attitude, who are able to validate and interpret data to assess both the operational behaviors and those associated with technology and expert systems. Then, digital awareness and training of managers and team leaders should also be fostered.

2.2.3.2 Lack of Training and Development Opportunities

Training is usually carried out during the implementation of technological systems and their updates. These types of training are generally limited to understanding the system through the use of the technology itself and rarely include complexities related to management and the insertion of “soft” skills. In addition, companies face functional barriers to implementing effective training approaches, such as increasing the workload of external training, remote training platforms and the creation of an operational simulation environment.

As already witnessed, training for the role of FC can be summarized as observing the work of other employees. Consequently, much of the training is designed based on the previous experiences of employees related to the tools and functionalities used or understood formerly. Few companies have a clear training or career progression plan for various positions involving data and operational management. In addition, many of these training plans still depend on technology supply companies, which generally focus on system tools and offer limited training in other job or behavioral skills.

Last but not least, production pressures and time constraints often limit the quality of the on-the-job training delivered, along with some hesitation in making people available to receive training in a non-critical production environment. That is why the discipline and training of people play a valuable role in the execution of activities in companies.

2.3. CASE STUDY—TRAINING THE OPERATIONAL MANAGEMENT TEAM

The case study was carried out in a mining company located in the Southeast region of Brazil. Through preliminary studies, an opportunity for improvement regarding the performance of professionals working in the mine control room was identified.

The target of the work was the training of FCs in best practices related to the operational management of the mine. A methodology was used that explores the main points in which control room professionals bring benefits to the production process.

2.3.1 Methodology

An innovative approach to instructing professionals provides FCs with value chain-wide recognition of the role requirements and responsibilities. Having a clear and appropriate work project for this function allows the development of these professionals and improves the selection process for hiring new employees.

Moreover, the methodology used for training is carried out considering five distinct phases—introduction to technology; assertive communication; functionalities of FMSs; operational strategies; and real examples—which will be detailed below.

2.3.2 Introduction to Technology and Operating Procedures

Knowing the definitions of technology and systems, along with their objectives, is fundamental for the development of high-performance professionals. Another key point is the explanation of the FC role within the mine operation area as well as its objectives and the possible generation of value in the production process. The future prospects of this function, career plans and definitions of key operational performance indicators (KPIs) are also discussed and exemplified.

2.3.3 Assertive Communication

Assertive communication is essential for FCs' activity because a communicative profile is part of their function. The partnership with managers, supervisors and equipment operators is also fundamental. That is why it is necessary to have an agile understanding of the information that travels by various means, such as radio, cell phones and on-board computers, to seek an effective direction to address possible identified abnormalities. Thus, this phase is aimed at developing technical, behavioral and advanced skills, as shown by Table 1, located in section 2.3.

2.3.4 Functionalities of the Fleet Management System

The controller must master the functions and tools contained in the FMS to transform the data generated by the system into reliable information. The main points are the following:

- Assertiveness in equipment allocation.
- Understanding and routine monitoring of information related to the operational cycle (cycle times, loading, maneuvering, etc.).
- Monitoring of operators' notes on on-board computers.
- Individual analysis of loading equipment, mainly referring to productivity and loading time.
- Ore quality control.
- Information about fleet availability and the main reasons for downtime.

Furthermore, automatic reports and dashboards with real-time updates direct FCs to perform their function with greater assertiveness, consider reliable information and enable the identification of possible operational problems with quick resolution.

2.3.5 Operating Strategies

This phase involves searching for better work strategies, from the adequate sizing of the fleet and determining the best moments for halting and inserting equipment into the operation to the control of queues and equipment idleness.

The establishment of criteria for the controllers' activities is fundamental for skillful direction of the activities undertaken by each professional linked to the process. Described below is the approach used to direct fleet controllers, aiming to improve their work strategy:

- Constant monitoring of reasons for downtime of mine equipment to guarantee the integrity of data and efficiency of the FMS.
- Routine communication with team leaders, informing them of necessary operational improvements, such as loading stations, mining fronts and dumping areas, with the aim of increasing the fleet productivity and attaining a better production flow.
- Definition of the ideal time for halting equipment for operational activities.
- Communication with the crushing control room, analyzing information on the duration of the activities and reasons for ore shortages, halting in the area and reestablishing forecasts.
- Interaction with the mine equipment maintenance team to forecast releases and schedule equipment shutdowns for preventive maintenance.

2.3.6 Real Examples—Improvement Opportunities and Success Cases

This section contains practical content, exposing examples related to good work practices performed in the control room and the consequences of possible communication errors and incorrect actions in the production process. This phase also aims to explore technical information such as productivity gains and losses with their respective associated financial values.

The main technical examples evaluated are the following:

- Variability in the loading time and productivity of excavators (Felsch et al., 2022).
- Management of the supply for cargo-handling and haulage equipment (Felsch et al., 2016).
- Failure to schedule equipment halting to adjust the square.
- Statistical analysis of maneuvering and loading times.
- Variability in equipment and driver performance.

2.4. RESULTS AND DISCUSSION

The result is dimensioned using the comparison of the performance of the haulage equipment fleet (t/h * km), evaluating two scenarios:

- **Scenario 1**: Operation prior to staff training.
- **Scenario 2**: Operation after staff training.

It is important to mention that the comparative analysis reflects similar working conditions with the same production equipment and the absence of rain and fog in the evaluated period. Figure 3 shows the daily evolution of the haulage fleet's performance:

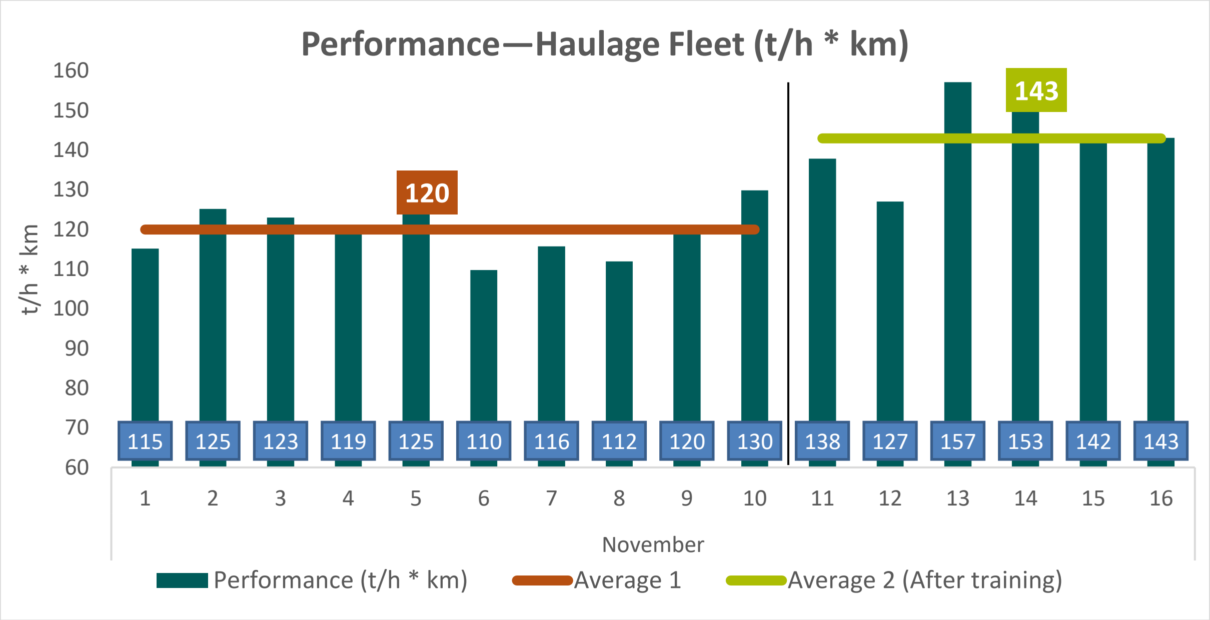

Figure 3 - Comparative analysis of the work results

Source: Author’s elaboration

According to the graphic analysis, there is a rise in the productive capacity of the haulage equipment fleet, resulting in an increase of 19% (average gain of 23 t/h * km), reflecting the addition of 17 loads loaded and transported per actual working day.

Recent technologies and the role of people in the production process in mining operations must be better acknowledged by companies and managers. That is why the OCC is usually on the frontline for answering questions and justifying possible events of low performance. Thus, investment in resources that support the continuous development of people associated with the main skills needed to promote new technologies will provide companies with positive results throughout their production chain.

By understanding that mining companies are moving toward automation and increasing their interest in innovation, it is evident that a skilled workforce will be required to operate and manage the new technologies. Furthermore, the benefits related to technological advances in mine operational control will be more effective when the focus of the work deeply involves the professionals who are responsible for managing the OCC.

In addition, the use of manual reports and spreadsheets is considered unproductive work regarding the concepts of Industry 4.0. Then, a point of great relevance is the automation of available tools to release the human factor for more complex work tasks, such as solving problems that automation is not capable of replicating.

Large volumes of reliable data have the potential to deliver a better customer experience, increase internal efficiency and ultimately improve the profitability and competitiveness of organizations across all industries (Alharthi et al., 2017).

3. AN INNOVATIVE CYBER-PHYSICAL SYSTEM AIMED AT INCREASING PRODUCTIVITY IN THE MINING INDUSTRY

3.1. INTRODUCTION

This research is based around an article published by the author in 2022[1]. Mining is an industry that uses equipment and technology intensively in its operations. Therefore, digital technologies are being implemented in the mining industry to improve operational efficiency and reduce environmental impacts and operational costs. In addition, responsible mining concepts are based on waste and greenhouse gas (GHG) emissions reduction, allowing for better integration among new mining projects and society (Pimentel et al., 2016).

The global mining market is always influenced by fluctuations in commodity prices and needs to remain competitive in all scenarios. Based on that, mining companies seek to find new technologies to improve critical areas of their operations, particularly in terms of efficient material handling, such as loading and hauling operations (Alarie & Gamache, 2002); (Topal & Ramazan, 2010); (Markovic et al.,2014); (Chaowasakooa et al., 2017); (Chen et al., 2017). Furthermore, from an operational perspective, optimal use of resource allocation is obtained through fleet management systems (FMS), as happens for the optimization of the movement of ore and waste, directed from different mining areas with the destination for crushers, stockpiles, or waste piles. The FMS has objectives for resizing fleets and reducing idle equipment and queues. In addition, the FMS has a strong mine safety component, with proximity detection sensors to avoid collisions and driver fatigue control. Another relevant feature of most FMS solutions is the interface with onboard telemetry systems, allowing fleet maintenance and equipment performance management. Also, studies done by mining experts indicate that loading and haulage costs are the highest

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[1] Felsch Jr. W.S., Ortiz C.A., Lima H.M., Rodovalho E.C. (2022). An innovative cyber-physical system aimed at increasing productivity in the mining industry. Mining Technology, 131:4, 228-238. DOI:10.1080/25726668.2022.2086357

ones in the mining phase, ranging between 50-60% of the total operating cost of open-pit mines (Trueman, 2001); (Mohutsiwa & Musingwini, 2015).

Data provided for each unitary operation (drilling, blasting, loading, haulage, dumping) from dedicated software and hardware utilized in the field have reached a level where advanced data analytics becomes applicable (Erkayaoglu & Dessureault, 2019). Also, classical analytical methods, such as manual spreadsheets, widely used for performance control, are not enough as they require specific and repetitive analyzes that delay the resolution of identified problems.

Digital technology is becoming increasingly popular in the mining industry. Over the past few years, many studies have been developed in the academic area and inside the mining companies. Studies using Artificial Intelligence techniques to predict rock fragmentation have also been analyzed (Philip et al., 2019), as well as other studies such as reduction of greenhouse gas emission in mining (Rodovalho & Tomi, 2017); (Soofastaei, 2018); (Rodovalho et al., 2020), optimal cycle time calculation for hydraulic shovels (Edwards & Griffiths, 2020) improved safety of coal mining operations (Lilic et al., 2010), integrate operations simulation and fleet productivity prediction (Yeganejou et al., 2021), fleet optimization and sizing using advanced programming models (Mohtasham et al., 2021), and the use of machine learning to forecast truck cycle times (Xiaoyu et al., 2018).

Currently, there is a demand for integrating human cognitive capabilities in the cycle of production-related processes rather than eliminating them. However, combining human skills and substantial information requires technological solutions that reduce the conflict among personnel and systems to amplify their intellectual capabilities to achieve more effective systems (Emmanouilidis et al., 2019). Hence, the approach proposed in this study integrates information in real-time to human decisions.

A cyber-physical system (CPS) is composed of collaborative computational elements intended to control physical entities. The interaction between physical and cyber elements is crucial (Mohammadinejad et al., 2020), (Lee et al., 2015). Also, CPS are control systems where physical entities are connected to digital services enabling intelligent services in control, support, or decision making. (Monostori, 2018); (Nikolakis et al., 2021).

Furthermore, in mining, the CPS may act as the link between computational elements, such as expert systems for controlling mine and plant equipment, and the professionals working in the control room, the physical entity that can make decisions.

Within this research, the CPS is the link between the FMS, the computational tool that interfaces data between the equipment operators and the fleet controllers, who are the decision-makers.

The decisions which affect the industrial processes are taken at different time scales to meet the short-, medium- and long-term objectives (Krishnamoorthy et al., 2019).

Nonetheless, the progression of innovation in the mining industry is bringing more products to the market to improve efficiencies and optimize processes, which produce data in real-time on various types of equipment and activities. That is why the control of performance indicators in real-time is necessary to allow the visibility of data in operations. Also, this data needs to be transmitted over a wireless network, and it needs to have a transmission capacity that meets the demands of the systems (Barr & Cook, 2007).

Among the main aspects necessary for the implementation of innovation in the mineral industry, the connectivity of technology to end-users, such as operators of equipment, supervisors, or mining engineers investigating the optimization of the mine's haulage fleet, has a low effect on the part of the companies. However, this aspect is of great importance in developing and implementing new proposals for operational improvements (Boulter & Hall, 2015). Furthermore, in each type of analysis, the required data is different in terms of treatment but essential to meet and complete the end task. Also, one of the requisites for acquiring reliable data is a well-structured communications network.

As a matter of fact, in terms of the information management viewpoint, the built environment is effectively siloed within growth stages and between investors, with data often stored in enterprise software solutions with poor interoperability, which results in manual and often ad-hoc exchanges of information (Heaton et al., 2019). In addition, a methodology has been developed using mathematical programming with real-time shop floor data for simulation and optimization purposes, and with determined parameters and policy, such as a data-driven control method for manufacturing (Kayyati & Tan, 2019).

The traffic monitoring application requires the integration between detection and tracking. Besides that, in real-life traffic scenarios, two requirements are important: occlusion handling and real-time performance (Fernandez et al., 2019).

Fault detection is a necessary task to assure performance in customized industrial systems, avoiding failure generation and helping to minimize downtime (Pulido et al., 2019). Therefore, the development of an efficient methodology is fundamental to guarantee a safe production process and reduce costs more effectively.

In summary, the main contributions are the development of a CPS for automated analysis of data related to the operation of the mine in real-time, seeking to identify low-performance events of load equipment and the introduction of an operation with a higher level of sustainability, increasing equipment performance and reducing the emission of greenhouse gases.

3.2. METHODOLOGY

In order to idealize the developed project and seek scenarios for improving the performance of loading equipment, this study considered a large iron mine located in Brazil. At the industrial unit, there was data collection, the application of mobile equipment management tools, and the performance of a field test. The work was started with a detailed analysis of the FMS database. FMS are widely used in mining companies due to improved fleet control and associated cost savings (Soumis et al., 1989); (Ercelebi & Bascetin, 2019); (Mena et al., 2013); (Barbosa et al., 2021). FMS has a fundamental role in mine operation activities and has been used for over 30 years. However, with the advent of digital technologies such as computational processing and data storage capacity, these systems have become current and are constantly updated.

Managers and operational staff generally understand production monitoring well, but equipment performance information requires data processing and reporting. This process creates a delay in identifying functional abnormalities and actions to resolve them. However, to optimize the potential of these systems, a continuous analytical effort is recommended to feed the improvement programs, with a focus on improving productivity (Gregory, 2017).

The best benefit of real-time data is knowing the condition and location of all the fleet equipment in a mining operation. Moreover, connecting real-time data to an operating center enables a system response in a period close to real-time, and it offers a more reliable decision-making capability at the center where actions may be taken to optimize the process. This concept can also be used to increase the productivity results of the mining equipment, detect deviations in the expected conditions, and increase the effective use of the equipment, considering the operational mining plan.

3.2.1 System description and boundaries

The project's initial concept was based on the creation of a CPS with the use of an operational warning/alarm system to be automatically triggered by the fleet controllers who have responsibility for the operational control of the fleet. Thus, the alarms are intended to inform technicians of potential operational problems that are periodically impacting loading productivity.

