HOW CONTINUOUS IMPROVEMENT METHODOLOGY – LEAN SIX SIGMA CAN INCREASE THE PRODUCTIVITY OF LOADING AND HAULING EQUIPMENT

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ABSTRACT

The objective of this work is to increase the productivity of truck and excavator fleets using Lean Six Sigma methodology in the mine production process. The application of the Lean Six Sigma methodology has proven to be highly effective in several areas, for improving processes through the use of statistical tools for problem identification, cause analysis, optimization actions, resolution, sustainability and improvement of results, thus being a powerful methodology for companies seeking operational excellence and greater competitiveness. The fleet of excavators and trucks are the main equipment for material handling and production in the mine, in which through a case study it is possible to evidence the use of statistical tools in the development and identification of problems that affect productivity. In this case study, it is possible to demonstrate the application of all stages of the Lean Six Sigma methodology – DMAIC (Define, measure, analyse, improve, control), as a result of this project, it was possible to increase the overall productivity of the trucks of about 21% and an increase in the effective productivity of the excavators of around 31%, thus generating relevant financial gains estimated at R$ 4,502,141 per year and non-financial gains with improved safety conditions, well-being of employees and reduction of carbon emissions by saving hours operated and diesel. The gain from reducing carbon emissions is estimated at 3,056 tons of carbon per year. In addition to the project's gains, the development of a culture of continuous improvement can be observed.

Keywords: Lean Six Sigma. Mining. Productivity. Infrastructure. Continuous improvement.

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INTRODUCTION

The objective of this work is to increase the productivity of truck and excavator fleets using Lean Six Sigma methodology in the mine production process. The application of the Lean Six Sigma methodology has proven to be highly effective in several areas, for improving processes through the use of statistical tools for problem identification, cause analysis, optimization actions, resolution, sustainability and improvement of results, thus being a powerful methodology for companies seeking operational excellence and greater competitiveness.

The open-pit method is the predominant one in the world's exploitation, covering 98% of the metallic ore mines and 97% of the non-metallic ores in the United States (Hartman and Mutmansky 2002). The mine in this case study fits this profile, using trucks and excavators for the extraction and transportation of the ore. The cost of transportation can be as high as 50% of a mine's costs. The productivity of the trucks is correlated by the average speed developed during the truck's journey (Hustrulid, 2013), other factors such as the average load transported and the conditions of the accesses are paramount for the fulfillment of good productivity in the mine.

In a study developed by Oliveira (2023), he presents results of increased productivity of 13% for the Caterpillar fleet and 10.8% for the Komatsu fleet.

Continuous improvement tools are methods used to constantly improve processes, products, and services. The objective is to increase efficiency, quality, and customer satisfaction, reducing waste and identifying opportunities for improvement according to Leão et al (2024).

The combination of Lean philosophies, focused on eliminating waste and non-essential activities, with the Six Sigma approach, dedicated to reducing variations and defects, becomes a catalyst for increased efficiency and effectiveness in the mining industry. Optimized workflows, better resource utilization, and higher product quality result in significant benefits for mining operations, such as reduced costs and increased productivity (Perez-Wilson, 1999).

The general objective of this article is to demonstrate how the application of the Lean Six Sigma methodology with a set of techniques and procedures can increase productivity in the mining sector, thus forming a reference material for professionals in the sector, thus fostering its use for the development of a culture of continuous improvement.

THEORETICAL FRAMEWORK

The methodology is widely used in mining, as an example, the work done by Silva (2019) can be cited, where from the use of the methodology, it was possible to obtain an increase in the drilling rate of a drill in the clean water mine by 13%, which resulted in a financial gain of R$ 275,025.16 for the company. For this, the author did a research on the history of the drilling rate to define an average of how much the company drilled over time, in addition to site visits and analysis of the materials used and the professionals working. From there, the author suggested some changes such as increasing the drilling place, sharpening the bits more frequently, adjusting the air pressure and feed according to the lithology of the site and more trained workers. The results were analyzed for six months.

In a case study developed by Pedrosa et al (2014) in the maintenance area, Six Sigma is an important ally in unveiling the main losses by identifying the cause-problem, determining blocking actions and solving problems that negatively interfere with performance indicators. Although recent and still lacking some adjustments in the conduct of Six Sigma projects, the results obtained so far confirm the potential to achieve the organization's strategic goals.

