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Energy Efficiency of Carajás Railway

Fernando Nunes da Silva
Operational Analyst, Operational reliability of EFC
Carajás Railroad to Vale S.A.
Av. dos Portugueses, S/N Anjo da Guarda, CEP 65085 580 São Luís, MA - Brazil
fernando.nunes@vale.com

Denio Oliveira da Fonseca
Operational Analyst, Railway Engineering of EFC
Carajás Railroad to Vale S.A.
Av. dos Portugueses, S/N Anjo da Guarda, CEP 65085 580 São Luís, MA - Brazil
denio.fonseca@vale.com

Gerisval Alves Pessoa
Specialist in Operational Excellence
Carajás Railway (EFC) - North Corridor - VALE S.A.
Av. dos Portugueses, S/N Itaqui, CEP 65085 580 São Luís, MA – Brazil
gerissval.pessoa@vale.com

Francisco Alves de Araujo Filho, Andre de Araujo Pereira, Abdo Frances de Sousa
Inspector Mentor, Railway Operation EFC
Carajás Railroad to Vale S.A.
Av. dos Portugueses, S/N Anjo da Guarda, CEP 65085 580 São Luís, MA - Brazil
francisco.filho5@vale.com, andre.pereira@vale.com, abdo.sousa@vale.com

Abstract

This article aims to present the application of the Six Sigma methodology to improve the energy efficiency of trains running on Vale's Carajás Railroad in Brazil, one of the largest corridors for the transportation of iron ore and general cargo, consuming over three hundred million liters of diesel annually. One of Vale's commitments is to reduce its greenhouse gas emissions, and currently, it faces the challenge of reversing the trend of increasing diesel consumption due to a projected 2.1% increase in energy efficiency. The problem was identified, and the goal was defined based on historical performance. Processes were then mapped using a tree diagram, Pareto analysis, run chart, boxplot, and histogram. Diesel consumption in major flows was identified, and the causes were investigated and organized in a cause-and-effect diagram, prioritized for statistical investigation through correlation analysis and boxplot. Subsequently, proven causes were prioritized, a series of pilot tests were realized, and an effective action plan was implemented. The project brought sustainability and cost gains to EFC, reducing diesel consumption by 535,366.73 liters, resulting in a real savings of US$ 546,311.15 and a reduction in emissions of 1,527,500.09 kg CO^2 eq. The projected real and potential gains for a one-year period amount to US$ 3,520,707.62 in Vale's costs. The project established a new record for the Energy efficiency of iron ore trains on the EFC.

Keywords
Energy, Efficiency, Sustainability, Diesel, Railway.

1.Introduction
In a globalized world of business competition, the convergence of operational efficiency, cost reduction, increased competitiveness and sustainability is emerging as an unavoidable challenge and, at the same time, a strategic opportunity for organizations committed to balancing economic performance and social and environmental responsibility. In this context, the Six Sigma methodology emerges as a catalyst that transcends traditional boundaries, offering an integrated approach to optimizing processes, reducing costs, and boosting competitiveness, while promoting sustainable practices. Welch (2001) emphasizes, the main objective of Six Sigma is to improve the quality of business processes, and the pursuit of quality is crucial to customer satisfaction and operational efficiency.

However, the uniqueness of this research is based on the direct association from Six Sigma methodology with cost reduction and two fundamental pillars of sustainability: energy efficiency and waste minimization. The article analyzes how the effective implementation of Six Sigma can optimize operations, reduce costs, and how these practices converge towards responsible resource management, in line with the principles of environmental sustainability. Costanza (1997) emphasizes that a sustainable economy must consider not only quantitative growth, but also the quality of development, incorporating ecological values to ensure a harmonious balance between economic prosperity and environmental health. Gates (2021), mentions that innovation is the key to achieving zero emissions. We need to invent new ways of doing everything.

Mineral extraction, processing, and transportation operations have significant environmental or social aspects and impacts and must have robust strategies to eliminate or reduce them. In a scenario where social and environmental responsibility is increasingly valued, understanding how organizations can achieve balance considering factors such as efficiency, competitiveness and sustainability becomes essential to establish a standard of organizational excellence in the 21st century. Therefore, connecting the strategy to the Six Sigma methodology can contribute to cost reduction, increased productivity, competitiveness, and sustainability. Eckes (2002), emphasizes the importance of collaboration, efficient communication, and leadership to ensure the success of Six Sigma project emissions.

The aim of this article is to describe the application of the Six Sigma methodology in the mining industry, with a focus on optimizing diesel consumption in the trains operated by Vale S.A. that run on the Carajás Railway, detailing the stages of identification, analysis and optimization of the critical factors related to diesel consumption in railway operations, and consequently, in carbon emissions and operating costs.

2. Literature Review
Six Sigma, a management methodology aimed at continuous process improvement, was developed by Motorola in 1987 and has become a widely adopted approach by companies around the world (Pessoa, 2012). The term "Six Sigma" refers to the goal of reducing variation in processes to the point of achieving only 3.4 defects per million opportunities, statistically represented as six standard deviations from the mean.