Considering that the main contribution of this study is a CPS for identifying low-performance occurrences of the loading fleet, it is necessary to define the limits and the performance range of the system. In this context, only variables that presented a high correlation with the Productivity of loading equipment in mining were analyzed. In this regard, researchers proposed a method for evaluating uncertainty in the decision support process named "the Statistical Value Chain" (SVC) (Hermann et al., 2013).

The premise, data analytics, and action steps consist of the mechanical part in the process, while the action step refers to human participation through decision making.

CPS was developed to read data directly from the FMS database. Using the Standard Query

Language (SQL), a logic programming was created to compare the effective Productivity performed by the loading equipment with its programmed goals, as shown in the functional diagram in figure 4.

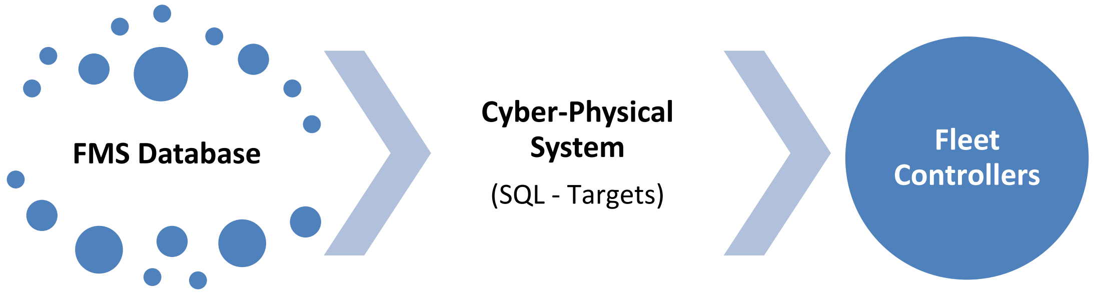

Figure 4 - The functional diagram on the CPS

Source: Author's elaboration

3.2.2 Variable selection and loading productivity target setting.

The main indicator used for performance control of loading equipment is Productivity, which is measured in tons of excavated material per hour worked (t/h). This indicator has great relevance in mining operations because it is possible to scale the optimal number of equipment required for the composition of the operational cycle and the achievement of the goals (Hall, 2002). Other indicators analyzed in this research are listed in Table 2.

The loading equipment has its location defined by a mining plan. Each piece of equipment is assigned to a specific location according to its mechanical characteristics. Furthermore, each site has its particularity, the type of excavated material being the most important one for defining the excavation volume and productivity that the equipment can perform. Thus, since each loading equipment has unique factors that impact its performance, it is necessary to monitor each one individually.

Table 2 - List of variables used to build the decision-making process

	Investigated variables Description	Unit
HP	Hourly productivity: relation between total production and effective hours	kt/h
AL	Average Loading: Average loaded mass per full cycle	t
LT	Load time: average time of loading	min
IT	Idle Time: Time when loading equipment awaits arrival of trucks	%
ST	Spot Time: Time for truck adjustment for correct positioning before loading	Min

Source: Author's elaboration

The main parameters affecting the efficiency of the loading operation are processes concerning drilling and blasting. This process is responsible for the particle size distribution of the fragmented material and must be sized considering the characteristics of the rocks, which are usually heterogeneous within a deposit. These events associated with occurrences of cycle breakdown, operator skills, and loading square conditions directly affect the performance of the operation. Also, these operational variables are not automatically identified by the FMS, so they may not enter the decision line of the developed CPS.

Figure 5 illustrates three levels of performance indicators for loading equipment. Level 1 refers to the target that is to track the Productivity of each loading equipment. Level 2 refers to the indicators that are identified automatically using the FMS database. These indicators are the basis for identifying possible underperformance problems. Then, the trigger is identifying the low performance referring to level 2 by the fleet controller who communicates a possible problem to the team leader, who may diagnose this problem in reduced time, accelerating its resolution.

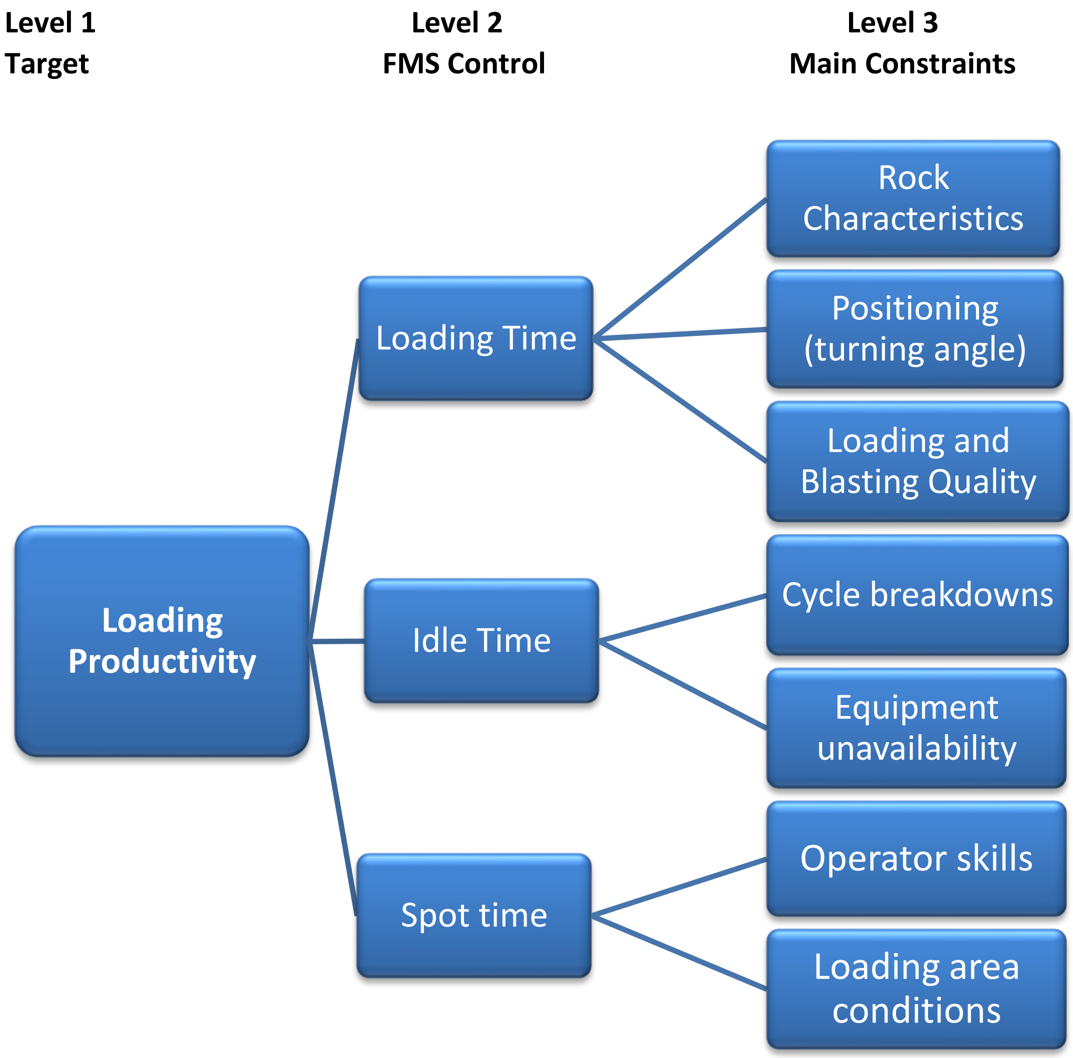

Figure 5 - Variables involving productivity and the main constraints for low performance

Source: Author's elaboration

The last level of analysis refers to the main constraints for low equipment performance: level 3. Then, these possible reasons for underperformance do not interface directly with the FMS, requiring identifying the problem in other ways, such as information from the equipment operator or a team leader in the field.

A short-term scenario requires a different approach to indicators than a long-term plan, as these indicators will define the production capacity in a shorter timeframe when long-term average values cannot be used (Campelo et al., 2018). The creation of individual targets, stratified by equipment and considering the type of material to be mined in the monthly mining plan is fundamental. This value is also reported by the short-term planning team, which uses information from the geological block model.

Hydraulic excavator-related productivity targets are defined by averaging the historical operating performances applied in each different lithotype of the mine, weighted by the predicted mining plan mass and each geological lithotype, at monthly intervals. Table 3, below illustrates the methodology used to calculate the productivity target for the SV-4 shovel. The example illustrates the historical performance of the SV-4 excavator in each lithotype (Hematite, Itabirite, and Waste). The planned mass for mining related to the equipment is used to weight the historical productivity values and generate the target productivity, which in this case is 3,043 t/h.

Table 3 - Calculation of shovel SV-4 operating target

Material	Historical Productivity Rate (t/h)	Mass Haulage - Mine Plan (t)
Hematite	3,190	245,000
Itabirite	3,012	290,000
Waste	2,841	135,000
Target (t/h)	3,043	

Source: Author’s elaboration

3.2.3 Statistical analysis of variables

In order to assess the variability of the variables associated with loading productivity, it is necessary to perform statistical analysis. The first step is to check if the population of the loading productivity follows a normal distribution. The normality test consists of evaluating the p-value and determining which statistical test is best to examine the variability of the population. The null hypothesis is accepted when the p-value is greater than the significance level of 0.05. The acceptance of a null hypothesis means that the loading productivity follows a normal distribution.

The adjustment degree is measured by the p-value, where through the normality test, it was measured, and the result was 0.289. Thus, the null hypothesis is accepted, meaning that the loading productivity follows a normal distribution (Montgomery & Runger, 2007).

The relevance of the variability among populations that follow a normal distribution, it is necessary to use parametric tests. This study applies the T-student test, which can be applied using statistical analysis software. The normality test is available in Appendix A (Figure A.1).

The correlation between the variables is an analytical factor that is of great importance to seek a better understanding of their systemic behavior in the face of possible low-performance impacts. Figure 6a shows the correlation matrix between the variables analyzed in this research. A strong correlation was verified between the central variable load productivity, with the idle time (-87%) and load time (-73%) variables. These values indicate that the smaller the loading time and idleness values, the larger the loading productivity will be. This statement is proved in Figure 6b, which shows that the smaller the values of loading time and idleness, the larger the loading productivity will be, which quantifies the forecast results associated with the loading productivity variable.

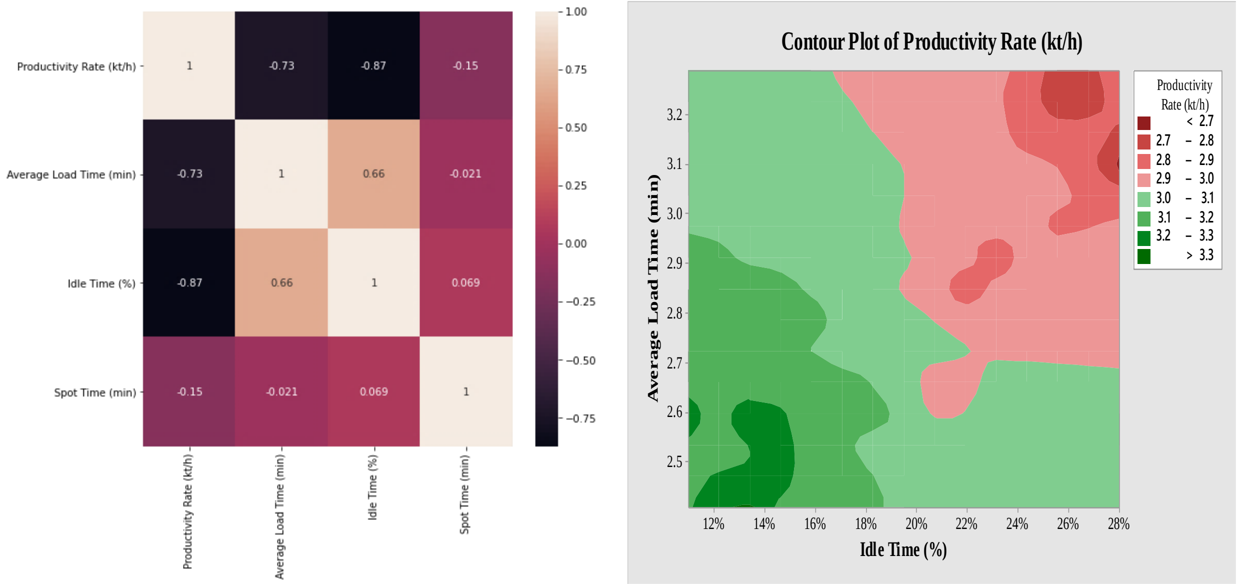

Figure 6 - Correlation matrix of the variables analyzed in the research (a) and Contour Plot of Productivity Rate (b).

Source: Author’s elaboration

The coefficient of variation (CV), also known as relative standard deviation (RSD), is a standardized measure of the dispersion of a probability distribution or frequency distribution (Forkman, 2009). It is usually expressed as a percentage and is defined as the standard deviation to the average ratio.

The CV was used to optimize an acceptable range (%) for an alarm activation to prevent false alarms from being generated in the process. Data regarding the effective loading productivity of the seven target excavators of this study were analyzed for six months of operation. Figure 7 illustrates the result of the analysis, which returned a figure of 7.5% for the lower limit of the variability of effective loading productivity, and this was used for configuring the operating alarm system.

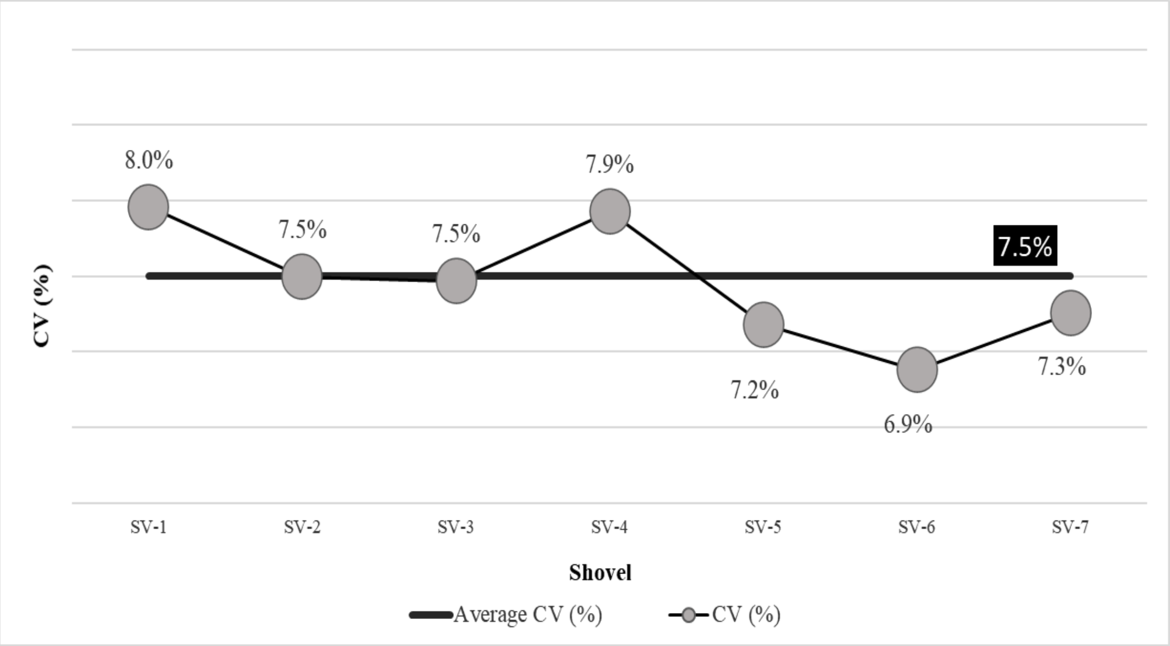

Figure 7 - Coefficient of Variation Analysis

Source: Author’s elaboration

3.2.4 Decision making process

The data is stored in a specific database that was generated by FMS. Then, when the CPS identifies poor equipment performance, it automatically sends an alarm to the fleet controller who is responsible for the mine production using a WEB application. After that, the controller notifies the equipment operator and his direct superior, informing him of the alarm and the possible problems identified: high loading time, difficulty in digging, and idleness, among other points. Operational alarms are divided into three distinct classes, as shown in Table 4 below:

Table 4 - Analysis criteria for alarm triggering

Indicator	Alarm Level	1	2	3
Productivity Rate	Target < 7.5%	2 hours	4 hours	6 hours

Source: Author's elaboration

For alarm generation, the shovel must perform less than 7.5% of its target during a given period of operation. Each triggered alarm demands an action to be performed by the technician responsible for the operation.

Alarm Level 1: Poor performance for two consecutive hours. The technician informs the mine supervisor responsible for the loading operation about the event. Supervisors must identify the reported problem in the field.