The Lean Six Sigma methodology was used by Pereira et. al (2021) for the increase in the operational efficiency of the High Intensity Magnetic Separation stage, given the fact that the metallurgical recovery was, on average, 7.21% lower than the expected value. The execution of the project was carried out following the DMAIC cycle, where the investigations carried out showed that 52.3% of the root causes were attributed to the operation of the equipment itself (magnetic separator). Interventions in the process and adjustments in the operation of the separator resulted in an increase of 9.66% in the average metallurgical recovery, which was 1.75% higher than the established goal (94.63%). A 65.66% reduction in the standard deviation of this variable was also observed, which translates into a reduction in the overall variability of the process.

In his master's thesis, Coutinho (2017) presents a set of continuous improvement projects applied in unit loading and transportation operations, in open-pit mining. Based on the Lean Six Sigma methodology, on good practices analyzed and on data collected in the field, some process improvements were applied, composing three case studies: a project to reduce the cost of tires, a project to increase the productivity of the trucks and a project to increase the production in the belt system, resulting in estimated financial gains in the order of R$ 31.6 million per year. in addition to gains in reducing environmental impact and increasing safety in mine operations.

Fleet management systems, such as smartime, among others, used in the company, provide information to identify failures and help in the management of the operation. These are applications that help automate the management of trucks and excavators, allow analysis of indicators, maximize production and minimize operating expenses from decision-making using real-time information. Therefore, it maximizes the use of the equipment and reduces operating costs (Campelo, 2018).

METHODOLOGY

This article was based on a historical database of a Brazilian mining company, located in Minas Gerais, focusing on the extraction, processing and commercialization of iron ore. The mine has a high annual production capacity and products with a high standard of quality. The database consists of information on loading and transport equipment managed by the fleet management system at the mine (Smartmine) in the period of 12 months of production. The data collected were mass transported, origin, destination, type of equipment, load times, transport times, hours operated, transport distance, among others. With the historical data, the project began.

Using techniques, graphs and statistical tools within them boxplot, histogram, pareto chart, among others, he applied the lean six Sigma methodology combined with the DMAIC cycle (Define, measure, analyse, improve, control). Lean Six Sigma - DMAIC is a methodology with a structured roadmap, which aims to identify and eliminate inefficiencies, ensuring the quality and efficiency of processes. In the Define phase, the problem or opportunity is clearly identified and documented. Then, in the Measure phase, relevant data is collected to understand the extent of the problem. The Analyze phase involves identifying the root causes of problems. In the Improve phase, solutions are implemented to eliminate the identified root causes. Finally, in the Control phase, mechanisms are established to ensure that improvements are sustainable over time (PACHECO, 2014). Rigorous application of these steps allows organizations to achieve significant results in terms of operational efficiency and quality.

Each of these steps has a specific objective to achieve the expected improvement result, which in this case will be increased productivity in cargo and transportation operations.

EQUIPMENT USED

The transport operation at the mine is carried out by off-highway diesel trucks with a payload capacity of 60t. The excavation and loading equipment has a payload capacity of

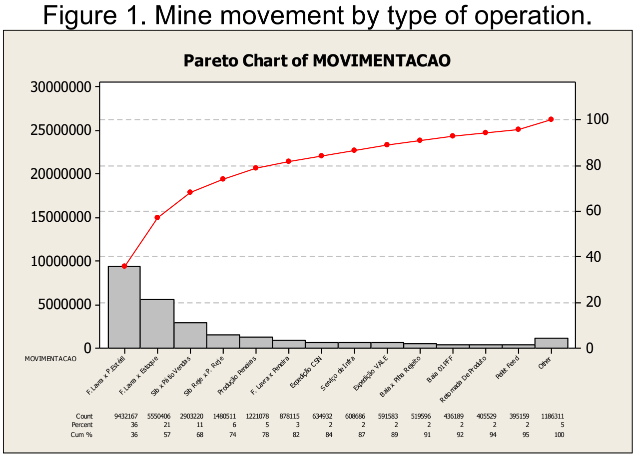
4.6 m³~12t (itabirite ore). These equipment form an ideal set of cargo and transport due to their potential specifications and dimensions, generating around 5 passes for each load. According to PERONI (2015) and COUTINHO (2017), the optimal ratio of the number of passes should not be less than three and not more than six.

LEAN SIGMA METHODOLOGY - DEFINE PHASE

The first step in the development of a lean six sigma work consists of identifying and defining the opportunity for improvement, a step known as Define, through the DMAIC cycle (Define, measure, analyse, improve and control). Through a survey of performance data we can identify the need for improvements, it was identified for this case the need to improve the productivity of loading and transport equipment, which is one of the main KPI´s (Key performance indicators) of the mine. Loading and transportation operations are carried out for various materials, such as ore, overburden, products, tailings, basin cleaning, infrastructure, among others. In order to identify which of these operations directly influence the project indicator, the Pareto test was performed.

