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Maintenance and Remanufacturing Strategies in Vehicle Fleets within the Circular Economy Context: A Financial and Operational Analysis[1]

Estratégias de Manutenção e Remanufatura em Frotas de Veículos no Contexto da Economia Circular: Uma Análise Financeira e Operacional

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ABSTRACT

Growing concern with sustainability and the circular economy has driven the search for greater efficiency in the use of resources and the reduction of emissions in transportation and cargo fleets. However, there is still resistance to the adoption of maintenance and remanufacturing strategies by companies and consumers. Such strategies are often associated with high costs and uncertain long-term results. The objective of this study is to analyze the influence of the adoption of maintenance and remanufacturing strategies on the variables of vehicle costs and availability. To this end, a case study was conducted to collect and analyze data on the maintenance and remanufacturing history of a fleet of diesel-powered vehicles. The results indicate that effective corrective and preventive maintenance management are essential for reducing costs, increasing vehicle availability, and stabilizing budget forecasts. Additionally, the use of remanufactured parts influences the reduction of repair time, increases the cost efficiency of maintenance processes, and contributes to the environmental aspect of resource reuse, aligning with the principles of the circular economy and promoting greater economic and environmental sustainability.

Keywords: maintenance, remanufacturing, financial performance, operational performance, circular economy

RESUMO

A crescente preocupação com a sustentabilidade e economia circular tem impulsionado a busca por maior eficiência no uso de recursos e redução de emissões em frotas de transporte e carga. Contudo, ainda há uma resistência na adoção de estratégias de manutenção e remanufatura por empresas e consumidores. Tais estratégias são, muitas vezes, associadas como soluções de alto custo e de resultados a longo prazo incertos. O objetivo deste estudo é analisar a influência da adoção das estratégias de manutenção e remanufatura nas variáveis de custos e disponibilidade de veículos. Para tanto, foi realizado um estudo de caso para coletar e analisar dados sobre o histórico de manutenção e remanufatura de uma frota de veículos movidos a diesel. Os

resultados indicam que a gestão eficaz da manutenção corretiva e preventiva são primordiais para a redução de custos, o aumento da disponibilidade dos veículos e a estabilidade da previsão orçamentária. Adicionalmente, o uso de peças remanufaturadas influencia na redução do tempo de reparo, aumenta a eficiência em custos dos processos de manutenção e colabora com a vertente ambiental de reaproveitamento de recursos, alinhando-se aos princípios da economia circular e promovendo maior sustentabilidade econômica e ambiental.
Palavras-chave: manutenção, remanufatura, desempenho financeiro, desempenho operacional, economia circular

1 INTRODUCTION

In the globalized and dynamic context of production and consumption, the demand for agile and efficient logistics solutions is constantly growing, imposing the need for greater punctuality, speed, and security in the delivery of products and services (Govindan et al., 2022; Nudurupati et al., 2021). At the same time, environmental concerns drive the need to optimize the use of transport or cargo vehicles in fleets, prioritizing energy efficiency and emissions reduction (Kechagias et al., 2020). In this context, the circular economy emerges as a restorative and regenerative economic model that seeks to maximize the value of resources throughout their life cycle, with the aim of promoting sustainability (Kirchherr et al., 2023).

Ensuring the operational continuity of organizations, with reliable fleets available when and where needed, while adopting a more rational and efficient approach to the use of available resources, can be considered the most important role of fleet management. However, there is still a need to promote business practices aligned with the principles of sustainability and the circular economy, given society's evolution toward adopting more sustainable consumption criteria, growing pressure for organizational practices and products that generate less environmental impact, and the establishment of public policies that aim to regulate and sanction the externalities allowed to productive sectors (Gaither & Frazier, 2002; Gomes et al., 2022).

An active, controlled maintenance system is crucial to increasing vehicle useful life and ensuring fleet safety (Melo & Junior, 2020; Campos & Belhot, 1994). Preventive maintenance is imperative; when neglected, it can have a negative, cascading effect on various vehicle components, increasing total maintenance costs, decreasing vehicle reliability, and increasing the likelihood of failures and accidents (Oliveira et al., 2017). In turn, vehicle components that are already showing faults, wear, or overload must undergo corrective maintenance (Berrade et al., 2023). Consequently, the replacement of damaged components is relatively common in a scenario of production, consumption, and disposal when they no longer have any use or value for the consumer (Stettiner et al., 2021). However, instead of discarding a component, the remanufacturing strategy can be employed to promote circularity (return to the production cycle) while restoring the functions of a damaged part or assembly, enabling it to operate at the reliability and quality levels of an original part (Shah et al., 2010).