Although Six Sigma methodology originated in industry, its application has expanded to various sectors, including services, health, and government. Companies such as General Electric, Toyota and Ford have successfully adopted this methodology, demonstrating that the principles of Six Sigma are universally applicable, regardless of the organizational context.

Pyzdek (2003), has reported that using statistical principles and the DMAIC methodology (Define, Measure, Analyze, Improve and Control), Six Sigma not only seeks to improve the quality of processes, but also positions itself as a strategic instrument for reducing operating costs. This systematic approach proposes an analysis of processes, identifying and eliminating waste, redundancies, and inefficiencies, thus contributing to a more effective management. In line with Welch (2001), defect reduction is essential to guarantee consistency in the delivery of products and services.

The Six Sigma methodology uses a variety of statistical and management tools known for years in the quest to eliminate defects in all company processes, including control charts, regression analysis and other advanced statistical techniques. However, Werkema (2012) reports that the success of this methodology is based on its approach and form of implementation being unique and effective, highlighting three main elements: direct measurement of the benefits of Six Sigma methodology by increasing the company's profitability (bottom-line results); structured method for achieving goals (DMAIC); High commitment from the company's senior management.
The development of Six Sigma projects is carried out based on a method called DMAIC, consisting of five stages described on Figure 1(Werkema, 2012).

Stages	Description
D – Define	Accurately define the scope of the project.
M – Measure	Determine the location or focus of the problem.
A - Analize	Determine the causes of each priority problem.
I - Improvement	Propose, evaluate, and implement solutions for each priority problem.
C - Control	Ensure that goal achievement is maintained in the long term.

Figure 1. DMAIC Description

According to Smętkowska and Mrugalska (2017), Six Sigma is perceived as a philosophy or concept of a broad sense. Using it as a philosophy helps with changing the world and with the transformation of an enterprise, so the gains of Six Sigma go beyond increasing productivity, reducing costs, improving operational efficiency and environmental sustainability.

Junior and Vieira (2020) have reported the positive impact of the Six Sigma methodology on diesel consumption in logistics, with tangible benefits such as cost savings and a reduced carbon footprint. In addition, Six Sigma's adaptability to the unique challenges of the rail industry, such as the need for continuous service, reinforces its suitability for driving sustainable improvements.

The direct economic and environmental impact of energy efficiency influences diesel consumption and carbon emissions. Rosa (2011) cites the importance of conducting logistics costs according to plan. Rifkin (2019) make a point of the urgency of sustainable actions and significant changes in the energy and economic systems to meet environmental challenges.

The challenges to optimizing energy efficiency are diverse, ranging from technological obstacles to the economic and social issues associated with the transition of energy matrices to more efficient diesel consumption practices. The analysis reveals the complexity of factors, including resistance to change, high initial investment costs and the need for coordination between different stakeholders. Shere (2013) emphasizes new forms of renewable energy and Smil (2017) takes an inclusive approach to community empowerment for the energy transition, which corroborates the complexity of factors. However, the outlook points to the transformative potential of continued investment in research and development, as well as the crucial role of education and awareness-raising in overcoming these challenges. According to Riabov et al. (2023) the growing use of mathematical modeling and computer simulations as essential tools in assessing energy efficiency.

This analysis supports the application of Six Sigma as a robust methodology for optimizing diesel consumption in railway operations and highlights the integration of knowledge from different disciplines, highlighting the need for holistic approaches to address existing challenges.

3. Methods

This research used a case study approach, combining qualitative and quantitative methods. According to Vergara (2004), a case study is the circumscription of one or a few units, understood as a person, a family, a product, a company, a public body, a community or even a country. The importance of case studies as a research approach to understanding complex phenomena is reinforced by Yin (2013) and Denzin & Lincoln (2011).

The research method is descriptive and applied, as it presents a case study at Vale. S.A. on the application of Six Sigma methodology using PDCA (Plan-Do-Check-Act), which is the practice adopted by Vale in its management model in the process of continuous improvement and problem-solving for any type of problem from strategic to operational (Vale 2023), unlike most companies that adopt DMAIC as the standard methodology for Six Sigma. According to Pessoa (2007), the Six Sigma program can be developed in companies using one of the two main problem-solving methodologies available, DMAIC and PDCA.
The working method used the PDCA stages: (i) identifying the problem, (ii) analyzing the phenomenon, (iii) analyzing the process, (iv) establishing the action plan, (v) conducting the actions, (vi) verifying the results and (vii) standardizing.

4. Data Collection

Quantitative and qualitative data was collected in each phase of the PDCA cycle, highlighting the importance of these approaches in the case study of the application of the Six Sigma method to the energy efficiency of the Carajás Railroad trains at Vale S.A. from Mar 2021 to Dec 2022.