Alarm Level 2: Poor performance for four consecutive hours. The technician informs the mine supervisors about the new event and records the reason identified by the supervisors who characterized this poor equipment performance during the first alarm.

Alarm Level 3: Poor performance for six consecutive hours. The technician must stop the shovel and alert the operator of "low performance" equipment until the problem is solved. Another action taken is to send an email reporting the situation to the managers responsible for the mine operation and mine planning. These managers, when informed, may choose to continue the operation, having knowledge of the problem and visualizing difficulties in solving it immediately.

The system is not designed to interrupt the mining activity performed by the loading equipment. On the other hand, it aims to inform related staff of operational problems at the moment of their occurrence, avoiding communication failures and difficulties in their identification. Also, managers responsible for the operations, infrastructure, and mine planning must be called promptly to make the best decision to solve the identified problems.

3.3. PRACTICAL APPLICATION

The research enables an overview of a data-driven structure for a mine, and it presents an implementation of real-time mining related data for improving the productivity of the loading fleet. In this case, there is variability in its operational performance due to several factors, such as excavated lithological types, material fragmentation, condition of the loading bay, and operator experience.

The model started with an analysis of the operational data related to load Productivity using specific Business Intelligence software. The analyzed indicators were average load (t), loading time (min), idle time (%), and spot time (min). These data were stratified by shovel type, determined periods (hours of the day), operating teams (operational shift), and analysis of each operator. This analysis allowed for identifying deviations and oscillations in the productivity indicator.

An application was developed using specific software for data visualization by fleet controllers. This application allows the identification of low-performance shovel equipment productivity and its possible reasons. Moreover, the application has a connection to the FMS database, and it is programmed to accumulate shovel productivity data on time and to trigger alarms when the values do not reach the optimal operating conditions.

The operational implementation of the work begins with the training of all technicians involved in the mining company's operational process. Understanding the data and the methodology used, associated with quick decision-making, are fundamental to obtaining favorable results.

The events identified as "low performance" are generated automatically, without impacting the technicians' work routine. Figure 8 illustrates a real practical example, showing one of the developed application screens and the operating performance of a shovel SV-4.

In the example, underperforming loading productivity can be identified for the 00:00 to 05:00 and 21:00 to 23:00 periods. The average load time indicator directly impacts the underperformance of the first period. The main reason is the presence of blocks, referring to an outcrop of an unmapped dolomite body. The action taken in this case is the displacement of the equipment to another loading site and informing the drilling and blasting team to fragment the dolomitic material.

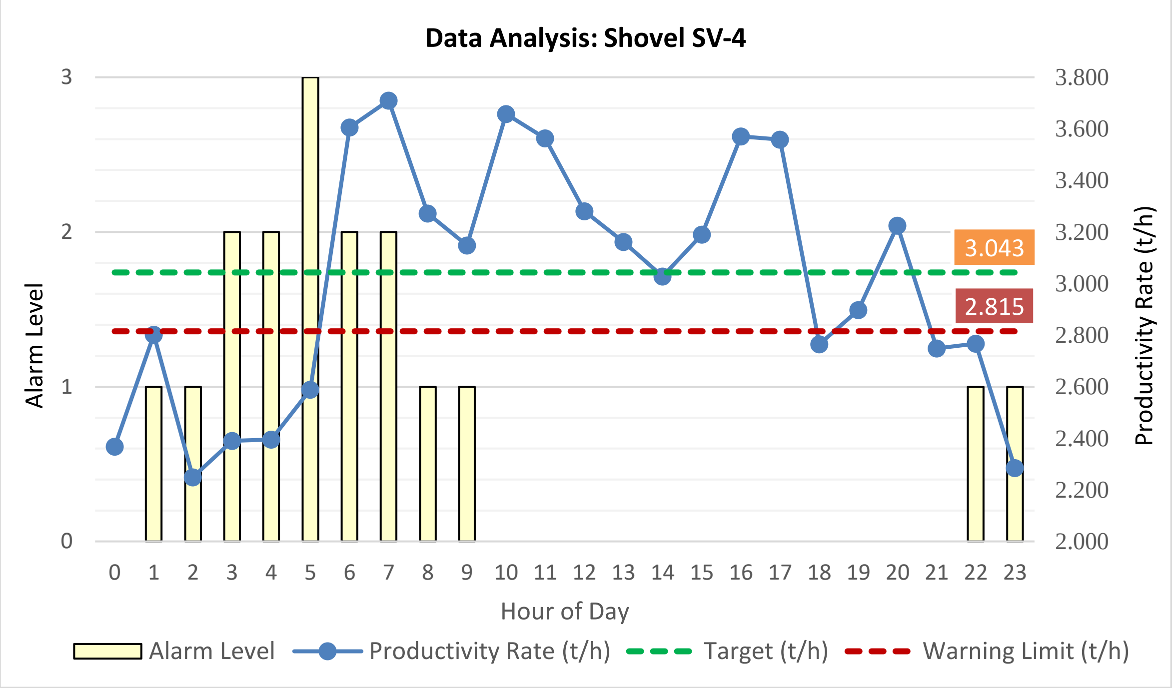

Figure 8 - Application screen created to control mine KPI's

Source: Author's elaboration

3.4. RESULTS

The first result from this study showed a reduction in the number of registered alarms. A test was performed for one week (seven consecutive days), with the system accumulating information but not triggering alarms or sending messages to the field staff. Thus, 93 operational alarms were detected, of which 12 correspond to level 3 alarms. Then, the system was implemented the following week, and the alarms were triggered. During this period, 46 operational alarms were identified, and none of them corresponded to level 3. Therefore, in this first analysis period, a 51% reduction in the overall number of operational alarm events and a 100% reduction in the number of operational alarms related to criticality level 3 could be observed. This result emphasizes greater agility in identifying and resolving problems related to the performance of loading equipment.

In Figure 9 below, it is possible to identify the results of this first test period, referring to the first two weeks of tool use.

After the initial testing period, the system remained reliable, and many outcomes related to improved fleet performance were found. Among the positive results, there is still a need to identify and disassemble the mining area and loading square arrangements, train equipment operators, and improve communication between mine operators and supervisors related to equipment operating conditions.

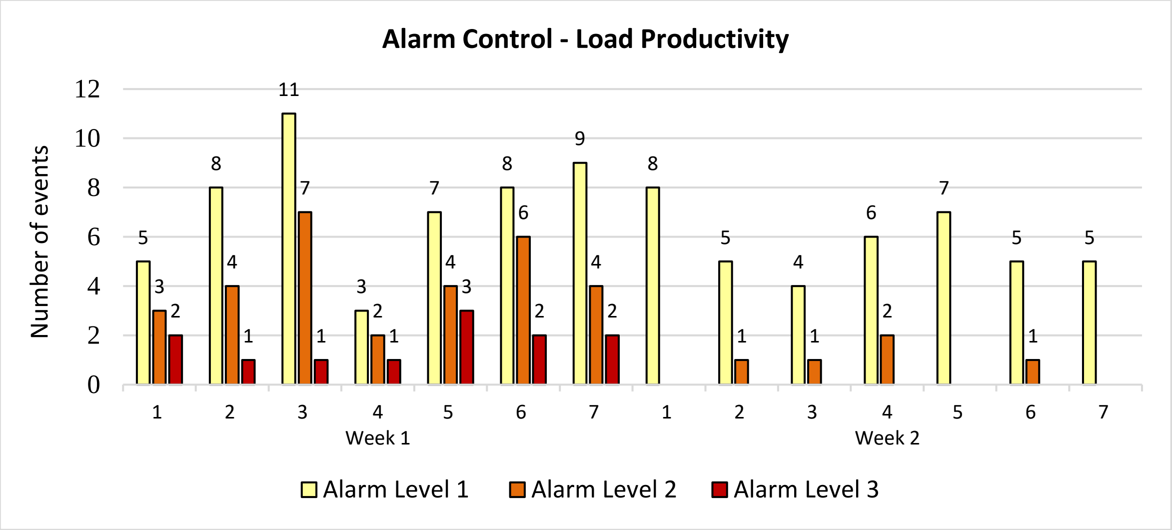

Figure 9 - Evolution of operational alarm events in the first two weeks of tool use

Source: Author’s elaboration

Figure 10 shows the results of the study comparing two distinct periods. The first period refers to the results of the shovel productivity rate in the first four months of 2018. During this period, the study had not been implemented yet. From the fifth month, with the proposed implementations, a slight increase in the productivity rate of shovels can be seen.

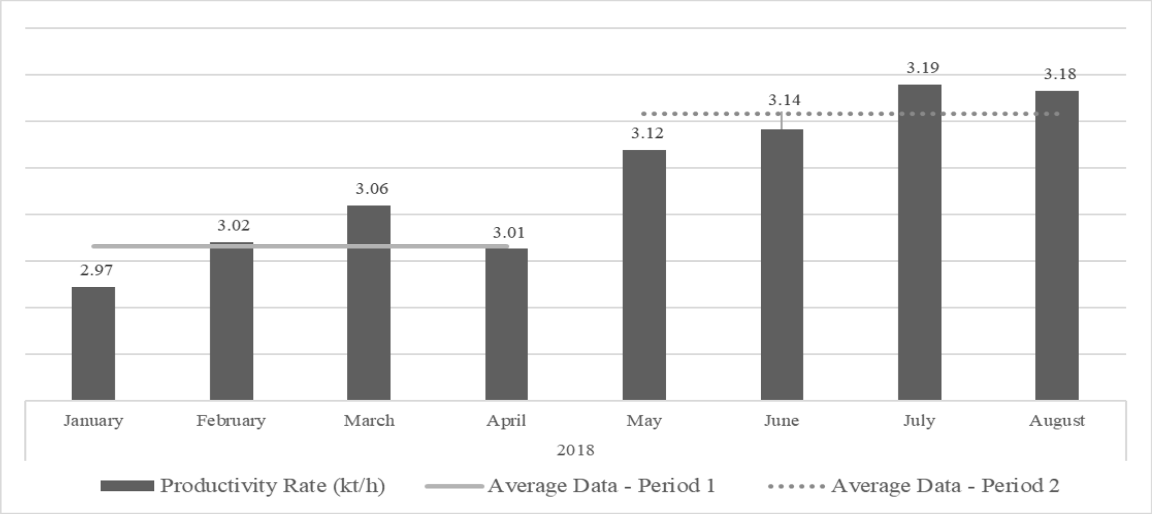

Figure 10 - Monthly Loading Productivity Tracking (kt/h)

Source: Authors

The improved performance of loading operations provides greater reliability and reduced variability in cycle times related to haulage equipment, as seen in Figure 11. Also, the reduction of 44.5% in the standard deviation of the loading time variable (Table 5) may explain the reduction in queuing time due to the greater adherence to the planned operations.

The performance related to the two scenarios was analyzed under similar operational characteristics, such as the same operators, equipment and material conditions, production goals, and others.

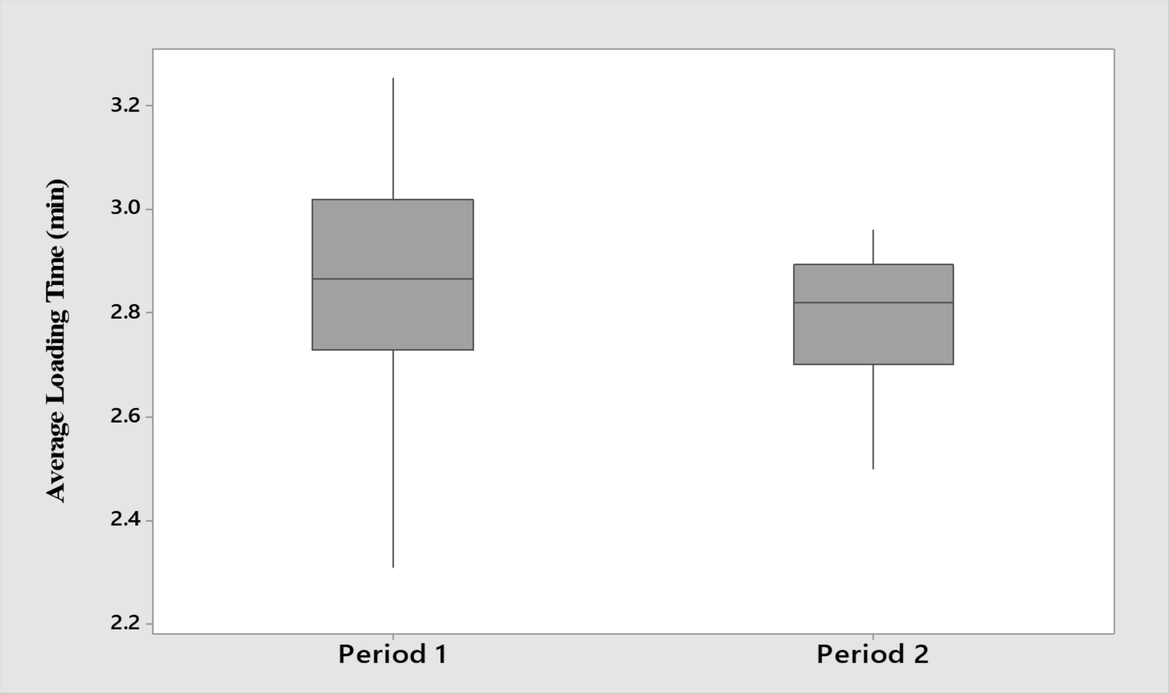

Figure 11 - Box plot comparing Load Time of Period 1 and Period 2

Source: Author's elaboration

The results are shown in Table 5. The average load productivity increased by 4.71%, and the average load fleet performance increased by 142 t/h. Also, the loading queue time was reduced by 6.49%.

Table 5 - Comparison of loading productivity between the two periods analyzed

Results			
	Period 1	Period 2	Δ (%)
Productivity Rate (t/h)	3,016	3,158	4.71%
Average Load Time (min)	2.87	2.79	-2.79%
Standard Deviation (load time)	0.22	0.12	-44.50%
Load Queue Time (%)	9.24	8.64	-6.49%

Source: Author's elaboration

The amount of diesel fuel that a stopped truck consumes may be considered 11.3 liters per hour (Kubler, 2015). The impact of a reduced queue time on loading is shown in Table 6.

Therefore, this research has the potential to reduce fuel consumption by 10,606 liters per year and generate a reduction of GHG emissions by 28.42 t in the same period. (Thomas et al., 2000); (Shen et al., 2014); (Felsch Jr. et al., 2020).

Table 6 - Variables used to calculate the reduction of GHG emissions

Queue Time reduction (h/year)	Average Fuel Consumption (l/h)	Fuel saved (l/year)	Conversion Factor (t CO2/l)	GHG Emission Reduction (t)
938.6	11.3	10,606	0.00268	28.42

Source: Author’s elaboration

3.5. DISCUSSION

The management system proposed in this research can be a useful tool for mines seeking to increase loading productivity and control operational failures. The main causes of failures associated with the system would be human mistakes in identifying and justifying anomalies spotted by the programming. The incorrect human diagnosis may lead to operational actions that do not solve or minimize the low performance when it is identified. Thus, this is one of the reasons for the great importance of specific training and education of personnel for the correct assessment of operational conditions. Also, these limitations and uncertainties may be investigated in further research and the analysis of operational variables related to haulage equipment, such as cycle times.

Firstly, digital technology coupled with the updated real-time database provides opportunities to control mining operations at new levels of supervision. Also, AI techniques allow various types of data to be analyzed automatically, making it possible to generate automatic warnings/alarms when a computer program identifies a predetermined abnormality. Concepts related to the 4.0 Industry, such as Big Data Analysis and AI, are increasingly present in industrial environments, and mining is no different. Thus, there is an excellent potential for improving production processes associated with these current concepts.

Secondly, the technical knowledge and confidence of the operational team of the studied mine were of great importance in the execution of the work. During the implementation phase, the entire technical team of the company was trained. In addition, the technology used, as well as its potential factors for cost reduction, were presented. The work also allowed for improvements in the management processes of the mine operation teams, as it made it easier to access the reasons for poor individual performance and favored commitment to reporting operational anomalies.

Thirdly, several reasons were identified to justify the poor performance of the shovels. The main ones were resistant mining area, loading squares with irregular geometry, poor condition of the loading square's floors, presence of blocks in the mining area, low physical availability of trucks, operators in training, equipment with maintenance failures, and operational errors. Moreover, many of these reported issues can only be identified in management control reports generated the day after the operation or even after extended periods such as weekends and holidays. Consequently, this routine impairs the flow of the mine and reduces the Productivity of the equipment, which can lead to some breaks in the haulage operating cycles, further impacting the operating cost.

Finally, operational alarm techniques have already been used to control KPIs from mine haulage equipment, such as cycle times. Operational targets and manual controls have been used via spreadsheets (Coronado & Tenorio, 2015). Most systems can generate information automatically, provided there is adequate computational infrastructure and data available.