Despite the benefits of maintenance and remanufacturing strategies in the automotive market, fleet owners remain reluctant to adopt them (Gunasekara et al., 2020). This hesitation may be rooted in the mistaken perception that implementing these strategies, even when aligned with the principles of the circular economy, would result in additional costs without providing savings compared to purchasing new components, and would not generate lasting, sustainable results (Vasudevan et al. 2012).

In this context, this study proposes to adopt a data-driven decision-making approach to mitigate these barriers. In recent years, the amount of available data has increased significantly (Mishra et al., 2018). The analysis of this data provides managers with valuable *insights* and a deeper understanding of their businesses, making the decision-making process more efficient (Marr, 2015; Sanders, 2016). Thus, both data and its analysis are central to decision-making, allowing for more accurate choices based on organizational and market realities. Companies are increasingly using data analysis to optimize operations, improve planning, accelerate innovation, create additional value for the business, and gain competitive advantage (Wang et al., 2016). In this study, the collection, organization, and systematic analysis of data related to the maintenance and remanufacturing of fleet vehicles were used to support strategic decisions. This approach not only supported preventive and corrective maintenance practices but also measured the economic and operational impact of these strategies, contributing to more efficient and sustainable fleet management aligned with the principles of the circular economy.

The objective of this study is to analyze the influence of adopting circular maintenance and remanufacturing strategies on vehicle cost and availability variables. The scope of the study focuses on diesel-powered vehicle fleets, based on a case study at a repair shop specializing in this segment. By conducting a longitudinal analysis of the fleet, the objective is to understand the effects of these strategies on two aspects: economic and operational vehicle availability, while accounting for downtime.

By offering concrete data that demonstrates the potential for resource savings, this study contributes by showing that the implementation of maintenance and remanufacturing strategies not only preserves resources from a circular economy perspective but also promotes better financial management and more efficient use over time. This approach can provide a solid basis for informed decisions in favor of promoting environmentally sustainable and financially efficient strategies in the management of diesel vehicle fleets.

This article is structured as follows: Section 2 provides a comprehensive review of the literature, covering the main definitions and concepts of maintenance and remanufacturing. Section 3 details the methodology adopted in the research. Section 4 presents and discusses the study's main results, offering a critical analysis of the findings. The article concludes with Section 5, which summarizes the theoretical and practical contributions of the research, as well as suggestions for future research.

2 THEORETICAL REFERENCE

This section addresses the concepts of maintenance and remanufacturing of damaged parts. The first part details the main types of maintenance adopted by organizations. The second part explores the remanufacturing strategy, where used parts are reused, offering a more environmentally sustainable alternative when part replacement is necessary.

2.1 Maintenance

Maintenance is the strategy organizations adopt to prevent failures in their equipment, physical facilities, and operations. Maintenance can be subdivided into five different types, namely: (i) detective maintenance; (ii) unscheduled corrective maintenance; (iii) scheduled corrective maintenance; (iv) preventive maintenance; and (v) predictive maintenance (Kardec & Nascif, 2009; Slack et al., 2009). Below is a brief definition of each type of maintenance in the automotive market, except for detective maintenance, which is outside the scope of this article.

ISSN: 2316-2341

Corrective maintenance is risky and costly to adopt as a standard maintenance policy, as it results from failures that can immobilize the vehicle for days, depending on variables such as the level of maintenance required, the availability and cost of spare parts, and the time required to perform the maintenance. This can harm the organization in operational and financial terms, impacting commercial relationships with customers (Corrêa & Corrêa, 2010). Unscheduled corrective maintenance is characterized by the execution of repairs in scenarios of failure or defects that have already occurred, usually without prior planning of resources or time. This implies high direct costs—such as personnel movement, emergency services, and equipment relocation—and indirect costs for organizations, such as unscheduled transportation downtime, delays in production lines and logistics flows, and compromised product/service quality (Guimarães, Nogueira & Da Silva, 2012). On the other hand, scheduled corrective maintenance refers to the correction of failures in an expected manner, i.e., the failure is anticipated, and it is decided to use the equipment until it reaches an unsustainable performance level or can no longer operate safely or efficiently. In this case, the costs are generally lower than those of unscheduled corrective maintenance (Guimarães, Nogueira & Da Silva, 2012), as maintenance is anticipated and resources can be planned more effectively.