In the planning stage, quantitative data was collected by means of a thorough analysis of historical diesel consumption data for 11,000 trains, categorized by the train's origin of departure and destination of arrival, transport flows, locomotive models, trains with loaded wagons and trains with empty wagons, with the purpose of defining the focus of the work on the largest fuel-consuming flows and set realistic goals.

To understand the tractive efforts required at each point on the railroad, information was collected on the railroad's planialtimetric survey, locomotive power, and data was extracted directly from locomotive operating recorders such as the Q-tron and ATC (Automatic Train Control). At the same time, data was collected from the control systems to understand the operational challenges and the statistical correlations between energy efficiency and the variables collected. This hybrid approach established a basis for action planning.

In the execution stage, during the implementation of the outlined strategies, projected diesel consumption information was collected in the train operation simulator, and in the field, diesel consumption was collected directly from the locomotive tank level to monitor diesel consumption in real time during the empirical tests conducted. This integrated approach was applied to theoretically and empirically confirm the proposed strategies. According to Gigerenzer (2002), simulation is a valuable tool for making decisions under uncertainty. It allows us to evaluate strategies and predict outcomes, providing crucial insights for a rational choice.

Quantitative in the verification phase is based on operational data, consumption records and performance reports. Data was collected from the company's official performance control systems from October to December 2022 to compare the results obtained with the goals set for the KPI (Key Performance Indicator) of the general goals and with the indicators defined in the planning phase and to objectively assess the energy efficiency achieved.

In the Standardization stage, qualitative and quantitative data was collected to find critical success factors and standardize new ways of operating and keeping the obtained results sustainable.

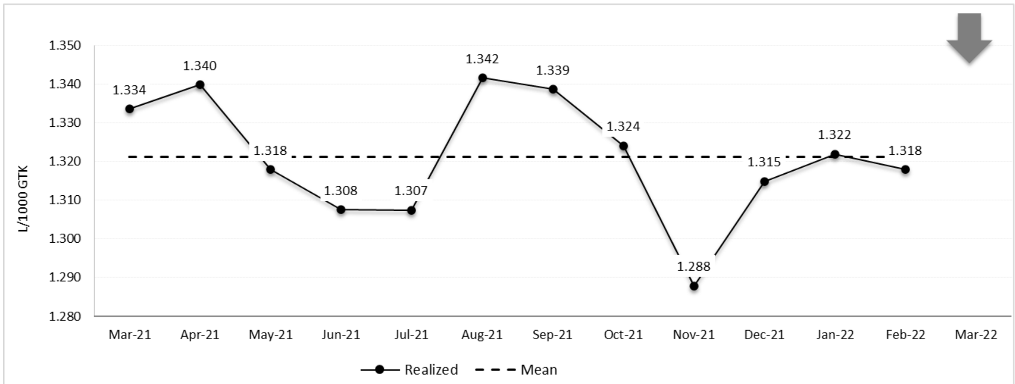
5. Results and discussion

The case study is about the application of the Six Sigma methodology at Vale S.A., one of the world's largest mining companies, headquartered in Brazil and operating globally, focusing on the optimization of energy efficiency in the railway operation of the Carajás Railway, which is 892 km long, has a fleet of 20,000 wagons and 270 high-powered locomotives for the transport of iron ore, in standard 330-wagon trains, from the mines located in the State of Pará to the port of Ponta da Madeira in the State of Maranhão.

The numerical data, graphical results, proposals for improvement and validations are described in the following PDCA stages:

Problem identification stage

To understand the problem, it was analyzed by run chart the historical performance of the Key Performance Indicator (KPI) that measures energy efficiency in the period from March 2021 to February 2022. (Figure 2).



Variable	Data Count	Mean	Standard Deviation	Minimum	1º Quartile	Median	3º Quartile	Maximum	Range
Real	12	1.321	0.016	1.288	1.310	1.320	1.338	1.342	0.054

Figure 2. EFC L/1000 GTK energy efficiency run chart.

The historical performance shows that during the period from March 2021 to February 2022, the Carajás Railway energy efficiency averaged 1.321 L/1000 GTK (Gross Ton-Kilometer), with a variation from 1.288 (minimum) to 1.342 L/1000 GTK (maximum). The high variability in a process makes it difficult to achieve high accuracy in any planning.

Based on the characteristics of the indicator and its historical performance, the goal was set to capture 6% of the GAP in relation to the best result of 1,288 L/1,000 GTK and the period average of 1,321 L/1,000 GTK, that is, reducing diesel consumption by 0.002 liters for every 1,000 tons transported per km, going from 1,321 L/1,000 GTK to 1,319 L/KTKB, until 12/31/2022. Historical data proves the possibility of achieving the proposed goal, as 50% of the monthly data performed above median line. The challenge, therefore, was to understand the reasons for the variations.

Phenomenon analysis stage

The principal factors contributing to the historical variability of energy efficiency (from March 2021 to February 2022) were defined by deployment the data categorized by types of trains, types of traction, transport flows, origin and destination using the tree diagram and Pareto diagram tools.