4. USE OF TELEMETRY TO MANAGE OPERATIONAL PROCESSES IN MINING

4.1. INTRODUCTION

This research is based around an article published by the author in 2018[2]. Production processes are constantly being optimized with the help of embedded electronics, information technology, and communication systems to obtain information in real time, so that decision making can be made more precise and can be given a more technical foundation.

In view of the current fluctuations in commodity prices, the implementation of mechanisms to increase the reliability and availability of assets and reduce the costs of operation has become essential to support the competitiveness of companies in the current mining market.

The study and development of new technologies for equipment monitoring in mining are therefore essential. Under current conditions, there is no more room for improvisation or rearrangement; competence, creativity, flexibility, speed, a culture of change and teamwork are now vital characteristics of companies and organizations with a focus on competitiveness for survival (Kardec & Nascif, 2009).

According to Nascif (2009), most companies that seek to remain in the market while maintaining or increasing their participation must measure their performance using performance indicators. These indicators allow for the quantification and monitoring of processes, the elimination of subjectivity, and appropriate corrections to production processes.

Lewis and Steinberg (2001) considered the maintenance of mobile mine equipment in the information age and the existing need in the mining sector for the integration of

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[2] Felsch, W.S., Arroyo, C.O., & Oliveira, V. (2018). Beneficios de la implementación de un sistema del telemetría para la gestión de las operaciones mineras. Interfases. Ed. 11 p. 87-102. 10.26439/interfases2018.n011.2955.

communication interfaces. According to these authors, remote monitoring of equipment has strong potential in terms of reducing maintenance costs and increasing production through increased availability of equipment.

In this context, the development of studies and additional work on process management in mining through telemetry has become important in order to allow collected data to be transformed into vital information, thereby improving the safety and performance of operations, and contributing to reducing the operating costs of the mine.

Telemetry can be defined as the transfer and use of data from a network of remote equipment for monitoring, measurement, and control. Communication may take place via a fixed or wireless network.

The implementation of equipment monitoring through telemetry relies on specific sensors that have been correctly installed, people that have been trained to carry out parameter analysis, and systematic analysis processes.

Araújo (1999) identifies three technological fronts in the evolution of telemetry:

I. Sensor technology and signal conditioning, of which the main characteristic is the capture of information.

II. Information processing and storage, which received a significant boost from the creation of microprocessor devices and memory.

III. The logistics of how information is handled, from the point of origin to its destination.

According to Knights and Desneshmend (2000), in order to maximize the benefits of using information technology, the mining industry must standardize the data formats and protocols used, to enable unrestricted data exchange. The adoption of these rules would facilitate the provision of real-time data to support managerial decisions.

The low productivity and high maintenance rates of transportation fleets arise from several factors, with the main ones being:

- Loads with volume below the transportation capacity.
- Critical conditions in the operating profile of the mines, such as unevenness in the track, high radii of curvature, and inadequate grades of track.
- Unsuitable speed limits for certain stretches of track.
- Operation outside of established standards, such as abrupt changes in the transmission system and inadequate use of braking systems.

Another point with strong relevance is the safety of mine operations: mines with steep profiles (i.e., with inclines above 10%) pose greater safety risks due to heating of the brake cooling oil and consequent loss of control of the equipment.

The design of access roads should take into consideration structural aspects, functional aspects, and maintenance plans, as discussed by Thompson and Visser (1997, 2000, 2003, 2006). The cost of the design and construction of access roads represents only a small proportion of the overall costs of maintenance and adequacy.

According to Tannant and Regensburg (2001), the economics of access road construction is more complex than simply calculating the construction costs. For a true understanding of the economics of transportation, the full lifecycle costs of access roads must be considered, including the following aspects:

- The construction cost of access roads.
- The cost of road removal.
- The impact on fleet productivity and operating costs.
- The operation and maintenance costs of additional equipment.
- Cash flow.

Dorigo and Kardec (2009) state that the maintenance team must ensure the reliability and availability of the assets needed to meet a production program or to provide a service while maintaining safety, preservation of the environment, and adequate costs.

Cochefski (2011) has reported that automated supply management can result in significant savings to companies through a reduction in manual management processes such as equipment allocation or manual entry of information into control spreadsheets.

Proper management of the supply process results in increased utilization of the haulage fleet by reducing the number of trips made to the gas station.

The importance of the application of process management technology in mining based on telemetry therefore becomes evident. The consolidation of all other information related to the operation and maintenance of the fleet in a place of common access is also essential for agility in decision making.

4.2. DEVELOPMENT

The use of equipment monitoring through telemetry emerged in the mining industry to address the drawbacks of processes with manual characteristics or a lack of control, such as the control of supply, road quality, and problems with the operation of equipment outside the standards established by manufacturers. These conditions can lead to premature failure in some equipment components, thereby impacting their ideal performance over the useful life for which they were designed, impairing their productivity and the quality of the service provided, and affecting the budget available to the company. The current problems in the mining industry include the following:

Mine operation:

- Frequency of supplies with a low volume of diesel oil.
- Lack of control over the condition of access roads.
- Cargoes transported with decentralized positioning.
- Lack of communication between teams.

Mine maintenance:

- High rate of brake cooling oil overheating events.
- Chassis damage and premature tire wear.

- Excessive unscheduled maintenance.
- Premature failure of cylinders and suspensions.
- Repeat failures due to a lack of control over the root causes.

4.2.1 Materials and methods

Monitoring begins with the collection of data by the telemetry system, which functions as an advanced monitoring and diagnostic tool that can help in evaluating and managing the health and performance of a machine. Telemetry is used to monitor a machine via signals from input devices (sensors and switches) and to provide action alerts via messages to the operator using an in-cab display (advisor). In addition, one of its main functions is to store data and records on the condition of the equipment, so that problems can be monitored and diagnosed. Figure 12 illustrates the operational flow for the process described above.

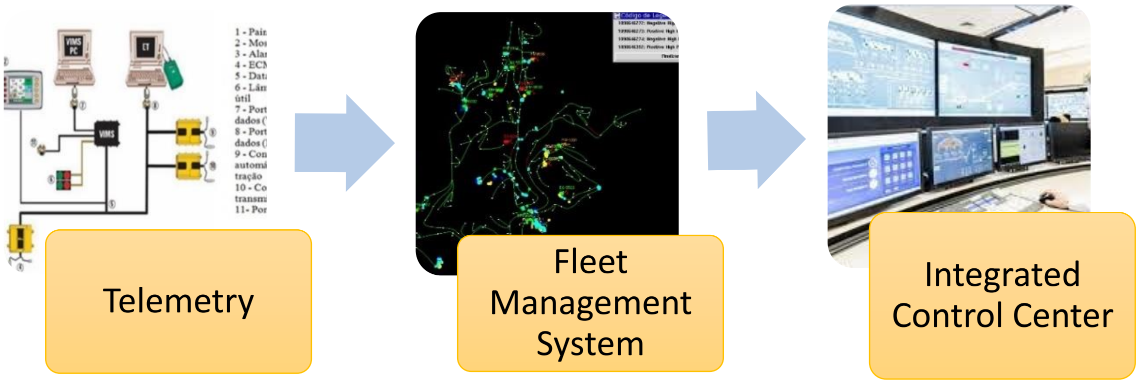


Figure 12 - Information flow and systems used for process management

Source: Author's elaboration

Based on the interaction between the FMS, which is responsible for directing the mining production equipment, and the telemetry system, an interface can be created to associate the type of problem identified with its geographic position in the mine. This information is passed to a control center, which monitors events and directs the teams responsible for the maintenance and operation of the equipment to analyze and solve the problems.

The main processes that are monitored in this work are:

- Operational processes: supply, condition of access roads, and centralization of transported loads.
- Maintenance: brake cooling oil temperature.

4.2.2 Supply control

Currently, there are three methods of controlling supplies for mining equipment:

(1) Manual supply control (via equipment drivers): An operator identifies the need for supply and requests a release to move to the gas station or train.

(2) Automatic supply control (via fuel decrement): A dispatch system applies a fuel decrement approach based on the average fuel consumption (liters/hour) and the number of hours of operation for each piece of equipment.

(3) Online supply control (telemetry): The FMS automatically reads the CAN (Controller Area Network) network of the equipment, extracting the diesel volume information in real time and allocating the equipment to the supply location.

The objective of this work was to reduce operational costs by reducing the frequency of equipment refueling and by reducing the travel time and queues at the gas station, thereby improving the effective use of the fleet.

This study considers the migration of the automatic supply control to the online supply control, through the configuration of the telemetry reading by the FMS. In this way, information about the volume of diesel oil in the tank of a vehicle can be monitored in real time by the technicians controlling the operation, directly from the mine's control room. The team uses a graphic interface to monitor and direct the vehicle to the fuel station.

After four months of development, the benefits included a continuous process of improvement in terms of an increase in the average volume supplied to the 38 trucks in the transportation fleet, in addition to a reduction in the standard deviation between the samples of the supplies.

Another point strongly related to the increase in the average supply volume was the creation of a key performance indicator called the supply volume, as a monthly management control for the team working in the control room. It was found that indicators based on periodic monitoring and control tended to be more effective.

4.2.3 Monitoring of Access Routes Using the Road Analysis Control Tool

The main objective of monitoring roads is to maintain the condition of the vehicles by ensuring that components such as tires, suspensions, cylinders, and truck chassis do not undergo failure caused by poor road conditions and that they can operate over the useful life span predicted by the manufacturers.

The road access control (RAC) tool is an onboard information technology product that forms part of the telemetry system, and was designed to measure the quality of the roads. It provides real-time feedback on road conditions, and enables the identification of detrimental effects on production cycles and maintenance components. Through an onboard computer located in the equipment cabin, two levels of RAC events can be identified and used to alert the operator to sections of the haul road that require attention, from the point of view of both the truck operator and the infrastructure equipment. Level one requires the operator to reduce the speed, while level two requires the operator to avoid the specific sections that trigger these events, and to immediately call for support equipment such as tractors and graders to service the problem areas.

The RAC events are generated based on pressure differentials in the four suspension systems of the truck, and sensors are installed to measure the internal pressure when these suffer some kind of strain, thereby allowing the conditions of the roads to be monitored based on the degree of deformation they undergo at certain points. The system collects individual pressure data from the suspension systems 10 times per second, and identifies three types of event according to the pressure of each one: rack (a difference in diagonal pressure), pitch (a difference in pressure between the front and rear suspensions), and bias (a differential lateral pressure between the suspensions).

The RAC and FMS were integrated to allow for visualization in real time of the places where rack, pitch, and bias events occurred, making it easier to direct the infrastructure equipment to the critical areas that need correction. In addition, this enabled the operation supervisors to inform the drivers in advance about the most critical areas, thus making operation safer for both the machine and the operators. Figure 13 below shows a mine map showing the events that have been plotted, drawn from the interface between these tools.

The first components to suffer the impact of poor road conditions are the tires, and the cost of these is one of the largest in the mining industry. Variations in pressure and temperature above certain limits can cause damage to their structure, reducing their useful life and putting operational safety at risk due to the countless cycles over which they operate at different speeds, and due to the quality of the roads they travel on. When either or both of the pressure or temperature is exceeded, there may be a so-called TKPH [(ton x (kilometer/hour)] burst, where the tires are already above their maximum operating point and irreversible damage can occur.

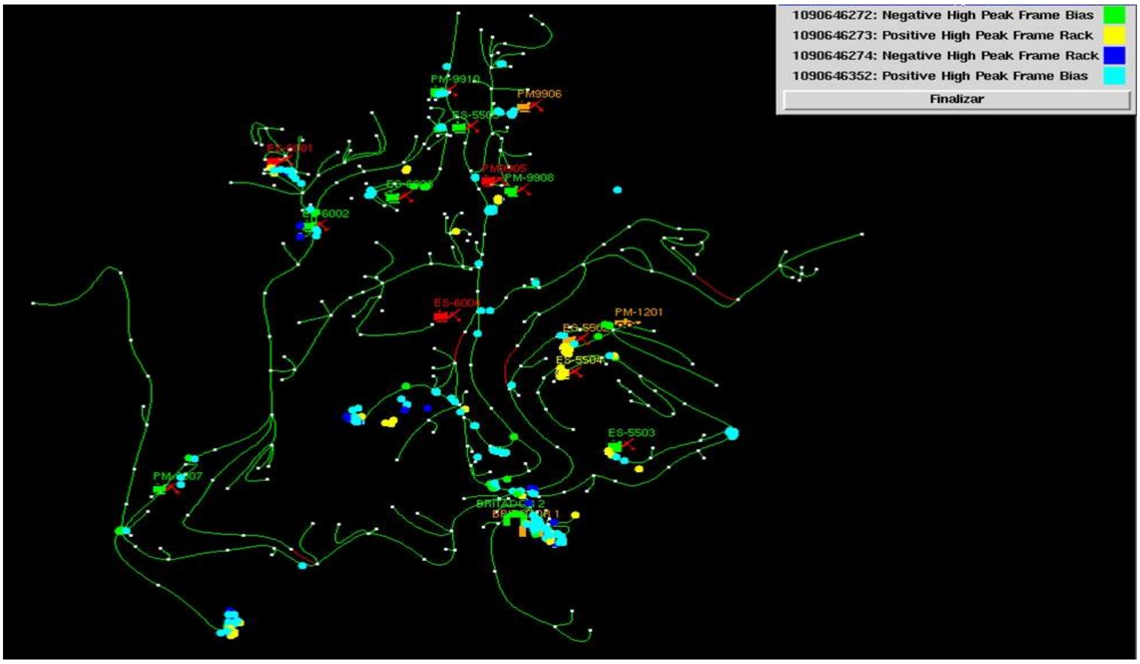


Figure 13 - Mine map highlighting the events identified by the RAC tool

Source: Personnel file

In this context, ensuring that these components operate within pre-established working conditions is the first step towards achieving better performance. Several points that needed improvement were diagnosed, such as depressions in the track (Figure 14), superelevations, and undulations. These problems create increased rates of TKPH and elevate the risk to the tires.

Figure 14 - Depressions on the runway

Source: Personnel file

This form of management makes it possible to intervene in the process in a preventive way, and to act on areas that could potentially cause functional failures based on the data highlighted by the tool and information crossing, thereby ensuring that uneven tracks do not cause failures in tires and other components such as cylinders and suspensions.

An improvement in the conditions of the access roads and loading squares also results in better performance, as measured by production indicators such as average speed, cycle time, and spot time.

4.2.4 Monitoring of Loading with the RAC Tool

The objective of this type of monitoring is to detect flaws in the truck loading operation. Off-center lateral loads cause damage to the chassis of the equipment by overloading the suspension and tires on the side with the largest amount of material. As a vehicle moves, it is subjected to dynamic forces that are aggravated by poor road conditions, generating even higher torsional forces on the structure of the truck.

The bias alarms (transverse forces) of the RAC tool can identify off-center loads; as these are mostly concentrated in one area of the bucket, this event is indicated by a transverse pressure differential between suspensions.

Figure 15 illustrates this effect. It was verified in the field by the fleet analyst and operation instructor that bias alarms could be caused by off-center loads, rather than solely by the poor condition of the access roads.

Figure 15 - Off-center loading

Source: Personnel file

This effect can significantly contribute to fatigue of the chassis and cylinders due to operational wear and tear, and is exacerbated at the point when the material is tipped out, as the overloaded cylinder needs to exert greater force to lift the bucket.

When these points had been identified, specific training sessions were held with the team of clogging operators to offer them instruction and guidance in maintaining safer and more suitable operating conditions, with less mechanical wear to the equipment and lower physical stress on the operator.

4.2.5 Brake cooling oil overheating event control

Through the use of telemetry and the FMS, it was also possible to control and monitor the brake cooling oil temperature of the trucks used in the mine.

First, a profile analysis of the ramps was carried out to determine the inclinations of their segments. The location of the central ramp and its slopes are illustrated in Figure 16. It can be seen that there are stretches in which the gradient exceeds 12%, thus falling outside the planning standards used in the company, which has a maximum slope of 10% for projects.