Brazilian Standard (NBR) 5462 defines preventive maintenance as "maintenance performed at predetermined intervals, or according to prescribed criteria, intended to reduce the probability of failure or degradation of an item's performance" (ABNT, 1994, p. 07). Although essential, automakers do not always provide a maintenance plan to customers, leaving it to the fleet manager to plan downtime and the items to be checked during preventive maintenance (Kardec & Nascif, 2009).

The main objective of predictive maintenance is to predict equipment failures using predefined parameters, allowing the vehicle to operate continuously for as long as possible (del Castillo & Parlikad, 2024). Predictive maintenance focuses on analyzing the condition of the vehicle, assisting in decision-making about the best time for intervention, providing scope for planning and optimizing the use of resources. Once the decision to stop the vehicle has been made, predictive maintenance becomes scheduled corrective maintenance, which is already planned and has less operational impact (Kardec & Nascif, 2009).

Older vehicles with no or poorly managed preventive and predictive maintenance tend to generate higher levels of externalities, which are adverse effects of an economic activity that

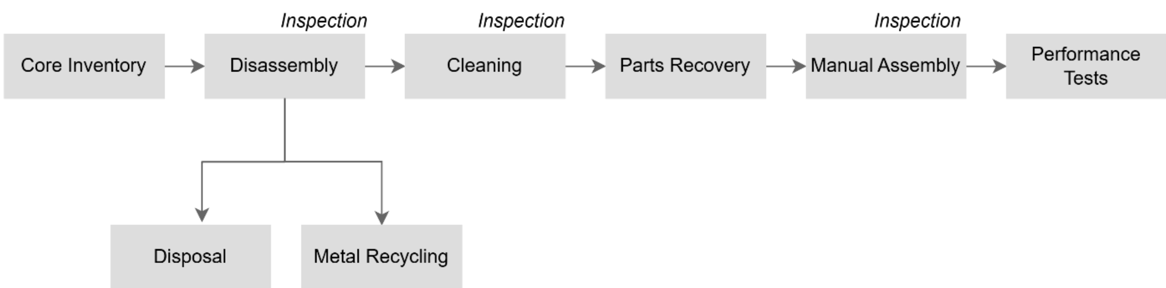
ISSN: 2316-2341

affect third parties and can be positive or negative (Dean & Mcmullen, 2007). Among the negative externalities, stand out high emissions of gases harmful to the environment, such as sulfur dioxide (SO_2) and nitrogen oxide (NO_2), especially in vehicles that do not comply with the EURO 5 standard, in force since 2012, which establishes that diesel engines must have a specialized system, such as EGR (Exhaust Gas Recirculation) or SCR (Selective Catalytic Reduction), for treating and reducing the emission of polluting gases into the environment (Carvalho Junior & Lacava, 2023). Additionally, lack of maintenance compromises vehicle safety, affecting essential components such as the brake system (responsible for slowing down or stopping the vehicle in motion) (Hussain et al., 2020), lighting components (such as lamps, flashlights, and headlights, which signal the driver's positions and actions), and the vehicle's suspension system, in addition to impacting delays in logistics processes, such as the non-delivery of products within a scheduled time frame (Kardec & Nascif, 2009).

2.2 Remanufacturing of damaged parts

In situations where corrective maintenance (scheduled or unscheduled) is necessary and requires the replacement of damaged parts, the alternative of using remanufactured parts, i.e., parts that have been reused and restored to conditions equivalent to new, can be an advantageous alternative (Wakiru et al., 2021). Figure 1 presents a representative summary of the remanufacturing process.