Table 1 shows the variables with the greatest influence on the overall diesel consumption of the Carajás Railway, and which were considered as the focus of the project, which is concentrated on iron ore transportation trains. For each focus, a reduction percentage was defined based on an analysis of historical performance so that the sum of all gains was sufficient to reach the main goal, 1.319 L/1000 GTK. Achieving a 0.23% reduction for each specific goal is equivalent to the expected reduction for the global target of 0.15%

Table 1. List of the eight specific goals

	Specific Goal 1	Specific Goal 2	Specific Goal 3	Specific Goal 4	Specific Goal 5	Specific Goal 6	Specific Goal 7	Specific Goal 8	
	1. Empty Ore Trains Serra Sul Mixed Traction	2. Empty Ore Trains Serra Norte Mixed Traction	3. Empty Ore Trains Serra Sul DC Traction	4. Empty Ore Trains Serra Norte DC Traction	5. Loaded Ore Trains Serra Sul Mixed Traction	6. Loaded Ore Trains Serra Norte Mixed Traction	7. Loaded Ore Trains Serra Sul DC Traction	8. Loaded Ore Trains Serra Norte DC Traction	Sum of Specific goals
1000 GTK	9,669,313	13,620,347	3,166,756	4,216,614	58,874,734	80,849,270	19,470,657	24,552,516	241,108,283
consumption (liters)	25,596,515	37,287,633	9,385,031	12,861,445	59,360,798	82,837,590	18,666,444	24,130,657	318,021,822
Reduction (liters)	58,205	85,077	21,341	29,345	134,983	189,005	42,447	55,058	615,461
Mean EE (L/1000 GTK)	2.647	2.738	2.964	3.05	1.008	1.025	0.959	0.983	
Target (L/1000 GTK)	2.641	2.731	2.957	3.043	1.006	1.022	0.957	0.981	1.319
Reduction (L/1000 GTK)	0.006	0.06	0.007	0.007	0.002	0.002	0.002	0.002	0.002
% reduction from target	0.23%	0.23%	0.23%	0.23%	0.23%	0.23%	0.23%	0.23%	0.15%

Process analysis stage

To find out the root causes of the eight focus problems and their validations, the following tools were used: process mapping, survey of the causes, prioritization of the causes and statistical quantification/proof of the causes (cause and effect relationship).

For variables that had historical data and understanding whether the causes analyzed, variable (*x*) had significant impacts or not on the response variable, focus problems under analysis (*y*), the most proper tools suggested were used in the Statistical Analysis Map (Seta, 2018).

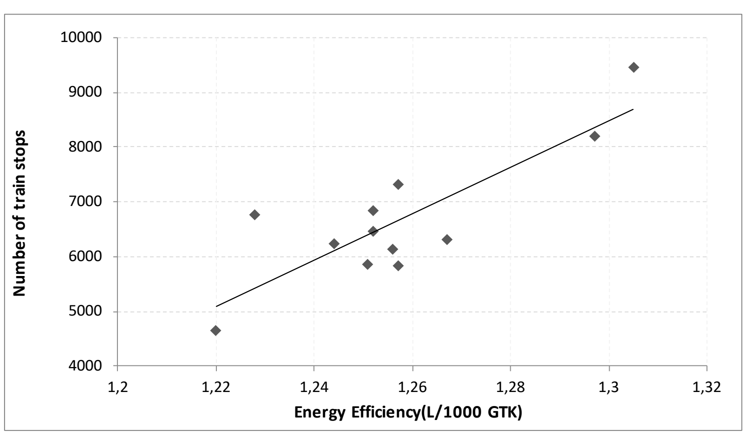
A total of eighteen potential causes were listed, which underwent a selection process using a weighted decision matrix with the following criteria: impact of cause on the problem, ease of eliminating the cause, and team autonomy. Eleven causes were selected, which then were subjected to validation tests, of which nine were proven as root causes. Figure 3 shows a summary of the validation tests.

Prioritized Causes	Evidence Presentation	Proven?
Number of Stops in Yards with High Consumption	Correlation Analysis	Yes
Loading Pellets with Wagons of Lower Capacity	Correlation Analysis	Yes
Locomotive turned on due to time limitation turned off (SD8)	Historical Consumption Analysis	Yes
Low Performance of Trip Optimizer	Analysis of trains with TRIP vs. without TRIP	Yes
Locomotive turned on without performing activity	Yard Historical Consumption Analysis	No
Train speed limitation	Consultation with engineering	Yes
Loading operation at terminals with excess Traction	Field Verification	Yes
Weight Variation between Serra Leste Railway Scales	Correlation Analysis	Yes
Power Excess in specific sections	Analysis of tractive effort difference	Yes
Traction allocation not based on Energy Efficiency	Analysis of traction formation	No
Stops due to helper traction cut	Analysis of Dynamic Helper Failures	Yes

Figure 3. Validation of causes

Figure 4, Table 2, and Figure 5 show examples of validations using the statistical tools suggested in the Statistical Analysis Map (SAM) considering the relationship of the dependent variable (*y*) - continuous data, and the independent variable (*x*) - continuous data or attributes (Vale, 2021).