Vilfredo Pareto, creator of the Pareto Diagram, was born in 1848 in Paris and was a sociologist, political theorist and economist. (BEZZERA, 2019). The Pareto Chart is considered one of the seven basic tools of quality and has as its principle that 80% of the consequences come from 20% of the causes. According to Koch (2015), the 80/20 principle states that there is an imbalance between causes and results, where the majority have low impact and the small majority have high impact. From the pareto test applied to the project data (Figure 1), ore operations were identified as priority operations as they represent the majority of operations with about 57% of the total movement in the mine. In this way, opportunities in the loading and transportation operations of ore and waste rock were prioritized.

Figure 1. Mine movement by type of operation.



Source: authors, 2024.

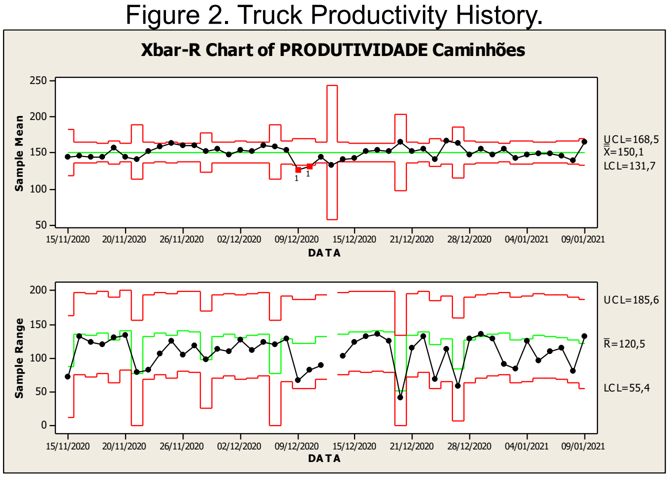
LEAN SIGMA METHODOLOGY - MESURE AND ANALYSE PHASE

The use of graphs and statistical bases are used in defining an achievable and challenging goal for the project. Figures 2 and 3 represent the productivity and normality test graphs of the truck fleet and figures 4 and 5 represent the excavation fleet.

The productivity history carried out by the control chart aims to identify stability (inside or outside control) and process healthiness (variability over time).

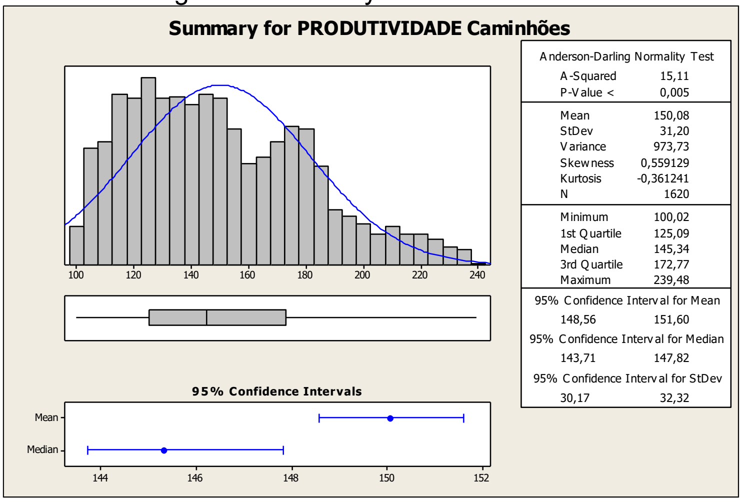
Normality tests are carried out to verify that the data are part of a normal and predictable distribution, which will influence the statistical analyses and methods to be developed throughout the project. To define the goal of the project, the normality test was used with the Anderson Darling Test 3rd quartile method. This method divides the data into four parts, in which each part represents the average of 25% of the results, with the 3rd quartile representing 25% of the best results in the historical productivity base, establishing the project goal for the truck transport fleet of 172.77 t/h (Figure 3 – Anderson Darling 3rd Quartile). In the excavator fleet, the mean confidence interval was used, using the maximum and minimum limits identified by the normality test (Figure 4 – Anderson Darling 95% Interval for Mean), highest average productivity: 540.98 / lowest average productivity: 513.43 * global average productivity: 527.21, establishing a target for the excavator fleet of 555 t/h.

Figure 2. Truck Productivity History.