Figure 1
Stages of the remanufacturing process



Source: Adapted from Kerr & Ryan (2001) and Shafiee, Saidi-Mehrabad & Naini (2009)

In the context of remanufacturing, *core inventory* refers to returned used components or products that serve as essential raw materials for the process of rebuilding, repairing, or renovating products (Wei, Tang & Sundin, 2015). These returned items are called "cores" and

ISSN: 2316-2341

represent the core of the remanufacturing process. Figure 1 shows that the items in the core inventory are inspected before disassembly. During disassembly, some parts need to be discarded (because they cannot be reused, such as hoses, gaskets, and sealing rings), while others can be recycled (such as metal parts) (Kerr & Ryan, 2001). Cleaning is performed on dependent or remanufacturable parts, usually by immersion in a tank with hot water and solvents to remove lubrication or corrosion residues. This step enables a more detailed technical evaluation to detect possible cracks that would make remanufacturing the part unfeasible. The remanufacturing process is completed after the recovery and reassembly of *the* remanufacturable *core, along with new parts, resulting* in a product with the same application as a genuine component (Shafiee, Saidi-Mehrabad & Naini, 2009). The final quality must be of equal or higher than that of the original product, but with lower cost and environmental impact (Wei, Tang & Sundin, 2015).

In other words, remanufacturing consists of completely disassembling the product, overhauling and upgrading defective components, a reassembling the product, with the aim of meeting customer requirements for a new product (Shah et al., 2010). The remanufacturing process, as illustrated in Figure 1, involves the repair and replacement of defective components, along with their overhaul and upgrade, providing a restored part that meets the manufacturer's standards at a lower cost than purchasing a new part (Kerr & Ryan, 2001). The same authors highlight the difference between remanufacturing and reconditioning strategies. While remanufacturing involves disassembly, overhaul, repair, upgrade, and reassembly, reconditioning is limited to repairing damaged components, reassembling the part without overhauling the other components. In addition, reconditioning does not account for the manufacturer's original quality requirements, which can create uncertainty for consumers (Kerr & Ryan, 2001).

It is important to note that the remanufacturing strategy can bring benefits in terms of both environmental sustainability and economic efficiency (de Jesus Santos et al., 2023), allowing parts considered suitable for reuse to be restored to working conditions equivalent to new ones, which contributes to reducing waste and consumption of natural resources (Shafiee et al., 2009). This strategy therefore reduces dependence on new parts, which is especially valuable in situations of resource scarcity, time constraints, or supply chain disruptions (Kerr & Ryan, 2001).

ISSN: 2316-2341

3 RESEARCH METHODOLOGY

To achieve the objective of this study, which was to collect and analyze data on the cost of maintaining the vehicle fleet, the number of vehicles undergoing maintenance, and the technical and economic feasibility of using remanufactured parts, the research was structured in two main stages.

The first stage consisted of a literature review on maintenance and remanufacturing strategies, aligned with the scope of this study. This review was conducted through searches on the Web of Science and Scopus platforms. It should be noted that the literature review proposes a new perspective on a topic through innovative approaches and methodologies (Lakatos & Marconi, 2003). In this regard, the initial part of this research aimed to improve knowledge of the concepts and influences of maintenance and remanufacturing applied to diesel-powered fleet vehicles (Sousa et al., 2021).

In the second stage of the research, empirical data was collected, which constituted the single case study. This approach allowed us to explore and analyze real data, complementing theoretical findings with practical evidence (Eisenhardt & Graebner, 1989). The case study was selected as the method because this research addresses a current problem, whose boundary conditions are largely influenced by contextual factors (Yin, 2018). Additionally, there is a need for further study regarding the conditions of application and their consequences (Eisenhardt & Graebner, 1989). In terms of nature, this case study is characterized as exploratory, as it is based on the collection and analysis of longitudinal empirical data (Gasque, 2007).

The case study was conducted at a repair shop specializing in diesel-powered vehicles, which has been in business for seven years and is headquartered in the city of Santa Bárbara D'Oeste, in the state of São Paulo (Brazil). The investigated company provides preventive and corrective maintenance services, using new and remanufactured parts. Its portfolio includes a wide range of customers from various economic sectors, and its services cover vehicles of different brands, such as Mercedes-Benz, Volkswagen, Ford, Iveco, and Volvo. The company is a leader in preventive and corrective maintenance for electronic injection systems, Arla 32 systems, and general mechanical systems (e.g., suspension, brakes, engine, and transmission). Most of its clients are companies with their own fleets, which use them to provide services or transport products to their end customers.