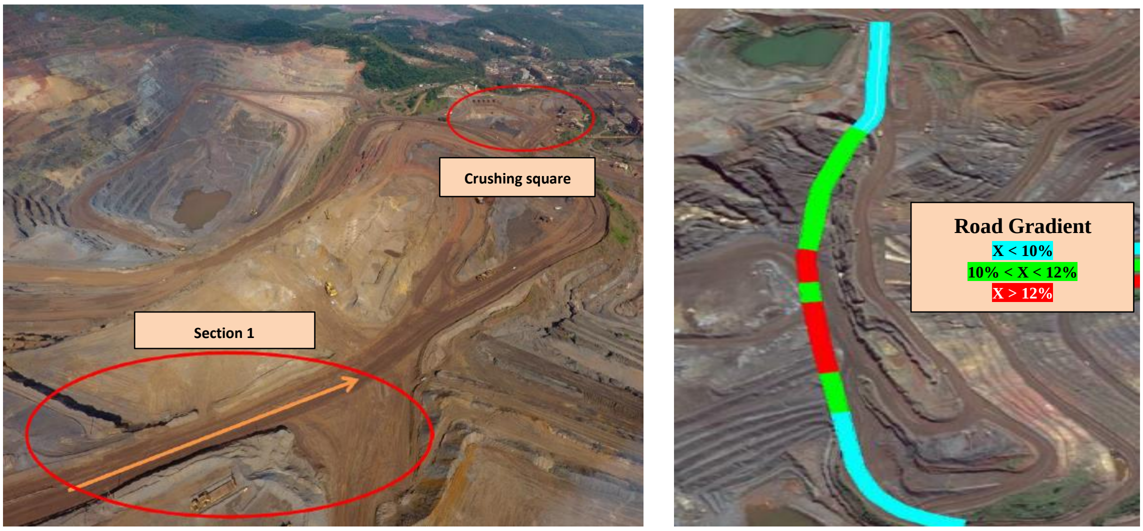


Figure 16 - Central ramp of the mine with stratification of its slopes

Source: Author’s elaboration

In addition to slopes that did not meet the planning standard, improper operational behaviors were identified, such as excessive speeds and the use of inappropriate gears.

Figure 17 shows a comparison of brake temperatures before and after the proposed system was applied. A high number of brake cooling oil overheating events were identified, mainly in the central ramp and the access ramp to the waste pile. These events cause premature wear of the brake system, and can severely impact the safety of operation.

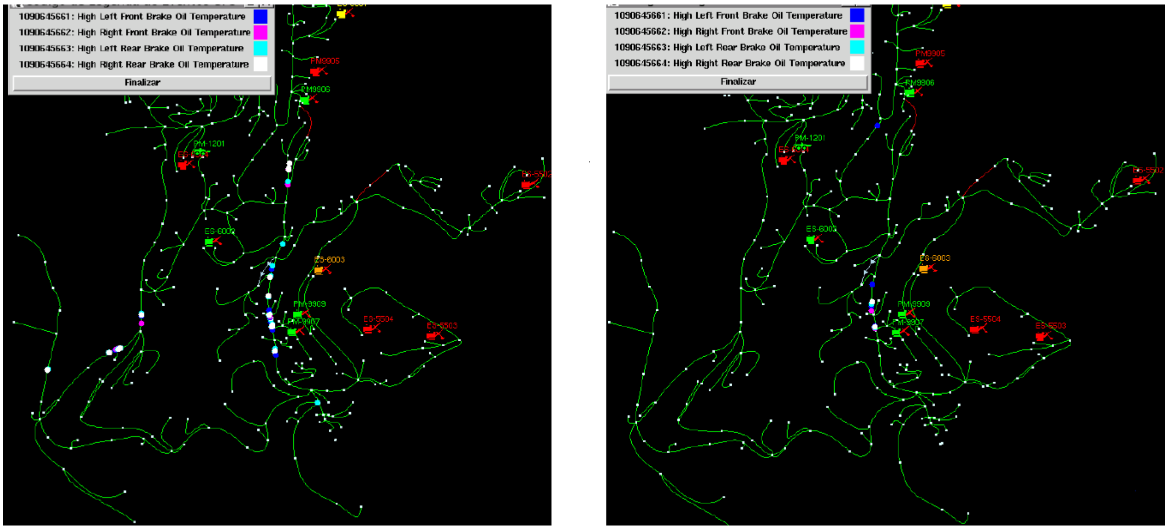


Figure 17 - Brake cooling oil overheating events

Source: Personnel file

These analyses generated action plans for the treatment and reduction of brake cooling oil overheating events, including:

- Topographic analysis of all mine accesses.
- Maintenance of identified accesses with inclinations above 10%.
- Theoretical and practical training of haulage equipment drivers.
- Review of the mine's signage, with a focus on permitted speeds and appropriate gears for use in each stretch.
- Weekly monitoring of brake overheating events, with a focus on equipment drivers and administrative penalties in case of recurrence.

4.3. RESULTS

Based on these studies, it was possible to achieve several operational improvements and financial gains, for example:

- A reduction in maintenance costs and extension of the useful life of components (tires, chassis, and suspension): no premature failures have yet been identified in these items after the implementation of process control.
- A reduction in fuel consumption due to a reduction in the need for braking and resumption of power to the equipment, arising from better road conditions.

- An increase of 5.6% in the average volume of diesel oil supplied to the haulage fleet.

- Period 1 was defined as the period before the implementation of the proposed scheme.
- Period 2 was defined as the period after execution of the proposed scheme.

Figure 18 shows the evolution of the results for the average volume and standard deviation in the supply volume.

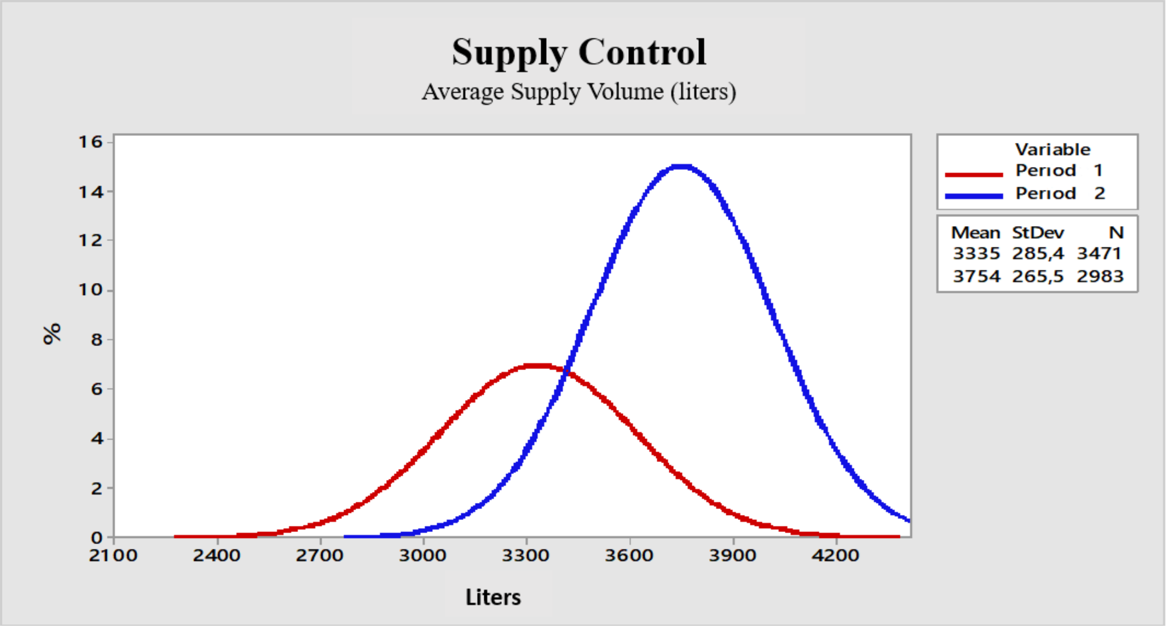


Figure 18 - Comparison of average volumes supplied in the two periods analyzed

Source: Author's elaboration

- A reduction of 21.8% in the average monthly number of supplies per transport equipment.
- An increase of 0.33% in the effective use of the haulage fleet.
- Better prioritization of infrastructure equipment for the maintenance of accesses based on their degree of criticality.
- A reduction in the number of TKPH events aggravated by irregularities in tracks, through ensuring optimal tire performance.
- An improvement in operational performance indicators at a mine access determined as Section 1 (haulage productivity, average speed, and cycle times), as per the example in Table 7.

Table 7 - Operational Analysis – Section 1

Operational Analysis – Section 1			
	Period 1	**Period 2**	**Δ (%)**
Haulage Productivity Rate (t/h)	609.4	615.8	1.10%
Average Cycle Time (min)	12.6	12.3	-2.20%
Average Speed (km/h)	20.84	21.13	1.40%

Source: Author’s elaboration

- A reduction of 78% in the number of brake oil overheating events in the loaded downhill profile.

The use of telemetry in operational processes enabled better management of mining activities. The proposed scheme resulted in greater control over the equipment in the refueling process, and proper maintenance of access roads led to safer and more productive operation, with less wear to the truck structure, thus creating greater comfort and safety for the operator.

The work carried out with the mining company resulted in an increase in the efficiency of the production phase of the mining process. The overall result of the studies and the implementation of improvement works was a reduction of 3.3% in the operational costs of the unit.

5. HIGH-PRECISION GPS IN THE MINING INDUSTRY

5.1. INTRODUCTION

Global navigation satellite systems (GNSSs) have been widely used for scientific and commercial applications such as air, sea, land, and space navigation, precision timing, geodesy, surveying and mapping, machine guidance and control, and military and emergency service operations (Smriti, et al., 2013). The mining industry has been at the forefront of the use of real-time GPS. Open-pit mining represents an ideal environment for GPS applications, as satellite visibility can be incorporated to meet the demand for safety and operational performance.

The introduction of new techniques in the mineral industry has given rise to a need for investment and research in technologies associated with mineral extraction, in order to improve safety and operational performance, and enable better use of mineral deposits. One important theme associated with recent technological advances is the popularization of the use of high-precision GPS in mining, with the most widely used being Real Time Kinect (RTK) (Tu et al., 2018; Wang et al., 2020). This technology currently has a high cost, but following the emergence of new companies and investments in this segment, it is becoming more popular, and the cost is likely to become more attractive, meaning that its implementation will be more viable in companies of all sizes.

Among the main benefits of using GPS in mining equipment is the possibility of fleet tracking and management of the loading and transport equipment, with more precise and productive allocations. The use of GPS can also improve safety for equipment drivers through the introduction of collision detection tools and autonomous equipment.

GPS can reduce environmental impacts by protecting legally preserved areas through the use of cadastral mapping, by highlighting georeferenced areas that are outside the legal limits of operation and automatically warning operators about possible unauthorized movements. This tool can also enable greater selectivity in mining operations and allow for more precise extraction activities, with a consequent reduction in environmental impact by reducing the unnecessary extraction of materials with no economic value. Studies of reductions in diesel and tire consumption can also help with equipment positioning through the identification of unproductive sites (access roads, curves, loading squares) (Curi et al., 2013; Rodovalho et al., 2020).

The introduction of mineral production data and high-precision positioning techniques (HPGPS) has enabled the development of innovative methodologies throughout the production chain in the mine-to-port process, for example in regard to ore quality control (Carter, 2005). Additional major benefits include increased efficiency of loading and transport operations, drainage control of loading squares (which will be addressed in the case study considered in this paper), and the operationalization of autonomous equipment in mining.

This technical contribution is related to the concept of sustainable mining. Through an analysis based on the principles of sustainability, this research can contribute to the development of solutions related to risk management, health and safety, and environmental performance. The findings of this research can be used to reduce costs, develop better operational practices, achieve greater safety and environmental performance in mining operations, and optimize the life of the mineral deposits using sound scientific data.

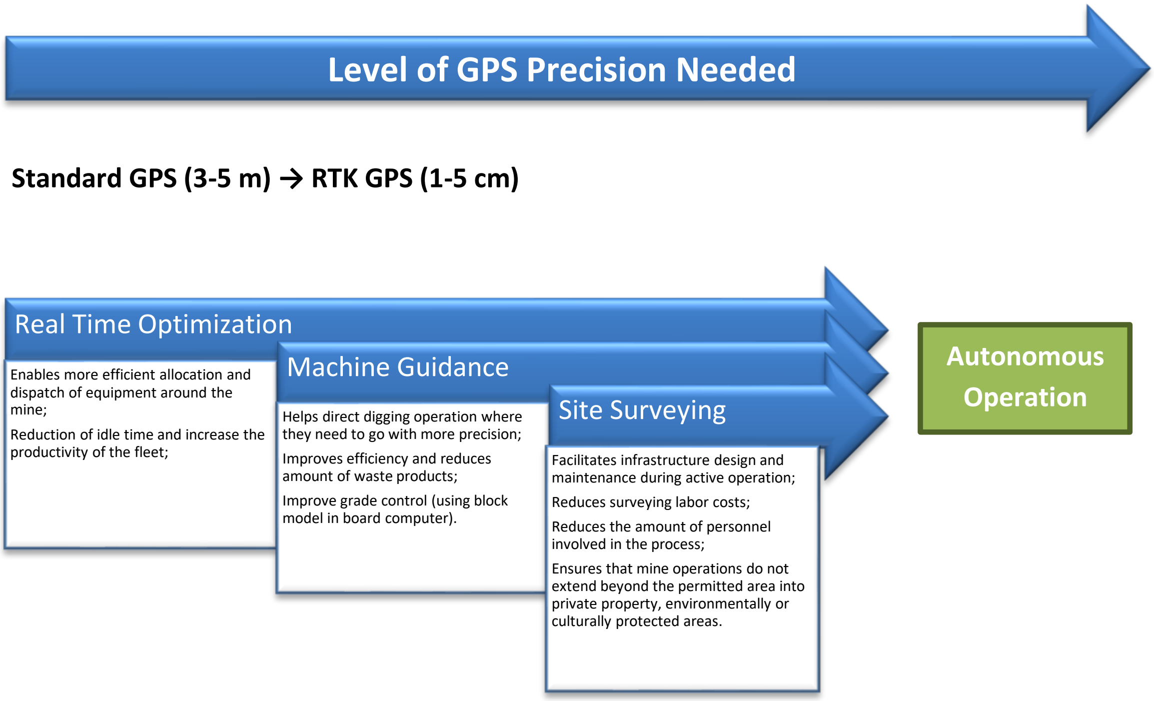
The aims of the study were to provide an overview of the use of high-precision GPS technology in mining operations and to develop an innovative technique for analyzing GPS data to monitor surface drainage in mine loading pits.

5.2. USE OF HIGH-PRECISION GPS IN MINING

One of the most important drawbacks related to the use of GPS in open-pit mining, and particularly high-accuracy RTK, which offers centimeter-level accuracy, is the need for five or more satellites to provide the accuracy necessary for its proper operation (Mekik & Arslanoglu, 2009).

An evaluation of the site at which mining activities will be carried out, in terms of the capacity of the telecommunications network and availability of GPS, is a fundamental requirement for correct operation. Events such as survey configuration failures, equipment inaccuracy, and the errors inherent to GPS satellite radio signals can cause incorrect information, and consequently failures in the decision-making process.

The currently available tools and techniques that can meet the precision requirements of the GPS implemented in the equipment can be seen in Figure 19. As higher levels of precision of positioning become possible, new products and controls will emerge that can offer great improvements and generate value in regard to the safety, environment, and financial health of the company.



Real Time Optimization

Enables more efficient allocation and dispatch of equipment around the mine;

Reduction of idle time and increase the productivity of the fleet;

Machine Guidance

Helps direct digging operation where they need to go with more precision;

Improves efficiency and reduces amount of waste products;

Improve grade control (using block model in board computer).

Site Surveying

Facilitates infrastructure design and maintenance during active operation;

Reduces surveying labor costs;

Reduces the amount of personnel involved in the process;

Ensures that mine operations do not extend beyond the permitted area into private property, environmentally or culturally protected areas.

Figure 19 – Level of mining precision positioning - timing uses and needs

Source: Author’s elaboration

5.3. REAL-TIME OPTIMIZATION

GPS is a key tool that can enable more efficient allocation of mine equipment, for example involving both loading and dumping of the material being transported. Dynamic allocation, which is a function seen in modern FMSs, uses GPS to identify the location of mine equipment in real time. This positioning system is used to direct or redirect the trucks used for loading and unloading to more productive locations, with the aim of reducing queues and idle time, and consequently increasing productivity (Felsch Jr. et al., 2020). Optimization in real time does not need high-precision GPS, but rather FMSs that include intelligent algorithms and skilled professionals to control the systems.

A knowledge of the positions of the vehicles in the mine in real time has many advantages, since it allows for the identification of possible sites of low performance, and also the fleet's direction for routine activities aiming at the optimization of its displacement, such as refueling, meals, and operator relays. The distance and time over which vehicles move in an empty condition can be reduced with the use of GPS coordinates. Auxiliary equipment such as tractors and graders can also benefit from a reduction in their range of movement during the execution of their activities.

The conditions of access roads in mines can be monitored with the help of GPS and onboard telemetry systems. This type of monitoring was developed to address the problem of a lack of quality control over roads, loading bays, and dumps, which made it difficult to take action appropriately and quickly. There were premature failures in some components of the equipment, which did not yield ideal performance over the useful life for which they were designed, thus harming both productivity and the quality of the services provided, and affecting the budgets of companies (Felsch Jr. et al, 2018). Plans for the creation of access roads should consider structural and functional aspects, and should include maintenance plans (Thompson & Visser, 2003).

5.4. MACHINE GUIDANCE

The use of accurate machine guidance systems relies on positioning technologies such as HPGPS to provide real-time guidance to equipment operators or directly to the machines.