Figure 4 shows the scatter plot of the cause "number of stops in yards with high diesel consumption (*y* - continuous variable)" with "energy efficiency (*x* - continuous variable)", with *p-value* = 0.001. As *p-value* <0.05 it is concluded that the two variables studied are dependent and there is a significant linear correlation. This positive relationship means that the greater the number of stops, the greater the diesel consumption of the ore train. The correlation is considered significant because the Pearson´s correlation coefficient is 0.836. Then, it is possible to use the regression line to model the linear relationship between x and y in the population.



Pearson's Correlation Coefficient:	0,836
P-value for the Correlation Test:	0,001

Figure 4. Scatter plot: variables train stoppages and energy efficiency

Table 2 shows the historical performance of the average weight of the wagons carrying Pellet Feed, separating the results for the GDT and GDU models wagons.

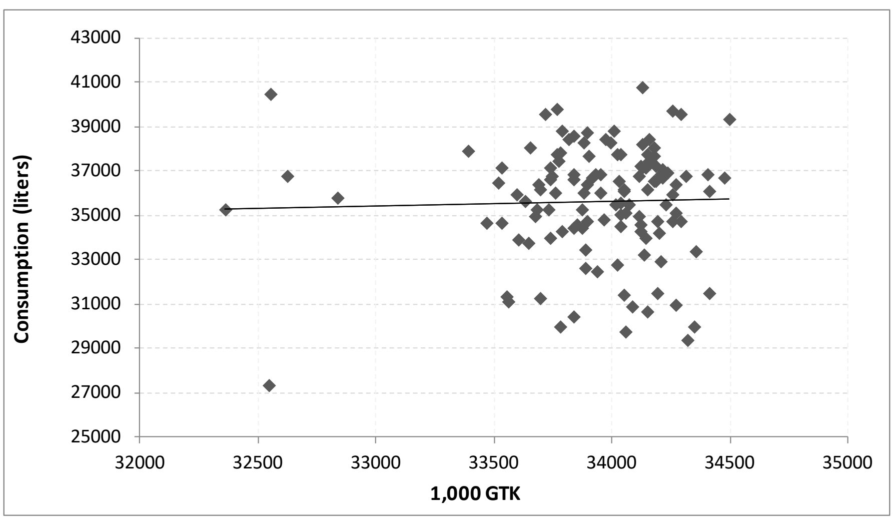
Based on these data presented, we can see that 60.02% the Pellet Feed's loads are conducted in GDT wagons, which performed less well than GDU wagons during the period.

Table 2. Pellet Feed Loading Table

	wagon	Mar-21	Apr-21	May-21	Jun-21	Jul-21	Aug-21	Sep-21	Oct-21	Nov-21	Dec-21	Jan-22	Feb-22	Global
Weight	GDT	101.56	99.88	100.07	99.87	99.35	97.60	96.22	96.53	98.46	99.94	100.33	99.52	99.20
	GDU	102.64	101.67	103.19	102.86	103.46	99.39	101.37	99.67	100.68	100.61	100.41	101.7	101.27
Distribution	GDT	73.61%	60.18%	72.58%	74.16%	49.62%	64.30%	66.44%	48.36%	38.44%	59.50%	59.46%	48.26%	60.02%
	GDU	26.39%	39.82%	27.42%	25.84%	50.38%	35.70%	33.56%	51.64%	61.56%	40.50%	40.54%	51.74%	39.98%

To understand whether this loading direction of the wagons influences Energy efficiency, a scatter plot was created comparing the continuous variable (x) “Gross Ton Kilometer” and the continuous variable (y) “diesel consumption” of the loaded ore trains, as shown in Figure 5.

The correlation shows *p-value* = 0.762, (*p-value* $\geq$ 0.05). We therefore conclude that there is no significant correlation between these two variables, i.e., ore trains loaded with wagons with an average weight below the average does not reduce diesel consumption. This proves that loading pellet feed into low-capacity wagons has a negative influence on the train's energy efficiency. The Pearson´s correlation coefficient is 0.027. Therefore, we cannot use the regression line to model a linear relationship between x and y in the population.



Pearson's Correlation Coefficient:	0,027
P-value for the Correlation Test:	0,762

Figure 5. GTK and diesel consumption Scatter plot

Action plan/improvement proposal stage

Initiatives were defined for all validated causes and then they were prioritized using the following criteria: Impact on the cause, complexity, cost, and implementation period. An action plan with thirty-three actions was proposed using the 5W2H method.

Figure 6 shows a summary of the proposed improvements for eliminating the causes that were proven to be true. The columns “who, when, how, where, and how much” have not been considered in this table, but they do exist and have been defined in practice.