ISSN: 2316-2341

The data analyzed in this study were collected from the maintenance history of a fleet of heavy vehicles belonging to one of the auto repair shop's client companies. This company is a leader in the installation and maintenance of poles, wiring, and generators for electricity transmission. The data collection covered a period of 22 months (from January 2022 to October 2023) and was based on historical records provided by the specialized auto repair shop.

Heavy-duty vehicles, the unit of analysis in the case study, are used to transport poles, operators, and machinery to locations designated to meet the requested demands. This fleet is mainly used for projects to install new power lines in residential, commercial, and industrial areas, as well as in rural areas and for the renovation of public infrastructure. Due to the nature of the work on uneven terrain, the vehicles are subject to frequent corrective maintenance on the suspension systems, including components such as bushings, shock absorbers, springs, steering terminals, and cab stops. The uneven terrain also significantly impacts the cooling system, including the radiator, *intercooler,* hoses, additives, thermostatic valve, and coolant reservoir. This is due to adverse conditions, such as dust and tall vegetation. The fleet analyzed has an average age of 5.25 years, which is considered relatively new by Brazilian standards.

4 RESULTS AND DISCUSSIONS

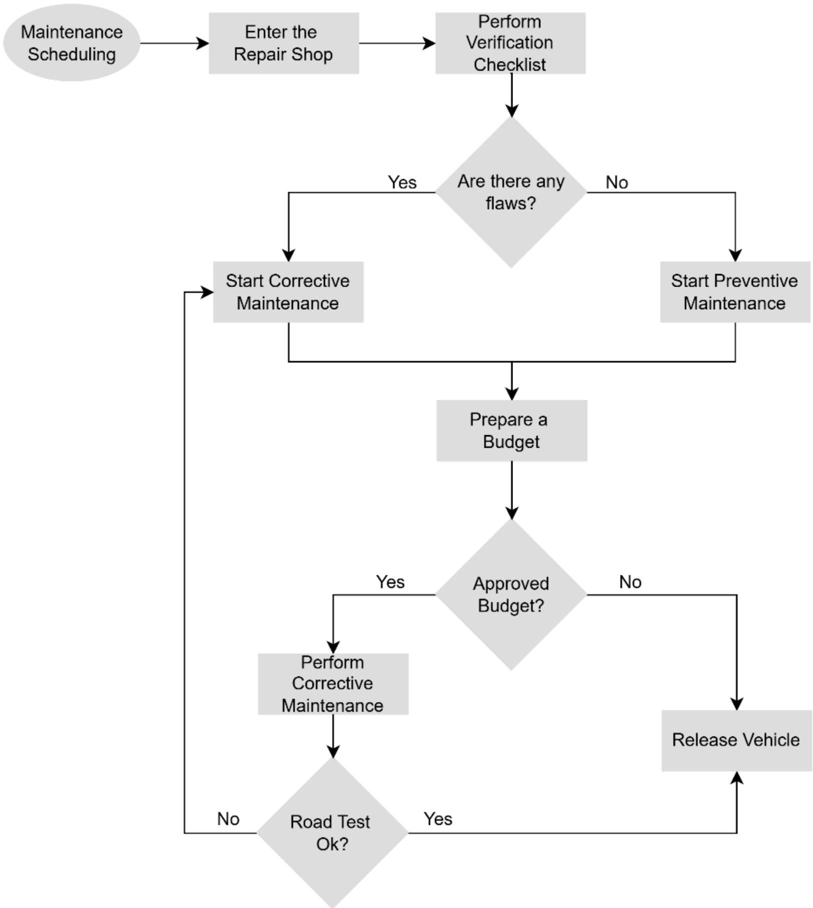
This section presents the results and discussion of the financial (operating costs) and operational (vehicle availability) analyses of maintenance and remanufacturing strategies, with a critical perspective in light of the circular economy.