In open-pit mining, a knowledge of the spatial positions of loading equipment and the types of material being loaded is of great importance in terms of improving the quality control of the ore. Loading operations in contact regions (ore/waste rock) can be very complex, especially with heterogeneous deposits. There are also several types of operations where visual identification is not possible.

In addition to determining the positions of the equipment, it is also necessary to consider information on the physical and chemical characteristics of the mine using specialized software. The inclusion of information on topography, lithotypes, and block models (BMs) is essential for the transformation of high-precision coordinate data into relevant and reliable mining information.

The scarcity of ore reserves with higher ore content has motivated studies focusing on the exploitation of ores with poorer content and more precise blending. In companies where revenues are dependent on the extraction of low-grade ores, the use of high-precision GPS can provide greater selectivity in extraction, thus reducing dilution. The results are reductions in production costs and maximization of profits.

Greater precision of extraction activities helps to reduce the volume of extracted materials that have no added value. An operator can visualize the geological contact using the onboard computer, which facilitates the identification of the type of material being mined and the possibility of interference in its allocation, whether for crushing or waste rock dumps. The main benefits are greater control over the sequencing of mining, the possibility of ore tracking, and instantaneous topographic updating.

One major challenge in mine planning involves the treatment of the geological BM information and the generation of optimized sequencing plans to meet the ore quality targets at the mill feed. The ability to determine the exact bucket position of the loading equipment, together with a well-structured BM, can enable the quality associated with each load to be determined, thereby allowing for real-time quality control of the material destined for the plant.

Determining the position of the equipment with high precision is essential in order to optimize the mining of the ore based on information from the BM. Integrating the BM with the FMS means that the company has the capability to identify loading coordinates and bucket positioning for each pass made. If the spatial position of the BM blocks can be synchronized with the geographic coordinates of the bucket of the loading equipment, with high accuracy, this will enable the development of real-time controls.

The possibility of managing ore quality data opens the way for significant improvements in process management (mining and milling), as well as reductions in mining costs (O’Connor et al., 2019). The prediction accuracy of the grading information of the mined blocks can be then maximized, leading to a reduction in the frequency of BM misclassification. As a result, the quality control of the ore produced will be higher, and the mineral deposit will be better optimized.

The main benefits of online control over ore quality include a reduction in the variability of global chemical contents between the BM and samplers, better control over the reconciliation between the volume of ore mined and the data displayed by the production systems, tracking of the mined ore as part of the mine-to-port flow, and online control over the granulo-chemical content of the mining fronts in operation.

Another important advantage of high-precision positioning systems is the possibility of level control for equipment such as excavators and tractors. The leveling of benches tends to be more uniform using the tool, which can be compared to drainage plans. This topic will be addressed in Section 5.6 of this chapter, which presents a case study.

5.5. SITE SURVEYING

This technology makes it possible to perform automatic topographic updates, thereby facilitating the preparation of monthly, weekly, or even daily mine plans. The benefits of using HPGPS in surveying operations include reduced labor costs and more accurate and reliable results. Furthermore, the quality and consistency of the data are increased, since HPGPS eliminates the systematic and random errors that can affect conventional measurements, such as reading errors and human error.

Additional benefits include reduced operating costs, improved safety of operations, and better utilization of the loading and transport fleet. The technology also makes it possible to highlight dangerous areas via the onboard computer, such as blasting areas, electrical networks, and underground pipes. Another safety-related benefit is that fewer people are exposed to risks in operational areas, such as surveyors and technicians. Avoiding accidents is crucial, both from the point of view of human well-being and from a financial perspective.

A further important aspect is the monitoring of deformations in slopes and civil structures (Jing-xiang et al., 2011; Tao et al., 2021). The evaluation of the behavior and stability of slopes and dams plays a large role in the safety of mining operations. The proposed technique enables the monitoring of large areas and critical points with few control stations, and facilitates the integration with other monitoring equipment such as inclinometers, piezometers, and extensometers. It provides spatial and temporal information about deformations, which can assist in risk analysis and decision making.

The concept of “zero entry mining” (Knights & Yeates, 2019) involves reducing the need for human beings in the mining zone. This approach not only reduces the exposure of personnel to risk, but can also be a significant source of added economic value through better utilization of equipment, increased revenue, reduced operating costs, reduced CAPEX, and fewer services (e.g. surveying). The creators of this concept argue that reducing the number of people within the mining area can provide a sharp increase in the safety and value of mining operations.

5.6. CASE STUDY: LOADING SQUARE DRAINAGE CONTROL

There is great potential for improvement in the control of mine infrastructure activities through the use of high-precision positioning tools. Drainage control of the loading bays is an important activity in mining operations. In particular, the use of automated processes in mining operations can reduce the number of people exposed in critical areas, thereby minimizing risks to the safety of personnel.

The proper location of the surface drainage structures is essential in terms of dissipating the energy of the rainwater and reducing the amount of sediment. Another relevant issue is the priorities of the surface drainage correction activities at the loading squares, which can be executed with the preventive maintenance of the loading equipment.

The use of drainage schemes that closely adhere to the initial project, developed by those responsible for mine planning, can reduce the auxiliary work and improve the effectiveness of execution. It also improves the effective use of the loading and infrastructure equipment, since it can avoid unnecessary stops and displacements, as well as rework.

5.6.1 Materials and Methods

The information used in this research was extracted from the FMS and the high-precision positioning system. The systems output data in real time, via a dedicated wireless network, with a GPS and onboard computer in each piece of equipment. All data were transmitted over the dedicated telecommunications network used at the target mine. This information was stored in relational databases, and was handled with a computer program based on SQL (Structured Query Language).

First, a random mining front was chosen at the target mine. An approach was then developed to split the drainage monitoring of the loading square to enable a comparison of data on the elevations of the mining front in two scenarios:

Scenario 1: Manual operation and automatic analysis. The drainage analysis practiced by the surveying team involved manual measurements at certain locations on the loading plaza using tachymeters. Based on the data, point clouds were generated, and a visual interface of the drainage behavior was created.

Scenario 2: Automatic operation and analysis. Data were obtained using the HPGPS associated with the FMS of the loading equipment allocated to the mining front.

As per the routine of the target mine, the mine planning team generated monthly planned mining advances, which contained the floor level suitable for mining. These projects were sent to the surveying team, who carried out marking in the field, adjustment activities, and checking of the work done by the loading equipment. The information on the leveling and drainage projects was passed to the onboard computers, which formed part of the FMS installed in the loading equipment, to provide the operators with guidance on the advances and the optimal elevation required for the work.

The operators of the loading equipment then saw the actual and projected levels and their deviation (elevation information, shown in the upper left of the figure). Figure 20 shows an image from the onboard computer, in which the leveling information for the square can be seen.

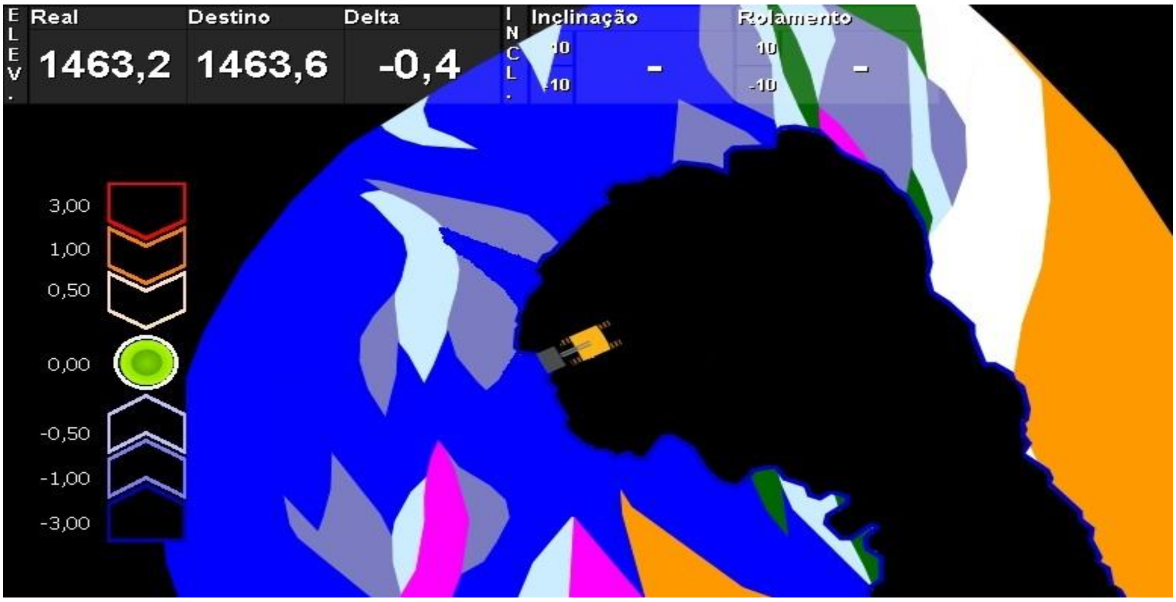


Figure 20 - Image from the onboard computer showing the information available to loading operators and highlighting the level scale

Source: Personnel file

The aim of the proposed methodology was to enable an automated search for a larger volume of measurement points for data treatment. This methodology does not require any manual topographical surveys, thereby reducing stoppages of load equipment for possible measurements.

5.6.2 Results

The two methodologies were compared with the drained mine feed project issued by the mine planning team on a monthly basis. Figure 21 below presents a comparison of the drainage information for a predefined mining advance. The methodology using the high-precision points considers a greater volume of information, and hence offers greater reliability in terms of the data generated.

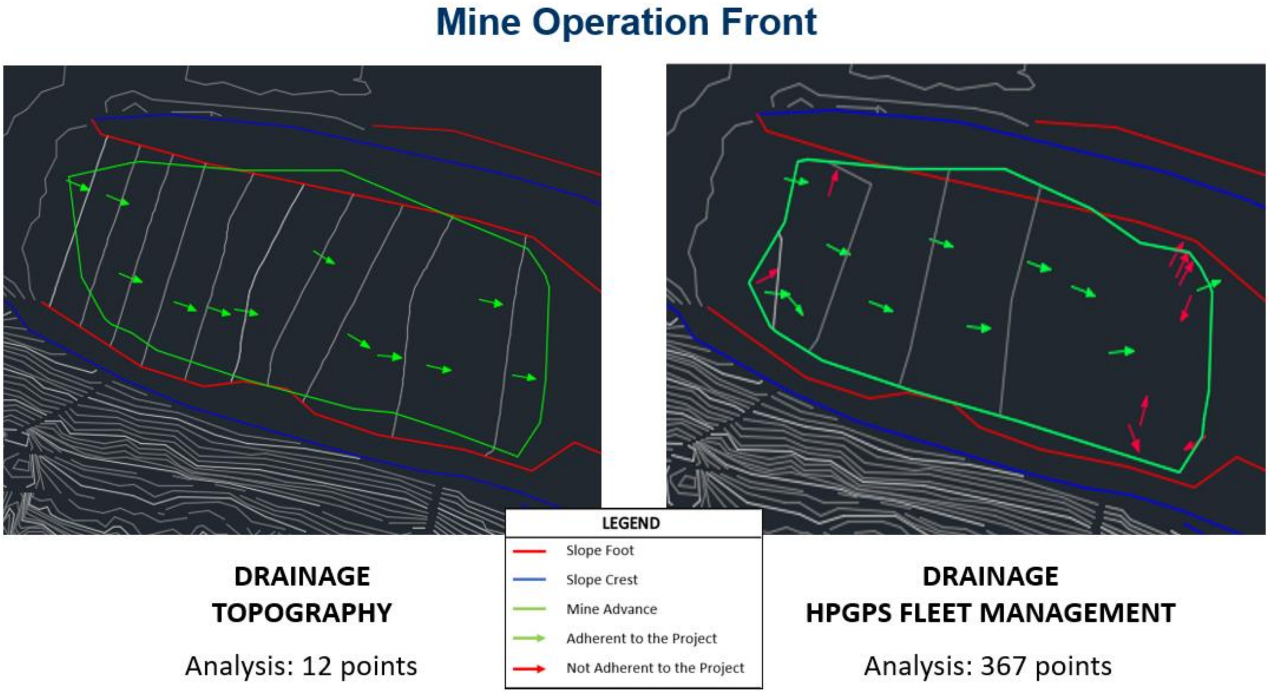


Figure 21 - Comparison of adherence to the drainage project with the two methodologies used

Source: Author’s elaboration

The arrows generated by the software establish the slope of the square (drainage). The green arrows indicate adherence with the project, while the red ones indicate non-adherence. The lines correspond to the slope (blue and red), and the green line shows the planned mining advance.

The image on the left shows drainage that adheres to the design, meaning that no operational intervention is required. However, when the same square in the image on the right is analyzed with the proposed methodology based on high-precision GPS points, it can be seen that the ends of the advances do not adhere to the project. If there is no intervention and adjustment of these points, water may accumulate, causing operational inefficiency and possibly even slope failure.

Benefits of drainage monitoring

Safety

- Operational safety: Improvements in the condition of the slopes and loading squares, and the ability to direct water to the appropriate regions of the pit.
- Reduction in the variability of deviations in the stipulated levels (quotas) of the loading squares, thereby ensuring the correct height of the plowed bench and drainage control.
- Elimination of the need for manual activities related to topographic marking in the mining process. Physical exposure of employees to risky conditions will be avoided.

Environmental aspects

- A reduction in the erosion processes caused by rainwater and the consequent carriage of fine materials to areas outside the mine, especially in regions near urban areas and permanent preservation areas.
- More agility and higher reliability of drainage information for the mine operation team.

Productivity and Cost Reduction:

- Better utilization of loading and transportation equipment due to a reduction in stop events for square setting and topographic analysis.
- Increased productivity of loading and transport equipment due to improvements in maneuvering and displacement activities.
- Reductions in the operational hours of auxiliary equipment for square adjustment activities and the operational hours of crawler tractors related to rework activities.

- A reduction in equipment downtime due to the topographic updating process, which will allow surveyors to perform other activities or even enable a reduction in the number of operational staff.
- Greater agility in the creation of ramps and maintenance of mine accesses.

5.7. DISCUSSION

One major challenge in mining is the ability to effectively distinguish between ore and waste rock contacts in heterogeneous deposits. The proposed approach can potentially save companies millions of dollars by reducing the volume of lost ore and the amount of contaminated ore going to the wrong destination.

A knowledge of the types of material being excavated in real time can improve the loading and transportation logistics, and can assist in planning and processing material and grade accounting. This information can enable better material planning and reconciliation practices, and can reduce losses and contamination by directing equipment to the best storage locations, since misallocation of a single load of high-grade ore or waste material can lead to significant monetary losses.

Control over the drainage level of the benches is essential in order to improve operational and economic factors, by reducing the erosion processes caused by rainwater and the consequent transportation of fines to areas outside the mine.

The work of conforming drainage on the benches will require fewer operational hours for auxiliary equipment, such as tire and crawler tractors, and will be a decisive factor in a new fleet sizing model.

6. ASSESSING THE PERFORMANCE OF MINING EQUIPMENT WITH A SIMULATION OF THE USE OF AUTONOMOUS TRUCKS

6.1 INTRODUCTION

This research is based around an article published by the author in 2019[3]. The demand for higher competitiveness based on the adoption of new technologies and knowledge is increasingly common in companies and organizations in all sectors. In the specific case of mining, increased productivity and decreased costs are possible whenever new knowledge and techniques are introduced to the operation of a mine. At the same time, security has become increasingly important in mining operations. In view of this, there are opportunities for expanding automation to the most critical and costly operations in the mining industry.

Automation refers to operations where human interference is minimal or not present, and thus allows for more stable, safe and continuous processes. In mining operations, automation involves control over operations at a safe distance, through the use of joysticks and cameras; in the case of the transportation of materials, autonomous operation involves a computer that controls the equipment via specialized software. The most important benefit is the withdrawal of human beings from areas with potential risk in the mine.

One of the primary areas that is being explored for possible automation in open-pit mining is the operation of mine haulage trucks. Autonomous haulage systems are receiving attention from operators in the industry, with both Komatsu and Caterpillar (leading manufacturers of haulage trucks) creating the first systems for use in mining (Parreira, 2013).

In the field of mining operations, the processes of greatest interest in terms of automation

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[3] Felsch, W.S.; Oliveira, A.F.; Ortiz, C.A. Approach of mining equipment performance with simulation of the use of autonomous trucks. In: Proceedings of the 39th International Symposium on Application of Computers and Operations Research in the Mineral Industry APCOM 2019, Mining Goes Digital.3 ed.: CRC Press, 2019, p. 542-550. ISBN: 9780429320774, https://www.taylorfrancis.com/books/9781000398229/chapters/10.1201/9780429320774-62

are drilling, loading and the material transport system. Self-propelled drills and trucks are being used in large mines and have yielded positive results in regard to increased productivity, better utilization, shorter downtime, and higher operational safety. In the area of material transport, Rivera (2014) estimates that the productivity gain for autonomous operations may be up to 20%, and that the equipment utilization gains are between 10% and 20%. This author also expects that the use of autonomous trucks will reduce operating costs, extend the life of certain components such as braking systems and tires, and reduce fuel consumption and gas emissions.