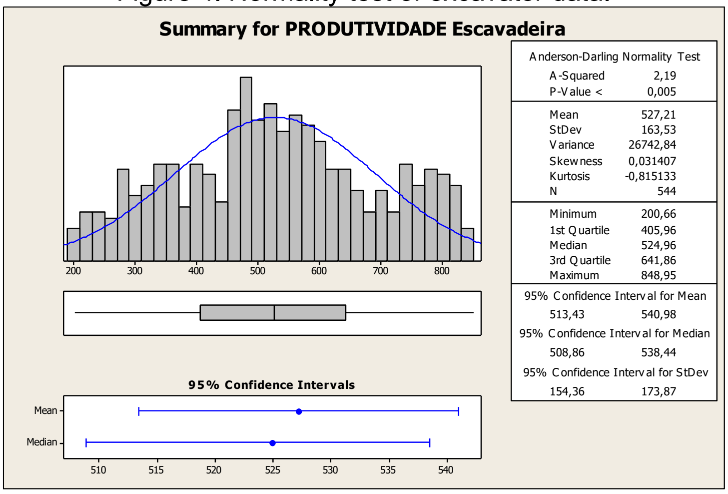
Source: authors, 2024.

Figure 3. Normality test of truck data.



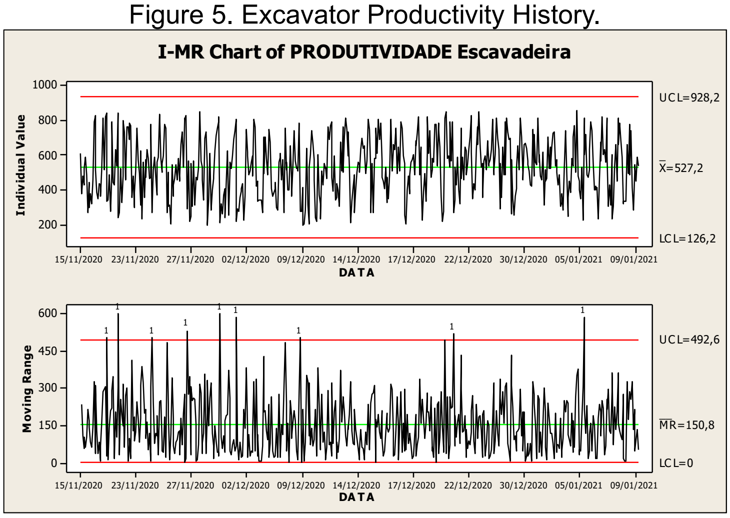
Source: authors, 2024.

Figure 4. Normality test of excavator data.



Source: authors, 2024.

Figure 5. Excavator Productivity History.



Source: authors, 2024.

The productivity of the equipment is calculated through the mass moved divided by the hours operated, productivity = mass moved (t) / hours operated (h). The increase in productivity generates a reduction in hours operated, since the process was more productive, we made the same dough with fewer hours, that is, the type of gain is avoided cost. The formula is used to calculate the financial and environmental benefit of the project.

Project Gain (h) = [(Mplanned / Prod.fin) - (Mplanned / Prod.ant)] * Ccost R$/h (1)

- Planned Mass of Waste Waste and Ore Handling (t): (Mplanned)
- Productivity before (t/h): Prod.ant truck ; Prod.ant excavator
- Productivity After(t/h): Prod.fin Truck; Excavator Prod.fin
- Equipment operating cost (R$/h): Truck cost + Excavator cost
- Productivity gain target in the truck fleet (t/h): Truck fin product: 173 - Truck product: 150: 23 t/h, estimated gain of 15%;
- Productivity gain target in the excavation fleet (t/h): Excavator end product: 556 - Excavator product: 488: 68 t/h, estimated gain of 14%;]

With the estimated gain in reduction of hours, we can estimate the cost avoided over one year of project operation (R$) = 634 thousand reais per year (Formula 2)

Project financial benefit (R$/year) = Project gain (h) * Ccost R$/h (2)

An extremely relevant benefit for our current situation is the environmental one, which with this project we will gain in reducing carbon emissions. With the estimated gain in hours reduction, we can estimate the carbon emission reduction = 500t/year equivalent to a 13% reduction;