4.1 Analysis of maintenance adoption

Figure 2 illustrates the flowchart for entering and maintaining a vehicle at the mechanical base, including activities from receipt through completion of maintenance services. After scheduling maintenance, a maintenance *checklist* is performed, in which safety items, lighting, oil and fluid levels, leaks, among others, are checked. If no faults are found, the vehicle is released. If adjustments and repairs are found to be necessary, corrective maintenance is performed. Final tests are then carried out to verify the vehicle's compliance and proper functioning. If the vehicle is approved, it is released for operation.

Figure 2

Maintenance Process Flowchart



Source: Prepared by the authors (2024).

Figure 3 shows how corrective and preventive maintenance costs evolved over the months, highlighting the significant reduction in costs, especially corrective costs, between 2022 and 2023. Total maintenance costs, which include both corrective and preventive maintenance, show a downward trend over the period analyzed. This decline indicates that the actions implemented, combining preventive and corrective maintenance, contributed to containing overall maintenance expenses.

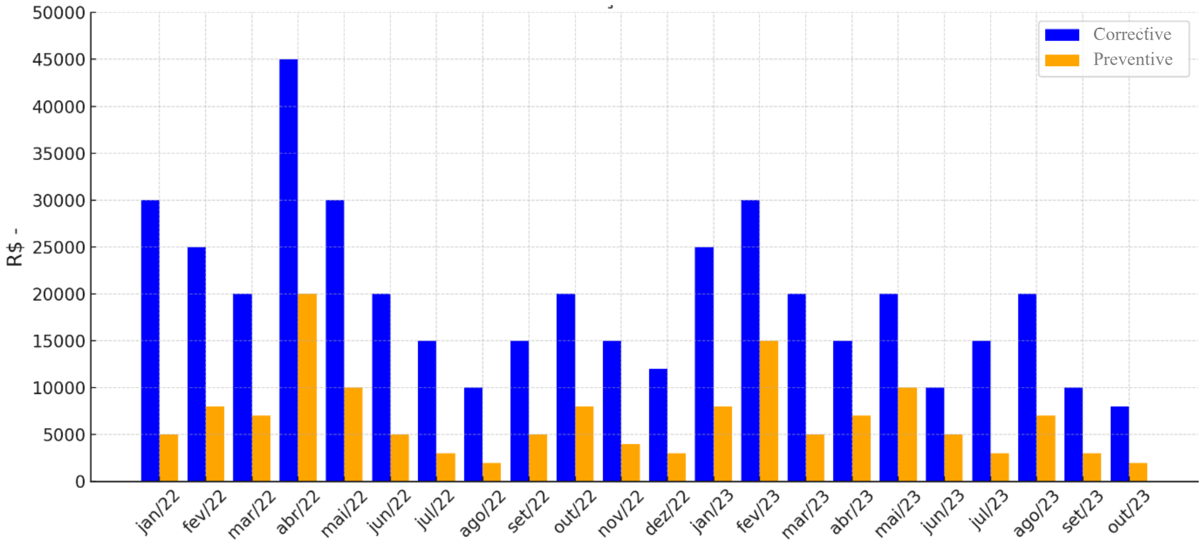
As shown in Figure 3, at the beginning of the period analyzed (January 2022), corrective maintenance costs were significantly high, reaching R$29,537.32. These values peaked in April of the same year, reaching R$44,692.22. For comparison purposes, the same months of the following year (2023) recorded a reduction of 20.01% in January and 80.64% in April, respectively. In relation to the total spent in the year, up to October 2022, corrective

ISSN: 2316-2341

maintenance costs totaled R$249,318.96, while spending in 2023, up to October, totaled R$151,469.94, resulting in a percentage decrease of approximately 39.19%, or R$97,849.02, in corrective costs compared to the previous year.

Figure 3

Record of Maintenance Costs / Month



Source: Prepared by the authors (2024).

In summary, Table 1 shows the evolution in the reduction of total maintenance costs, highlighting the positive relationship between the implementation of this strategy and the financial benefits achieved. These results suggest that adopting this strategy can be an effective solution for cost management, contributing to the financial sustainability of fleet operations.