In addition to gains related to equipment and operation, automation of the transport system can also reduce the losses associated with human factors by overlapping the variability of each operator's equipment, and reducing shutdowns due to physiological needs, shift changes and absenteeism. In this way, the operation becomes more continuous, stable and safe.

Many parameters can affect the efficiency of the fleet in open-pit mining (Australian Gov, 2010; Curi et al., 2013), for example the mine plan and layout; speeds, payloads and cycle times; tire wear and rolling resistance; the age and maintenance of the vehicles; the design of the dump site; idle times; engine operating parameters; and transmission shift patterns.

Baloo (2008) and Curi et al. (2013) reported that the mine haulage truck selection was based on the following criteria: loading tool match required for mining ore and waste; availability of capital and delivery dates; productivity rate needed to achieve the mine plan; and the pit geometry and haulage routes.

However, mines with problems in terms of design, access maintenance conditions, crossings and excess auxiliary equipment would not be likely to obtain the full range of benefits offered by the implementation of autonomous trucks. A preliminary analysis of the mine conditions is necessary in order to maximize equipment performance and to avoid unnecessary downtime.

According to Rasmussen (1997), the dynamics of the current working world impose stress on the human-machine system due to the intense pace of technological modifications, competitive markets and pressures from different backgrounds in the workplace.

A driver’s knowledge of the position and speed of the vehicle (especially relative to other vehicles) can prevent accidents and reduce the cost of maintenance and replacement. Although driverless haulage trucks are not free from breakdowns, the increased consistency and scheduled maintenance will improve the lifetime of the machine components, leading to longer periods between maintenance, meaning that the costs associated with maintenance will decline. Lost production can be also minimized or eliminated, as the frequency of unpredicted breakdowns will also decline (Bennink, 2008).

To predict future results, it is important to know the degree to which an autonomous haulage system can match or outperform a manual system. Simulation software can be used to predict benchmarked KPIs and to discover new KPIs that might represent better measures of future changes due to the introduction of new technology.

6.2 SIMULATION

Simulation has become a useful and versatile computer-based tool for analyzing the behavior of complex systems involving several variables. Prado (2014) states that "Simulation is the technique of solving a problem by analyzing a model that describes the behavior of the system using a digital computer." In the same vein, Cassandras and Lafortune (2010) state that a simulation can be understood as the process of designing and creating a computer model of an actual or proposed system, with the purpose of conducting numerical experiments to provide a better understanding of the behavior of the system for a given set of conditions.

Sakurada and Miyake (2009) described discrete event simulation (DES) as the study of simulation models whose variables change state instantaneously at specific points of time, in contrast to continuous models, whose variables can change state gradually over time. Sturgul (2001) highlighted the important applications of simulations in mining operations for open-pit mines, including ore handling, fleet dimensioning, loading and transport, and the allocation of equipment, among others. Parreira (2013) noted that a conventional transport fleet in a mine can be adapted to an autonomous operating system, although it is necessary to invest in a wireless network and digital mapping of the mine, as well as installing precision GPS systems in all of the transport equipment.

Trucks with autonomous technology are equipped with high-precision GPS systems, allowing the operator to track their position in real time and manage them from the control room. They are also equipped with wireless communication systems, which allow for continuous flow of information with the control room, and obstacle detection sensors, which enable detection of the presence of other equipment and people in the vicinity and judgment of whether to slow down or stop completely (Rivera, 2014).

Using simulation software, Parreira and Meech (2012) modeled an open pit to compare some performance indicators between systems of autonomous and conventional trucks. Tan et al. (2012) developed and applied a computational optimization simulation model to support the management of operations in an open pit copper mine, while Guimarães et al. (2007) developed a computational simulation model to validate the results of a mathematical programming model for dynamic truck allocation in order to meet quality and production targets in open-pit mines.

6.3 METHODOLOGY

The data used to conduct this research were drawn from the database of an FMS implemented in a mining company located in Brazil. The data sent by the mine equipment were stored in a server, thus allowing for frequent queries and the generation of reliable information. The system database contained the operation logs, and customized reports were generated in real time, using predetermined queries in SQL, on the data collected during the operations.

The software used to perform the simulations was the Delphos Open Pit Simulator (DSIM), a discrete event simulation tool developed at the Advanced Technological Mining Center (AMTC) at the University of Chile. DSIM can estimate the production of a mining plan from three basic elements: the mine layout (topography, operation fronts and routes), the fleet of cargo and transportation equipment, and a detailed production plan.

A simulation was first performed in order to validate the actual operation and to compare it with the information from DSIM. Information representing one day of operation of the mine under study, with a duration of 24 h, was input to the simulator. The following variables were set in the software: a detailed production plan including origins and destinations; operational losses (reasons for stopping the equipment); Mean Time Between Failure (MTBF); Mean Time To Repair (MTTR); average speed; distributions of values related to loading times, download time and queue time.

On the day modeled in the simulation, the layout of the mine consisted of nine mining fronts and 12 destinations, including two crushers and one stock. The topography and routes used are shown in Figure 22. The layout also included a parking lot, from which the trucks left after the shift.

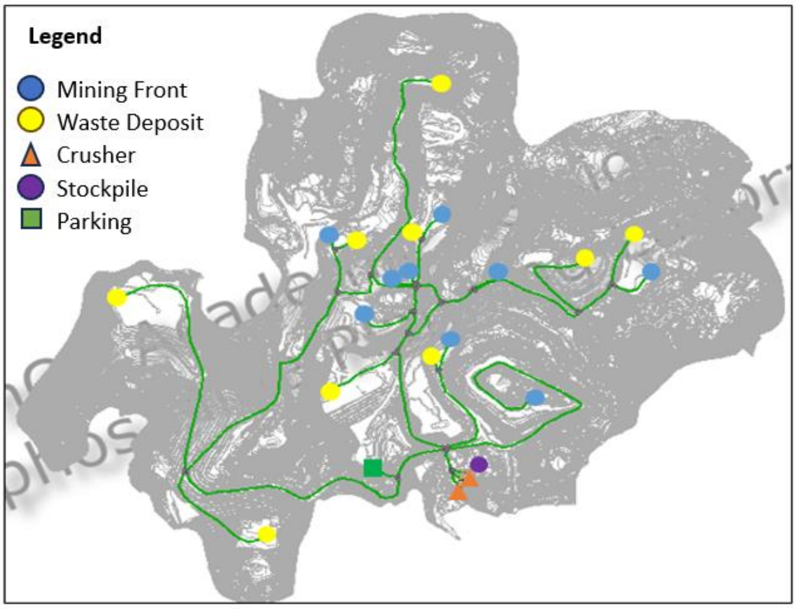

Figure 22 - Topographic map of the mine with the paths used

Source: Personnel file

Simulation 1 involved 100 replicates, and the results can be seen in Figure 23 and Table 8. The deviations identified in the indicators mass and hours worked in the transport fleet were satisfactory and representative. The model was validated, and new simulations were carried out.

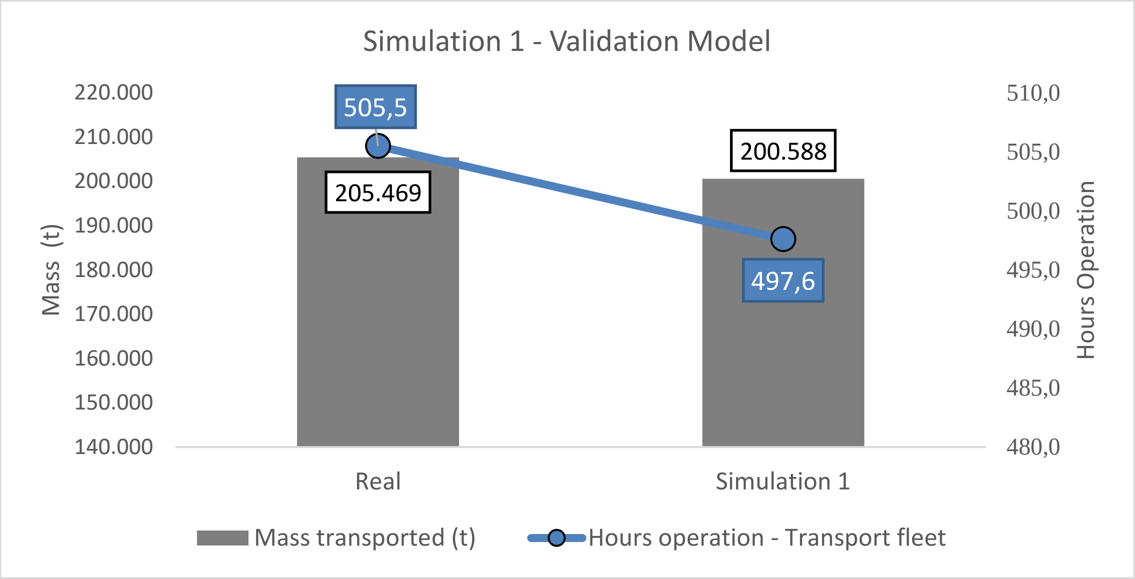

Figure 23 - Results of simulation 1

Source: Author’s elaboration

Table 8 summarizes the differences between the data on the actual operation and those obtained from the simulator.

Table 8 - Result of Simulation 1 and model validation

Indicator	Δ (1/real)
Mass (t)	-2.4%
Hours - Haulage fleet	-1.6%

Source: Author’s elaboration

When the model had been validated, two more simulation scenarios were considered, and were compared with Simulation 1.

6.3.1 Simulation 2

Operation with speed stipulated through the 3rd quartile.

This scenario involved a simulation of the operational improvements that could be achieved in the mine from implementing the autonomous technology, which has a direct impact on the average speed of the trucks. The simulation included the preliminary activities needed before introducing the autonomous technology. Based on a statistical analysis, the average fleet speed was stratified for each mine operator, and was calculated through the normal distribution the value of its 3rd quartile, as shown in Table 9.

Table 9 - Average speeds for different haulage profiles

AVERAGE SPEEDS						
	Empty Trucks			**Loaded Trucks**		
	Lower Level	Plane	Upper Level	Lower Level	Plane	Upper Level
Average Speed (km/h)	25.26	26.75	25.02	16.98	17.83	15.23
Third quartile (km/h)	29.13	30.85	28.85	19.35	20.32	17.35
% operators third quartile	12.39%			15.31%		

Source: Author’s elaboration

It can be seen that there are several operators that already practice simulated speed through the third quartile. In addition to the improvements from the conditions discussed above, the training of the operators is shown with great importance to leverage the results.

6.3.2 Simulation 3

Autonomous operation with speed stipulated through the third quartile.

Autonomous operation was modeled in the simulator by excluding the operational stops of the trucks that were directly associated with the operators. The reasons for stopping that were eliminated were shift changes, fog, meetings, meals, lack of available operators, checklists, inspections, operator displacement, physiological needs, and tiredness of the operator. These stops were replaced by continuous operation of the equipment.

6.4 CASE STUDY

The case study considered here was based on a mine located in the Brazilian state of Minas

Gerais. The company is notable for the extraction of iron ore of high content, and for having an integrated system of distribution of its production formed by [mine - railroad - port] that supports the attendance of all the current operations from the production, haulage, and shipment of the ore for export.

The objective of the research was to simulate three different mine scenarios, and to compare the results from operational improvements and autonomous operation. The results were then analyzed based on mine operation indicators such as the transported mass (t), the utilization (%) and productivity (t/h) of the load and transportation equipment, the index of loading queues (%), and the idle index for the loading equipment (%).

The autonomous equipment technology relies on the presence of sensors and positioning projections, and analyzes information obtained from the embedded telemetry system. Events such as high braking rates, pressure variations between the suspensions, and high rolling resistance can cause reductions in speed and even shutdown of the equipment.

In projects relating to the implementation of autonomous equipment in mining, it is necessary to avoid the problems that the technology can cause. Unnecessary equipment stops can occur in situations where the system identifies risks to the equipment. The main factors that need to be analyzed at the outset of a project include:

- The width of the loading locations.
- The construction, design, and maintenance of access roads.
- Clovers and crosses.
- The impact of the presence of auxiliary equipment in the mine (tractors, motor graders, vans).
- The drainage plans.
- Operational interventions (displacements, quality control, and detonations, among others).

Ensuring the adequacy of these parameters is essential in order to maximize the benefits of an autonomous mine project.

6.5 RESULTS

The results of the simulations can be seen in Figures 24 to 26.

Simulation 2 resulted in a 5% increase in the mass moved during the simulated period of one day of operation, and a 4% reduction in the effective use of haulage equipment. Simulation 3 was 16% more productive, with a 6% increase in the actual use of the trucks.

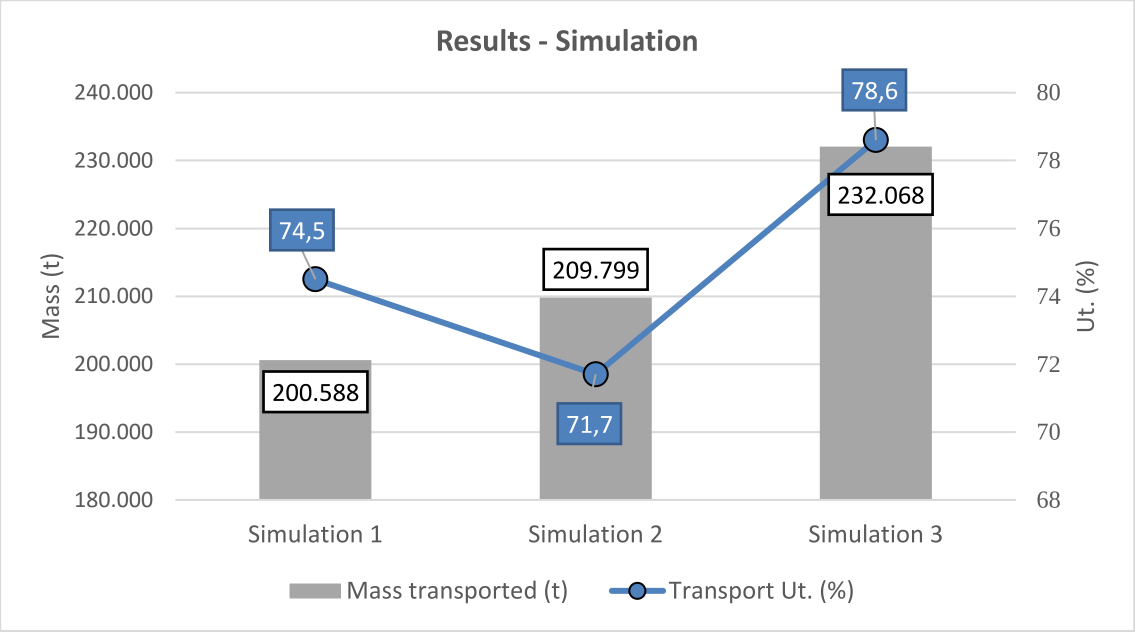

Figure 24 - Results for mass transported (t) and use (Ut.) of haulage equipment (%)

Source: Author's elaboration

The results for the haulage equipment are shown in Figure 25, and it can be seen that the indicator of loading queues rises as the mass increases. This means that there is an excess number of trucks used in the operation, and hence a possibility of reducing the haulage fleet. This effect related to queues can also be seen in haulage productivity. The indicator increases by 6% in Simulation 2, but is reduced by 2% in comparison with the autonomous scenario, influenced by the increase in the queues.