Causes to be treated	Solutions to be implemented	What?
Pellet loading with a lower capacity wagon	Review planning for prioritizing Pellet Feed Loading for use in GDU wagons	Prioritize pellet loading for GDU wagons and restrict GDT wagons to exceptions
Trip Optimizer's low performance	Update Trip Operating System	Complete the installation of Trip Optimizer on the Dash 9 fleet (6 kits).
Stops in yards with high diesel consumption for start-ups	Adjust train stop process with Energy Efficiency vieis	Build a panel with a map of train stops on the EFC with Energy Efficiency videos
		Implement routine use of the stop panel with Energy Efficiency vieis
		Train Travel drivers on the optimum stopping points for each location
		Train train drivers in the new MT of operation
Speed limit for ore trains Loaded at 70 km/h	Standardize with IOC Circulation up to 80km/h on specific stretches	Release stretches for ore trains to run at 80 km/h
Loading operation at terminals with surplus Traction	Standardize charging operations at terminals to focus on Energy Efficiency	Train Yard Drivers in the new loading standard
Power surplus in specific sections	Adjust operating procedure to capture gain in train consumption	Train helper drivers in the new operation between km 603 and km 587.
		Update operating procedure with new standard for type of traction (MIXED-DC)
Stops due to helper traction cut-off	Dynamic helper hardware and software update	Update hardware and software on the 11 locomotives in the dynamic helper circuit
	Implementation of improvement using double check of laser and locomotive GPS after coupling	Develop and implement laser and GPS double checks for the 11 dynamic helper locomotives

Figure 6. 5W2H Action Plan Pellet Feed Loading Table

Execution stage

The "S" curve was used to ensure adherence to the implementation of the actions. All the planned actions were checked monthly to ensure compliance and the effectiveness of the results. Figure 7 shows 100% adherence, i.e., all thirty-four planned actions were implemented. It is understood that some of the actions were not conducted on schedule, but all were completed within the project deadline.

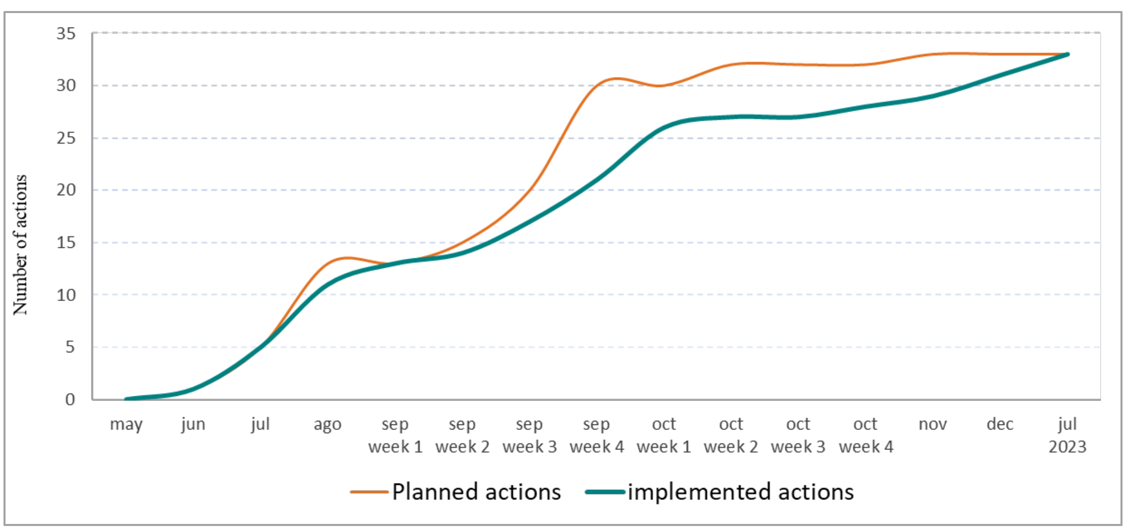


Figure 7. S-curve of the 5W2H plan

Results verification stage

The implemented actions proved sufficient to achieve and sustain the results. In addition, we exceeded the 2022 goal of 1.319 L/1000 GTK, and in the verification period from October to December 2022 we achieved an average energy efficiency performance of 1.315 L/1000 GTK. Figure 8 shows a comparison of energy efficiency (baseline) and during the check period. It can also be verified a change in performance level and a reduction of variability.