Table 1

Phases of evolution of total maintenance costs

Phase	Months	Preventive Cost	Corrective Cost	Total	Reduction
1	Jan/22 to Jul/22	R$ 50,572.85	R$ 198,487.36	R$ 249,060.21	-
2	Aug/22 to Feb/23	R$ 49,028.08	R$ 117,965.52	R$ 166,993.60	33
3	Mar/23 to Oct/23	R$ 52,495.63	R$ 103,629.62	R$ 156,125.25	7

Source: Prepared by the authors (2024).

The decline in corrective costs and stability in preventive maintenance are consistent with an increase in vehicle availability for operation. Figure 4 shows the number of vehicles stopped for corrective maintenance, showing a significant drop in recent months compared to the first months of the period analyzed. These data confirm that corrective and preventive maintenance management reduced vehicle downtime and inactivity, optimizing operations.

Thus, it can be inferred that the maintenance interventions performed on vehicles during the first half of 2022 generated sequential positive impacts on subsequent maintenance. This is evidenced by the substantial 65% reduction in the number of vehicles stopped for maintenance in the same period of 2023. With vehicles being checked on a regular basis, faults were prevented or assessed at an early stage, before they developed into a total vehicle breakdown and consequently halted operations. This indicates a continuous improvement in maintenance efficiency and management, which contributed to greater vehicle availability and performance over time, consistent with the findings of del Castillo & Parlikad (2024).

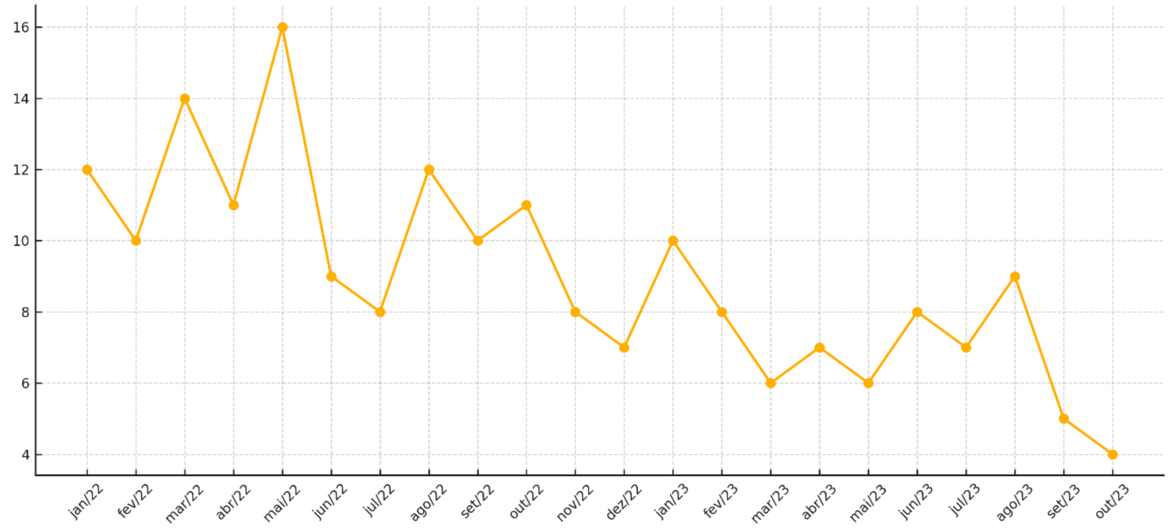
The analysis of vehicle costs and availability suggests that effective corrective and preventive maintenance and early fault identification contributed to reduced operating costs and resource optimization, with increased fleet availability. Thus, there are positive indications of the maintenance strategy's financial and operational performance.

In addition, the increase in vehicle availability demonstrates that maintenance directly contributes to maximizing the useful life of vehicles and their components, in line with the principles of the circular economy. Through effective maintenance management, it is possible to postpone the need for parts replacement, ensuring that vehicles remain in use for as long as possible. Thus, in addition to increasing the durability and performance of vehicles (Hussain et al., 2020), the maintenance strategy plays an important role in sustainability, being one of the means to promote the circular economy.

At the same time, in the case of corrective maintenance, an integrated remanufacturing approach can be paramount for a positive impact on maintenance costs, as found by Shafiee et al. (2009). It can also have a positive long-term environmental impact, as remanufacturing reduces the consumption of new components and decreases waste generation (de Jesus Santos et al., 2023).