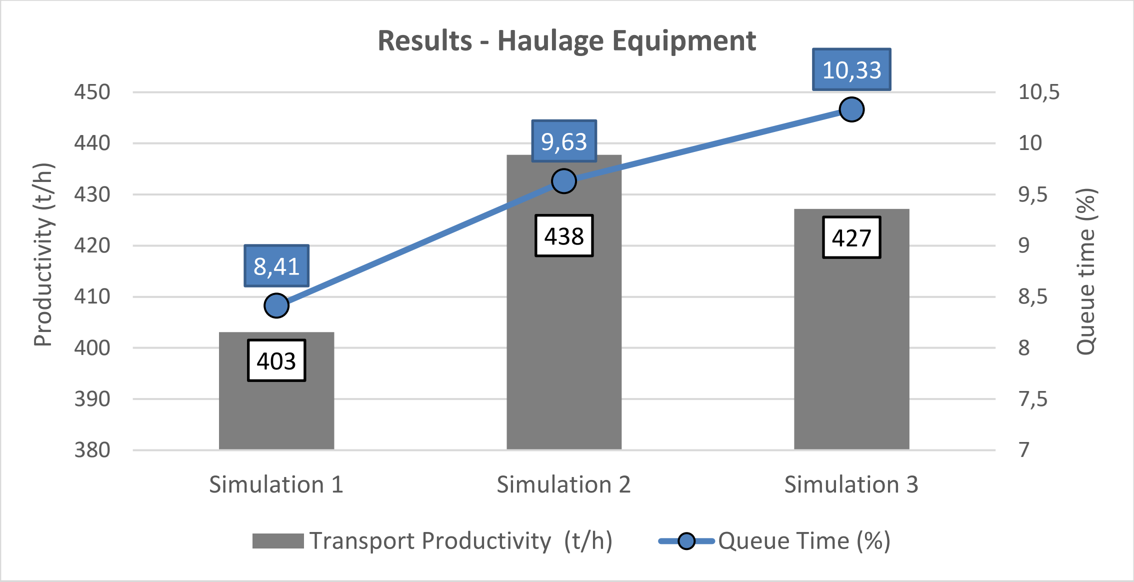

Figure 25 - Results related to haulage equipment

Source: Author's elaboration

The usage of the load equipment increased by 17% following implementation of the autonomous equipment fleet. This shows that the current operation, as modeled in Simulation 1, has a larger dimensioning in loading and excessive equipment available. The loading productivity increased by 25%, mainly due to the 31% reduction in equipment idleness.

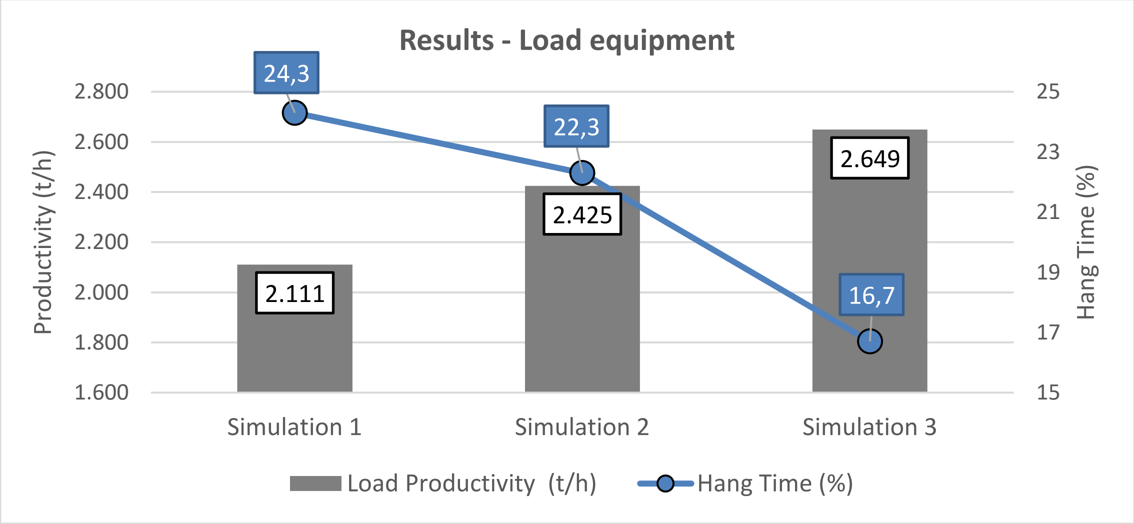

Figure 26 - Results related to load equipment

Source: Author's elaboration

Table 10 shows the results of the tests and a comparison of the simulated scenarios.

Table 10 - Simulation results and the variations between them

Simulation Results				**Δ (%)**		
	Simulation 1	Simulation 2	Simulation 3	Δ (2/1)	Δ (3/1)	Δ (3/2)
Mass transported (t)	200,588	209,799	232,068	5%	16%	11%
Haulage Productivity (t/h)	403	438	427	9%	6%	-2%
Haulage Ut. (%)	74.5	71.7	78.6	-4%	6%	10%
Queue Time (%)	8.41	9.63	10.33	15%	23%	7%
Load Productivity (t/h)	2,111	2,425	2,649	15%	25%	9%
Load Ut. (%)	55.7	63.3	65	14%	17%	3%
Hang Time (%)	24.3	22.3	16.7	-8%	-31%	-25%

7. CONTRIBUTIONS AND FINAL CONSIDERATIONS

DT is emerging as a driver of radical change in the world. In the mining industry, it is a transformative agent that is altering the strategic aims of companies and their interactions with stakeholders, workers, communities, and the environment. It has also blurred the boundaries of traditional industry and enabled the development of new operating models with a more agile and profitable business concept.

Technology plays a key role in managing mining operations, automating tasks, and generating valuable insights; however, it is critical to recognize that technology is only one part of the foundation that underpins DT. When implementing technological solutions in mining operations, it is essential to analyze business rules that relate to production processes and to hire key people to conduct the projects. In this way, the introduction of technology and innovation in the mining industry can create more market opportunities, improve efficiency, and optimize operations by producing real-time data on equipment and processes.

In the corporate context, interpersonal skills are highly sought after by companies in a variety of sectors, as they contribute to a healthier, more diverse, and productive organizational environment.

With a view to the success of projects related to the digital transformation of mining companies and the interaction of people with various processes and the implementation of new technologies, the following skills can be highlighted: Good verbal and written communication; Emotional intelligence; Ability to work in a team: Resilience; Ability to solve problems in an agile way and technical knowledge about Technology and Information Technology.

In order to improve the interaction between people, processes, and technology, people need to be prepared to deal with the changes, challenges, and opportunities that arise in this context. Interpersonal skills enable people to communicate better, collaborate more, solve problems more quickly and creatively, learn faster, and become more engaged with the organization's objectives. They also contribute to building a more innovative, inclusive, and sustainable organizational culture.

Therefore, developing interpersonal skills is a necessity to ensure the success of digital transformation in organizations. To this end, it is important to invest in training, feedback, recognition, and incentives that encourage the development of these skills in your employees. In this way, they will be able to count on teams that are better prepared to face the challenges of the digital world.

Finally, it can be concluded that although technology is the engine that drives the management of mining operations, it is the continuous improvement in production processes and personnel training that ensures success.

8. CONCLUSIONS

The conclusions chapter was divided into 5 topics, referring to each article and subject covered in this thesis.

8.1 HUMAN FACTORS ASSOCIATED WITH OPERATIONAL MANAGEMENT TECHNOLOGY IN MINING

The research findings in regard to the human factors associated with operational management technology in mining are as follows. This research focused on the importance of the role of people in technological solutions for the management of mining operations. It has also described the cultural challenges that exist in the sector in terms of training. A case study was presented to demonstrate the potential improvements in operational efficiency generated by trained professionals. For instance, the productive capacity of the haulage fleet increased by 19%, corresponding to 17 additional loads loaded and transported per effective working day.

The differences between professionals with high and low levels of qualification, in addition to compromising the competitiveness of companies in the market, can determine the success or failure of expert systems and operation centers. Thus, mining managers' understanding of the importance of people in operations and the high potential for cost reduction is fundamental to the pursuit of operational excellence.

The benefits generated by innovation can be maximized and capitalized on through training, education and recruitment. It is therefore necessary to look for people with the right profile to carry out activities that involve taking immediate decisions, and valuing professionals who perform their work efficiently. The future of mining must include people with extensive technical skills in addition to analytical and behavioral skills, to further the search for better decision-making actions aided by technology.

The main challenges or obstacles to the success of operational management are currently a lack of trained professionals, ineffective training systems, inadequate strategies for motivating and retaining people, and low awareness of the importance of digitization in the mineral industry as a whole. We can conclude that workers need to acquire new skills, and that it is vital to make periodic updates to the work routine. There is therefore a need to develop appropriate training practices in order to adapt to a work environment that is constantly evolving. The benefits of implementing a new training approach extend beyond improvements in work safety, environmental impacts and cost reduction, and may also include personal development, career planning and evolution of the decision-making process.

8.2 AN INNOVATIVE CYBER-PHYSICAL SYSTEM AIMED AT INCREASING PRODUCTIVITY IN THE MINING INDUSTRY

The research findings on the cyber-physical system that was developed to increase the productivity of loading equipment are as follows. Specific, real-time information can help managers to make decisions with a focus on improving the mining production process. Good data management practices and effective uses of data are also vital in order to realize the value of technology. The use of data analytics techniques to generate continuous improvement has been the focus of various researchers and mining specialists.

This study has reviewed the main factors that impact the implementation of this technology, and has compared the operational impacts to the result of the operation. These gains tend to increase over the years, offering the possibility of using the system and expanding the methodology for controlling operational indicators for haulage equipment.

The analysis and implementation of this work made it possible to raise the productivity level of the loading fleet of a mine through more efficient management, with rapid identification of operational abnormalities using new data analysis technologies. In addition, digital technology associated with people and process management enabled an increase in the productivity of the shovels by 4.71%, with a concomitant reduction of 28.4 t of CO_2 emissions per year.

The use of new technologies in mine operating processes may add beneficial features to existing processes, resulting in effective productivity gains, reductions in greenhouse gas emissions, higher cost savings, and great competitive advantage to companies. A knowledge of mining and the benefits associated with mathematics (statistics) and computer science (programming) enables the generation of studies, and artificial intelligence (AI) methods of process optimization and problem-solving.

8.3 USE OF TELEMETRY TO MANAGE OPERATIONAL PROCESSES IN MINING

The results illustrate the importance of the implementation of telemetry for the management of operational processes and maintenance control in mining. The actions taken as part of the case study provided an increase in the reliability and availability of equipment, thereby contributing to the sustainability of the business. Monitoring of processes is a determining factor in the cultural change experienced by those involved in the production chain, meaning that a combination of the use of technology with human factors is the key ingredient for achieving results.

The implementation of an on-board telemetry system for mining transport equipment has led to the creation of a variety of control points, from methodologies for managing the maintenance of mine roads, monitoring the frequency of refueling and controlling the volume of diesel fuel supplied by the equipment, to monitoring the temperature of the brake cooling oil. The benefits are immense, mainly in terms of the safety of drivers and equipment and also in terms of sustainability, as well-executed operations reduce fuel consumption and greenhouse gas emissions.

This justifies the need for new information technology with the aim of identifying, understanding, avoiding, or minimizing the weak points and problems that cause undesirable results in an organization. When data are obtained through telemetry, it is possible to create efficient management systems in which resources are optimized and used more effectively, thus significantly improving the performance of the equipment and the production process.

8.4 USE OF HIGH-PRECISION GPS IN MINING

This thesis has presented an innovative tool that was developed for the analysis and monitoring of the drainage of loading squares. The methodology was based on a comparison of routine drainage control actions performed by the surveying team with a drainage system that relied on high-precision coordinates. The two methodologies were compared with the drainage plan issued by the mine planning team. The objective of the work was to develop a product that enabled mine operators and managers to identify the exact points at which water is directed to the loading area. Another important issue is the identification of critical points in the direction of surface drainage of the mine, which directly affect the execution of the production process.

It was found that the use of this approach enabled faster identification of deviations in the operational indicators for the mine, and that it was easier to guide the loading and infrastructure operators. This finding paves the way for reductions in the companies' production operating costs by increasing the productivity of the mine loading and transportation equipment. In addition, it can enable improvements in the safety of operations through the reduction of manual activities and the number of people exposed to hazards, and can optimize the life of the mineral deposit via real-time ROM quality control.

The results include improved performance and confidence for the loading operator, who can more easily recognize the type of material being excavated and hence differentiate ore from waste with greater assurance. We can conclude that the use of high-precision GPS in mining can offer competitive advantages to the mineral sector, and can increase its efficiency, sustainability, and safety.

8.5 PERFORMANCE ANALYSIS OF MINING EQUIPMENT THROUGH SIMULATIONS OF THE USE OF AUTONOMOUS TRUCKS

The research findings from the performance analysis of mining equipment through simulations of the use of autonomous trucks are as follows. In view of the recent advances in technology and its incorporation in the mineral sector, studies of the automation of transport systems in open-pit mines are very important. The objective of the simulations was to evaluate the potential gains from the introduction of autonomous equipment into the operation of the mine.

Maximization of the benefits from the implementation of autonomous technology requires some adjustments and standardization of the mine layout, such as accesses, square widths, operational stops and the number of auxiliary equipment that travel with the production equipment. However, the results presented here show significant gains in terms of increased productivity and the use of haulage equipment. Another point of great importance is the possibility of reducing the number of vehicles needed to execute the production plan. A technical-economic analysis of each site is required to make the implementation of autonomous transport systems feasible.

The main benefit of this technology is the elimination of manual incidents and accidents that originate from distraction and fatigue of the operators. The economic value of the system is also maximized by reducing the maintenance costs, as the equipment is used more consistently and is better managed under the control of software.

Each mine project has unique variables, such as climatic and geotechnical conditions, types of material, size of equipment, volume of production, among others. As a result, different setpoints are required for each project. For the industry as a whole to adapt to this challenge, innovative leadership will be required, with appropriate decisions on the acquisition of new technologies, the definition of processes, and the allocation of talent and financial resources.

8.6 RESEARCH LIMITATIONS AND BOUNDARIES

Studies on digital transformation in mining operations face some limitations that can affect the scope of the research. Some of these limitations include:

- Scale and context: Mining activities vary in scale, location, and context, which makes it difficult to generalize study results to different situations and other sites.
- Security and privacy: Much data related to mine operations is sensitive and protected by security and privacy concerns. This can limit access to critical information for research.
- Technological maturity: The technological maturity of mining operations can vary, which affects the viability and relevance of digital solutions in different scenarios.
- Resistance to change: Digital transformation often faces cultural and organizational resistance within mining companies, which can limit the adoption and effectiveness of innovations.

This research did not evaluate or develop operational management tools based on the concepts of Artificial Intelligence, Machine Learning, and Blockchain.

9. SUGGESTIONS FOR FURTHER RESEARCH

This research could be extended by carrying out practical work on the tools and technologies that have recently been integrated into mining, such as drones, real data from autonomous and semi-autonomous operations, training simulators, and fatigue avoidance systems, among others.

Another technological approach that has been gaining ground in the mining industry is Artificial Intelligence, which has strong potential in terms of identifying operational bottlenecks, carrying out automatic data analysis, and providing virtual assistants such as chatbots. Suggestions for further research in this field:

- Optimization of Extraction Processes: Develop algorithms to optimize drilling, blasting and ore transport processes, maximizing efficiency, and minimizing waste.
- Predictive Maintenance of Equipment: Create AI models to predict failures in mining equipment, enabling proactive maintenance, and reducing downtime.
- Mine Safety: Using computer vision techniques to monitor the safety of workers in the mine, identifying risky behavior, and implementing preventive measures.
- Risk Assessment and Geology: Develop algorithms to analyze geological data and predict risks of landslides, collapses and other emergencies, helping to make safe decisions.
- Mine Simulation and Modeling: Develop simulation models using AI to predict mine behavior in different scenarios, aiding strategic planning, and decision-making.
- Reinforcement Learning for Equipment Control: Implement reinforcement learning algorithms to train autonomous equipment, such as trucks and drills, to continuously improve their operations.
- Socio-economic Impact Assessment: Develop predictive models to assess the socio-economic impact of mining operations on local communities, considering factors such as employment, the local economy, and quality of life.

Furthermore, with the increasing volume of data provided by onboard systems such as telemetry and GPS, it is possible to identify unique operational patterns for each mining project. This data, if properly processed and correlated with appropriate sources, can generate valuable insights for improvements in ESG issues and operating costs.

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APPENDIX A. Statistical analysis of loading productivity

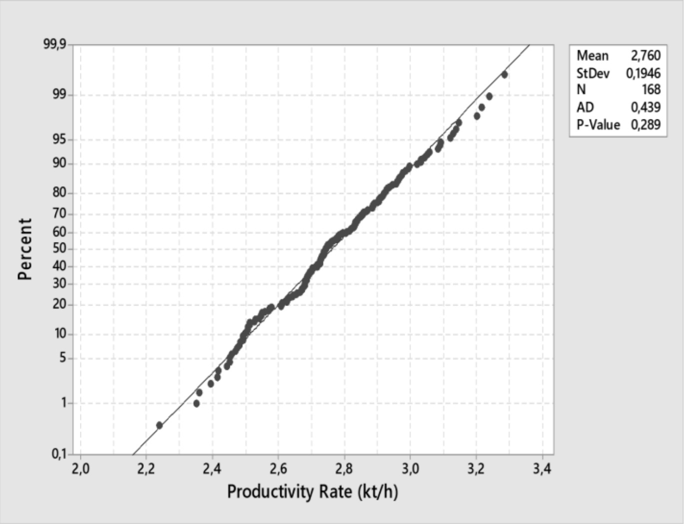

Figure 27 – Normality test for loading Productivity Rate.

Source: Author’s elaboration