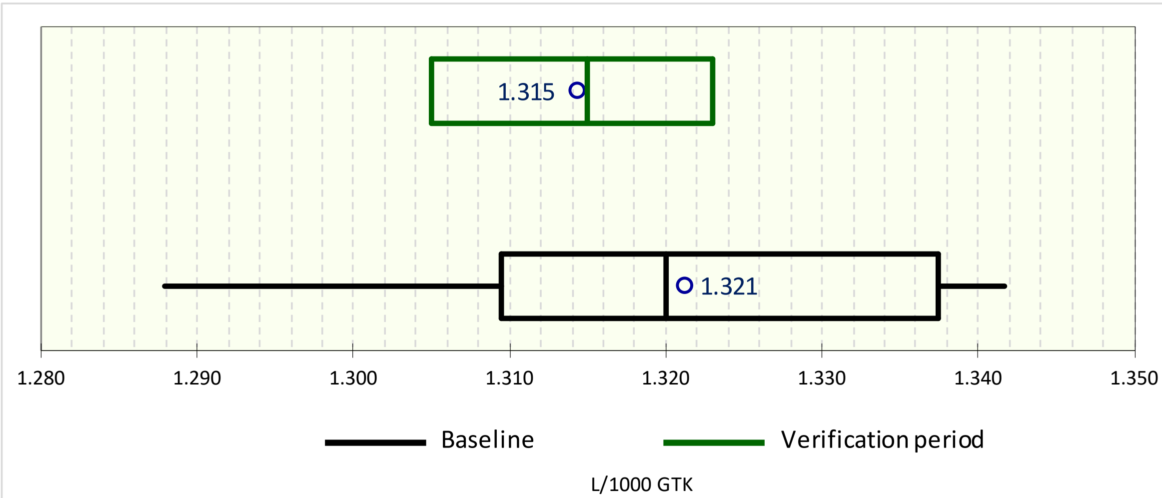


Figure 8. Boxplot comparing EFC L/1000 GTK energy efficiency.

Based on the descriptive analysis of the baseline and the check period (Table 3), it can be concluded that there was an improvement in energy efficiency performance when comparing the two averages, as well as a reduction in process variability, showed by the reduction in range and standard deviation. The baseline range has been reduced from 0.54 L/1000 GTK to 0.18 L/1000 GTK and the standard deviation has been reduced from 0.16 L/1000 GTK to 0.09 L/1000 GTK.

Table 3. Descriptive analysis of energy efficiency compared to before and after the study.

Variable	Data Count	Mean	Standard Deviation	Minimum	1º Quartile	Median	3º Quartile	Maximum	Range
Baseline	12	1.321	0.16	1.288	1.309	1.320	1.337	1.342	0.54
Verification Period	3	1.315	0.09	1.305	1.305	1.315	1.323	1.323	0.18

The overall gains of the project are detailed in Table 4, categorized by business dimensions: the environment, with diesel savings and a reduction in carbon gas emissions and, in the cost dimension, with a reduction in the Capital Expenditure and Operational (OPEX) of the Carajás Railway.

Table 4. Overall Project Gains

Dimennsion	Description	Gains
Environment	Reduction in diesel consumption	535,366.73 liters of diesel
Environment	Reduction in emissions	1,527,500.09 kg CO^2 eq
Cost	Reduction in the operational cost of the company	US$ 546,311.15
Cost	Potential carbon credit	US$ 56,778.00

Qualitative gains were also captured by the project: definition of parameters for energy efficiency by type of train (origin-traction-empty/loaded), connection with the continuous improvement groups with engagement to obtain better performances in energy efficiency, and reinforcement of the energy efficiency culture linking with the commitments we have made to society.

Standardization stage
In order to maintain control of the process and guarantee the sustainability of the results in the medium and long term, standards were created and revised from the operation of the iron ore loading terminal in Carajás, in the State of Pará, to the end of the journey with the arrival of the train at the Ponta da Madeira Maritime Terminal in São Luís, Maranhão, Brazil.

Figure 9 shows the list of standard operating procedures and technical documents revised or created in this study.

Operational Procedures and Technical documents
- PRO-021600 • Maneuver Plan for the Serra Leste Terminal
- PRO-001194 • Operation of trains on Carajás Railway
- Engineering circular 003/2022 - Section extension with circulation of loaded trains at 80 km/h and VMA on Carajás Railway
- Reliability Operation Circular Carajás Railway 003/2022 - Economic Operation in Empty Ore Trains
- Reliability Operation Circular Carajás Railway 004/2022 - Operation in Loaded Ore Trains Operation
- Operation Information III 003/2022 - Energy Efficiency Operation-Carajás Railway Terminal
- Carajás Railway map of Critical Stopping Points for 330-Wagon Ore Trains"
- PRO-020531 • Carajás Terminal Railway Maneuver Plan

Figure 9. Standard Operational Procedures and Technical documents

To ensure that everyone follows the revised standard operating procedures, more than five hundred operators have been trained in train driving and loading terminal operations. Also, to deal with possible daily deviations, the OCAP (Out control Action Plan) was implemented, as well as the revitalization of the daily management of efficiency performance with the addition of performance monitoring indicators in railway operation management.

6. Conclusion

The aim of this article was to describe the application of the Six Sigma methodology in the mining industry, with a focus on optimizing diesel consumption in the trains operated by Vale S.A. that run on the Carajás Railway, detailing the stages of identification, analysis and optimization of the critical factors related to diesel consumption in railway operations. The results presented in the case study and the use of Six Sigma tools associated with the PDCA method proved that the objective was achieved.