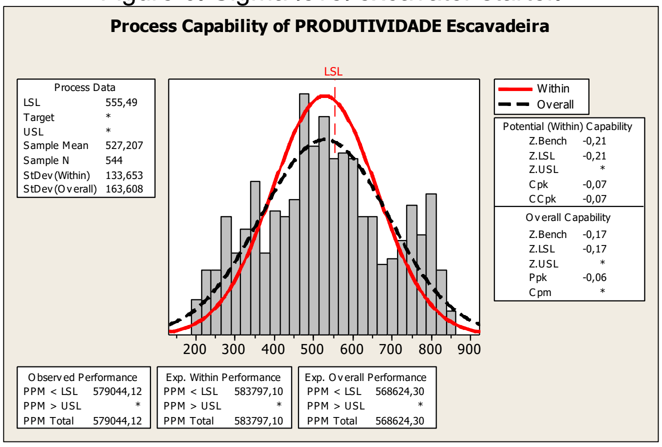
Environmental benefit of the project (carbon emission reduction/year) = Project gain (h) * Carbon emission/hr (3)

With the definition of the project scope, goal and calculated gain, a thorough analysis was initiated to measure the problem, measurement stage (Measure) using several tools applied from Lean Sigma. The first step was to calculate the sigma level of the project (capability) so that we can see the current loss level of the process. It indicates the probability of defects occurring and helps organizations direct their improvement efforts, representing how many standard deviations (sigma) fit between the process average and the nearest specification limit. A process with sigma level 6, for example, has a very low probability of producing defects, with only 3.4 defects per million opportunities.

The sigma level is determined by the number of failures in the process, for mine equipment it was calculated based on historical data and the productivity target stipulated as a reference (trucks: 173 t/h and excavators: 556 t/h), where all productivity data that is below the target would be a failure.

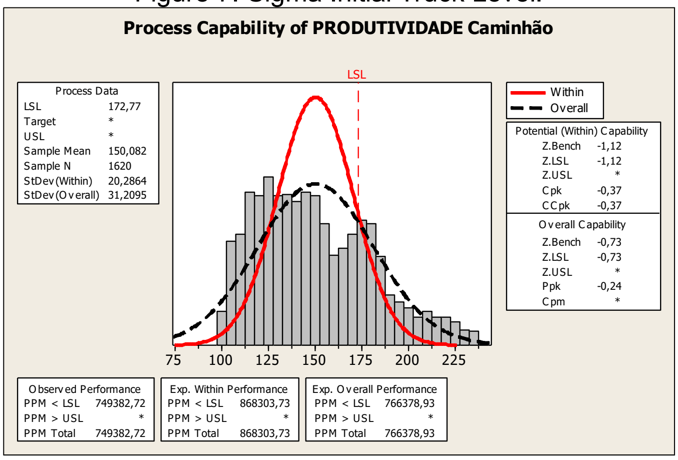
In the graphs below, we have the graph of productivity capability in cargo equipment (Figure 6) and transport equipment (Figure 7). In the graph of the excavators, the LSL (upper specification limit) was used at 556 t/h, which is the goal of the project, thus generating a sigma level of -0.17 (Z.LSL) which, added to 1.5 (convergence factor), generates a current level of 1.33 sigma. In the truck graph, the LSL (upper specification limit) was used at 173 t/h, which is the target of the project, thus generating a sigma level of -0.73 (Z.LSL) that added to 1.5 (convergence factor) generates a current level of 0.77 sigma.

Figure 6. Sigma level excavator starter.



Source: authors, 2024.

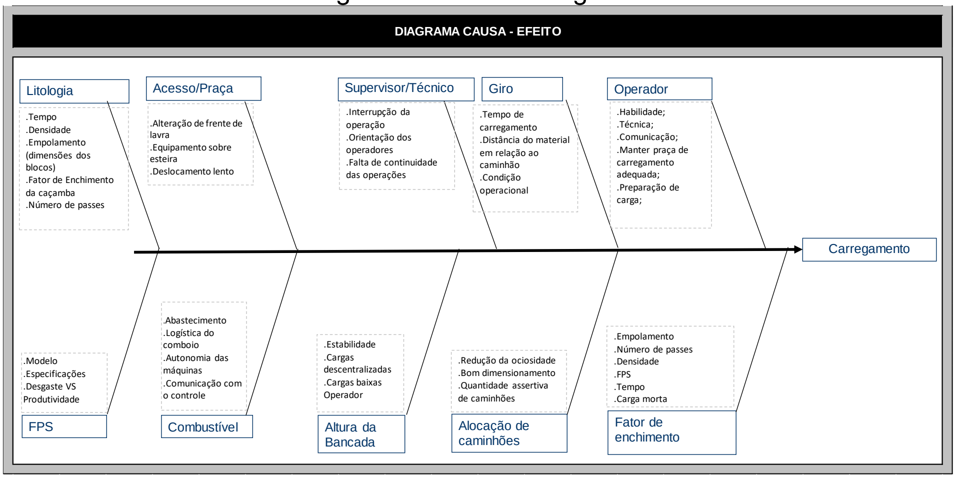
Figure 7. Sigma Initial Truck Level.