Figure 4

Number of vehicles out of service for maintenance / Month



Source: Prepared by the authors (2024).

4.2 Analysis of the adoption of remanufacturing

In this case study, the company opted for the remanufacturing strategy on six occasions, four of which involved the vehicle's brake system, specifically the pneumatic valves. These valves play an important role in transmitting, regulating, and metering the air needed to activate the linings, drums, ratchets, and the "maneco" brake. The remanufactured part studied in the research was the 4-way or 4-circuit valve, whose function is to receive air from the compressor and distribute it throughout the vehicle's system. When there are failures, the valve leaks air, which leads to a decrease in the vehicle's barometric pressure, compromising the vehicle's operational safety. During the period analyzed, this component presented this critical failure and underwent the remanufacturing process. Figure 5 shows a set of images of the 4-way valve remanufacturing process.

Figure 5

Example of the remanufacturing process applied to the 4-way valve

ISSN: 2316-2341

Image 1 – 4-way valve

Image 2 – Disassembly

Image 3 – Cleaning and Inspection

Image 4 – Bench testing

Image 5 – Release of the part

Source: Internal collection of the mechanical repair workshop (2024).

Table 2 presents a comparative analysis of remanufacturing adoption and the acquisition of a new part (without adopting remanufacturing). When using remanufactured parts, the vehicle is released on the same day, with an average turnaround time of 3 hours, which does not interfere with operations. This agility eliminates the need to reallocate personnel and mobilize another vehicle to serve the customer, ensuring operational continuity. In addition, the cost of a remanufactured part is approximately 76% lower than that of a new part, with the same warranty period and the same level of quality. This indicates that remanufacturing is also an advantageous strategy in terms of financial and operational performance.

ISSN: 2316-2341

The choice to remanufacture reflects a decision aligned with the principles of the circular economy, as it avoids complete replacement with a new component, promoting the recovery and reuse of the part.

Table 2

Comparative analysis of cost and time, with and without remanufacturing

	Price	Time to vehicle availability	Warranty
With remanufacturing	R$120.00	3 hours	6 months
Without remanufacturing	R$ 504.50	1 business day	6 months

Source: Prepared by the authors (2024).

In addition to reducing operating costs (Table 2), it also minimizes waste generation and the demand for new resources, including virgin raw materials, contributing to the sustainability of operations. These findings reinforce the findings of Jesus Santos et al. (2023) and Wakiru et al. (2021).

5 CONCLUSION

The objective of this study was to analyze the influence of adopting maintenance and remanufacturing strategies on the cost and availability variables of diesel-powered vehicles through a case study conducted at a specialized auto repair shop in the sector. The results show that both strategies offer significant benefits, contributing to financial and operational improvements for companies and customers. The adoption of these strategies resulted in a significant reduction in costs over the life cycle of the vehicles, in addition to maximizing operational availability.

This study enriches the literature on sustainability and the circular economy by exploring how maintenance and remanufacturing strategies enhance financial and operational performance, thereby promoting greater economic and environmental efficiency. This strengthens the theoretical basis for the use of these strategies as viable within sustainable logistics chains.

The practical contributions of this study are based on supporting data-driven decision-making for managers, considering the analysis of the benefits of maintenance and remanufacturing strategies, facilitating informed decisions that promote efficiency and sustainability. Data collection and analysis provided valuable contextual and quantitative results, demonstrating the relevance of data integration and strategic management for the success of the strategies implemented. The study serves as a practical case for organizations seeking to adopt circular economy principles, showing that maintenance and remanufacturing not only add environmental value but also reduce costs and increase the operational availability of assets.

However, this research also has limitations. The study was conducted based on a single case study, in a specialized auto repair shop, focusing exclusively on diesel vehicles. Although the study results demonstrate the relevance of these strategies from a financial and operational perspective, this narrow focus may limit the generalization of results to other contexts or types of vehicles (such as electric vehicles). For future research, we suggest broadening the scope to include different types of vehicles and fuels, incorporating other customers of the organization to create important and comparative evidence for the evolution of the business model, adding credibility to the service, and highlighting the importance of fleet management to other customers and partners. In addition to financial and operational analyses, it is also suggested that more detailed environmental and social analyses be incorporated.

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