The case study demonstrates the efficiency of Six Sigma methodology and the solutions resulting from the analysis made it possible to improve the energy efficiency of trains on the Carajás Railroad with: (i) a reduction in the consumption of 535,366.73 liters of diesel, (ii) increased loading of pellets in the GDU wagon, which has the highest capacity, (iii) reduction in variability, (iv) definition of parameters for energy efficiency by type of train, (v) increased number of locations where loaded ore trains are allowed to run at the Speed Limited of 80 km/h, (vi) reduction in stopping trains in yards with a planialtimetric survey, which increases diesel consumption, (vii) revision of the standard with optimization of the locomotives' tractor effort, (viii) reduction in carbon emissions.

The obtained results not only met the established goal, but also point to significant gains for the sustainability of rail transportation. We believe that the findings presented here will serve as a basis for implementing more sustainable practices, promoting both economic and environmental benefits for any railroad.

This important work, which focused on the ore train, is a pilot study that can be applied to other processes, such as the general cargo trains of Vale S.A. and VLI S.A. that run on the Carajás Railroad.

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Biographies

Fernando N. Silva has been in the railway industry for 22 years. He is Graduated in Mathematics from the State University of Maranhão, Brazil, and in Production Engineering and Civil Engineering from the University of Santo Amaro, Brazil. He is specialized in Human Resources Management from Uninter, Brazil. He has technical training in electromechanical from the Federal Center for Technological Education, Brazil. He is a certified green belt in Six Sigma and has experience in transport planning and checking operational performance indicators. In 2023, he was chosen as the Standard Railroader of Carajás Railroad, receiving the award from Vale S.A.

Denio O. Fonseca has been a postgraduate degree in Railway Engineering, Financial Management, He is graduated in Mathematics from the State University of Maranhão; with 20 years of experience in the railway industry, working on major projects for Vale S.A. in the implementation of long trains with 440 and 660 wagons, reaching trains with over 6.5 km in length in operation worldwide. A specialist in railway dynamics, he is responsible for developing operational procedures for super heavy trains with loads exceeding 56,000 tons. He has been involved in complex railway projects such as dynamic helper, where train coupling occurs in motion, the implementation of fully electric locomotives in EFC, a study on load lifting per axle in wagons, and increasing the speed of ore trains with a model of 330 wagons. In 2018, he was chosen as the Standard Railroader of VALE, receiving the award from Revista Ferroviária, the most relevant railway magazine in the country. Today, he is part of the Railway Engineering team at the largest mining company in Brazil, Vale S.A.

Gerisval A. Pessoa is Professor of undergraduate and postgraduate. He is Graduated in Industrial Chemistry from the Federal University of Maranhão - Brazil, Specialization in Quality Engineering from the State University of Maranhão and master's in business administration from the Getulio Vargas - RJ - Brazil. He has experience in Management, with emphasis in Administration, Administration of Production and Logistics, Strategic Planning, Quality Management, Quality Management System, Project Management and Entrepreneurship. He has been Certified in Lean Six Sigma Master Black Belt, Total Productive Maintenance (TPM), Lead assessor integrated management system (quality, environment, health, and occupational safety). He has attended Total Quality Control Seminar for Brazil Middle Management and TQC Coordinators (JUSE - Tokyo) and MIT-Sloan School of Management (Entrepreneurship Development Program - 2014). He has guided 156 Six Sigma projects.

Francisco A. Filho has been in the railway industry for 18 years. He has technical training in Electrical Engineering from the Federal Center for Technological Education, Brazil, and obtained a degree in Management Processes from Uninter, Brazil. He has experience as a Journeyman Engineer and Inspector Mentor. He is part of the technical team as a Railroad Inspector at Estrada de Ferro Carajás, responsible for training new operators and taking part in extraordinarily complex projects, such as increasing the speed of ore trains with a model of 330 wagons, merging freight trains, and implementing long trains with 440 and 660 wagons.

Andre de A. Pereira has been in the railway industry for 18 years. He has experience as a Journeyman Engineer and Inspector Mentor. He is part of the technical team as a Railroad Inspector at Estrada de Ferro Carajás, responsible for training new operators and taking part in extraordinarily complex projects, such as increasing the speed of ore trains with a model of 330 wagons, merging freight trains, and implementing long trains with 440 and 660 wagons.

Abdo F. Sousa has been in the railway industry for 22 years. He has technical training in mechanical engineering from the Federal Technical School of Pará, Brazil. He has experience as a Journeyman Engineer and Inspector Mentor. He is part of the technical team as a Railroad Inspector at Estrada de Ferro Carajás, responsible for training new operators and participating in highly complex projects, such as dynamic helper where train coupling occurs in motion, increasing the speed of ore trains with a model of 330 wagons, merging freight trains, and implementing long trains with 440 and 660 wagons.