Source: authors, 2024.

The next stage of the project is the analysis phase (Analyze) of the DMAIC methodology, in which analyses of the problems were generated to identify the causes, using some tools such as the Ishikawa Diagram (fishbone).

Figure 8. Ishikawa diagram.



Source: authors, 2024.

All variables (x's) throughout the mine production process that influence the productivity process were then identified, being quantified in 35. Therefore, there was a need to use the prioritization matrices to determine the main variables (x's) to be improved. The effort x impact matrix was generated, where the variables (x's) of high impact with low effort, high impact with high effort, low impact and low effort respectively were prioritized, and the items identified as low impact and high effort were discarded.

Figure 9. Effort and impact matrix.

MATRIZ DE ESFORÇO x IMPACTO

ESFORÇO	IMPACTO: ALTO		IMPACTO: BAIXO		ESFORÇO
ALTO	Número de passes		Balança		ALTO
ALTO	Largura do acesso		Controlar a chegada dos ônibus		ALTO
ALTO	Continuidade de operação		SETUP do inclinômetro		ALTO
ALTO	Despacho otimizado		Cerca virtual de velocidade		ALTO
ALTO	DMTs longas		Uso de celular na mina		ALTO
ALTO	Automatização da manobra				ALTO
BAIXO	ângulo de giro	Fator de enchimento da caçamba	Preferência pelo caminhão carregado	Aumentar para 5% as pesagens	BAIXO
BAIXO	Alocação de caminhões	Desgaste do FPS	Preparação de carga		BAIXO
BAIXO	Grade do acesso	Melhoria de sinal do smartmine	Instalar registro de ponto no escritório novo		BAIXO
BAIXO	Volume de concha	Carga morta	Eliminar Armários		BAIXO
BAIXO	Altura da bancada		Eliminar o Check-list de papel		BAIXO
BAIXO	Padronizar a troca de turno		Finalizar distribuição de mochilas		BAIXO
BAIXO	Pré-manobra		Padronização da manobra		BAIXO
BAIXO	Condição do piso		Controlar KPI Km cheio/KM vazio		BAIXO
BAIXO	Velocidade média		Utilização do rolo nas frentes de carregamento e basculamento		BAIXO
BAIXO			Padronizar as configurações dos rádios		BAIXO

Source: authors, 2024.

LEAN SIGMA METHODOLOGY - IMPROVE PHASE

A set of actions were carried out in order to ensure the improvement of the productivity process with standardization, where first, materials discarded from the plant were used, which previously did not have a defined destination for maintenance of the accesses, material with a known granulometry favoring the condition of the accesses, improving the productivity of the transport equipment, as seen in the figure below.

Figure 10. Improvement of access conditions with ceiling material.

Source: authors, 2024.

There was also a need to standardize some processes such as ROM tipping of the plant and equipment supply, so fixed layouts were defined for these activities, thus defining an adequate supply location, which generate gains in reducing supply time, maintaining the cycle of standardized equipment.

It was implemented along with fleet monitoring definition of the logic between some states such as tipping and moving empty, or loading and moving full, as well as the check-list state automatically, ensuring greater data reliability.

Figure 11. Improvements in the logic of the dispatch system.

Source: authors, 2024.

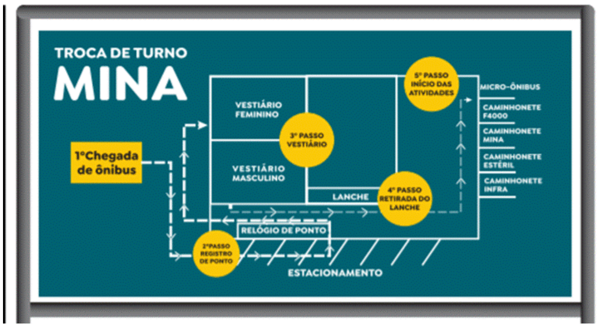
It was verified, especially for waste rock operations, a recurrent presence of material remaining in the truck bed, also called death load. From this, the team went to the market to look for a technology to apply to the truck's bed, also called lining, to reduce the remaining material and to mitigate this situation. After application testing, a coating material was defined for the truck bed, which solved this problem of material overload after tipping.

Figure 12. Application of technology for lining the bucket.

Source: authors, 2024.

Actions were carried out to map and classify the accesses, creating a maintenance schedule, in addition to the creation of an online form for inspection of the conditions of access. From this form and mapping, routines were created with the infrastructure team, to act on the problems raised and thus improve the general conditions of the accesses. In addition to the actions mentioned above, standards were also created for shift change as a roadmap and the shift change board in order to facilitate the flow of employees in shift changes, to improve the utilization indicator, reducing idle hours.

Figure 13. Roadmap for shift change.

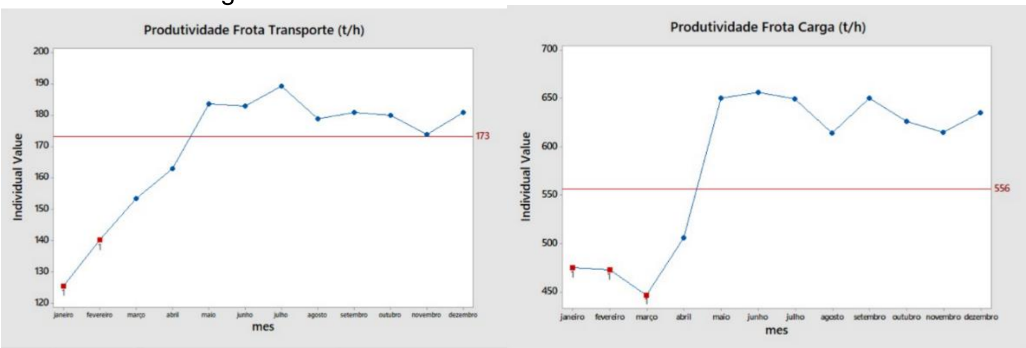


Source: authors, 2024.

LEAN SIGMA METHODOLOGY - CONTROL PHASE

With all the actions put into practice, we started the results control stage. A statistical process control (SPC) was implemented to monitor the results and prevent the process from being out of control.

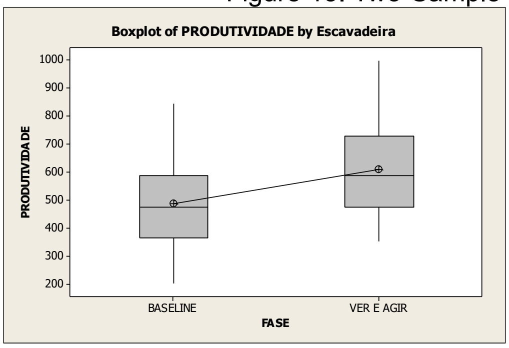
Figure 14. Statistical control of trucks and excavators.



Source: authors, 2024.

The Two Sample t-test is a statistical analysis used to determine whether there is a significant difference between the means of two independent populations. A two-sample test was performed with the excavator process with an average of 622.83 t/h and a truck process of 179.21 t/h.

Figure 15. Two-Sample T Test for Excavators.



Two-Sample T-Test and CI: PRODUTIVIDADE; FASE

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Two-sample T for PRODUTIVIDADE
FASE          N  Mean  StDev  SE Mean
BASELINE    598   475    155      6,4
VER E AGIR  735   622    162      6,0
Difference = mu (BASELINE) - mu (VER E AGIR)
Estimate for difference:  -121,892
95% CI for difference:  (-139,001; -104,783)
T-Test of difference = 0 (vs not =): T-Value = -
13,98  P-Value = 0,000  DF =1295
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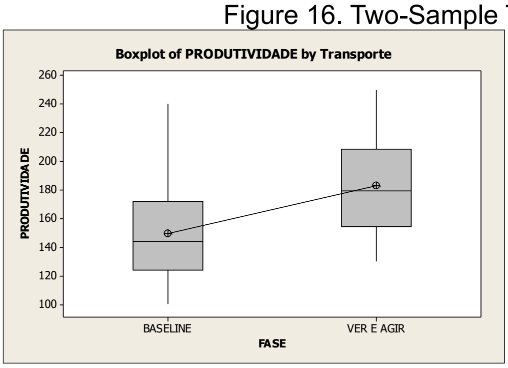
Source: authors, 2024.

Figure 16. Two-Sample T Test for Trucks.



Two-Sample T-Test and CI: PRODUTIVIDADE; FASE

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Two-sample T for PRODUTIVIDADE
FASE           N    Mean  StDev  SE Mean
BASELINE    3440  145,34   32,1     0,55
VER E AGIR  2181  179,21   32,9     0,70
Difference = mu (BASELINE) - mu (VER E AGIR)
Estimate for difference:  -33,0844
95% CI for difference:  (-34,8315; -31,3373)
T-Test of difference = 0 (vs not =): T-Value
= -37,12  P-Value = 0,000  DF =4551
```

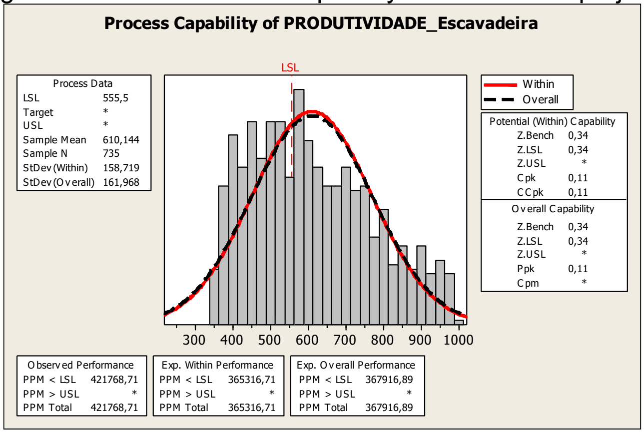
Source: authors, 2024.

RESULTS AND DISCUSSIONS

As a result of the projects, after all the improvements were made, we can see that the sigma level (capability) that measures the number of losses per million reached 1.84 for excavators and 1.8 for trucks, thus significantly improving the processes.

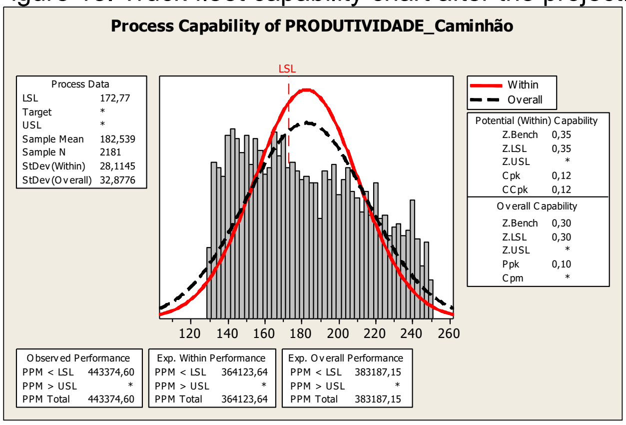
After the end of the project, all the stipulated goals were achieved. Through a detailed analysis and as a result of the actions taken towards these objectives, we achieved an increase in the overall productivity of the trucks of about 21% (the initial target was 15%), and an increase in the effective productivity of the excavators of around 31% (the target of 14%), thus exceeding the initially proposed targets.

Figure 17. Excavator fleet capability chart after the project.



Source: authors, 2024.

Figure 18. Truck fleet capability chart after the project.



Source: authors, 2024.

CONCLUSION

Through this project, with the gains in productivity of cargo (31%) and transportation (21%) equipment, relevant financial gains estimated at R$ 4,502,141 per year and non-financial gains were generated with improved safety conditions, employee well-being and reduced carbon emissions by saving hours and diesel generated with increased productivity. The gain from reducing carbon emissions is estimated at 3,056 tons of carbon per year. In addition to the financial gains of the project, it is possible to observe the development of the Lean Six Sigma methodology, fostering a culture of continuous improvement and technical development of people, reinforcing the importance of teamwork with a multidisciplinary team involving supervisory people, engineers, analysts, mine operators and professionals from other sectors such as mine planning and maintenance. The planning of actions and the involvement of those responsible were fundamental for the good development of solutions, with quality and speed.

We can conclude that the Lean Six Sigma methodology and its tools allow, in a practical and efficient way, to identify and solve problems inherent to the production processes in mining, thus helping several professionals and society as a whole through this methodology. With this case study, the applicability of this methodology with all stages of DMAIC (Define, Measure, Analyze, Improve, Control) can be proven and its effectiveness can be proven by optimizing the productivity of the excavator and truck fleet.

LIMITATIONS OF THE RESEARCH AND RECOMMENDATIONS FOR FUTURE WORK

In this work we had the application of the methodology to increase the productivity of loading and transport equipment in mining, where in this scope it can be demonstrated its effectiveness through the results. For future work, it is suggested the application and demonstration of the Lean Six Sigma methodology for objectives and in processes different from the one applied, such as the environment, safety, maintenance, processing, among others.

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