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COMPARATIVE ANALYSIS BETWEEN GRAPHENE-BASED HYBRID VEHICLES WITH COMPOSITE GRAPHENE, BY APPLYING THE SAPEVO H2 METHOD

ANÁLISE COMPARATIVA ENTRE VEÍCULOS HÍBRIDOS COM GRAFENO, APLICANDO O MÉTODO SAPEVO H2

ANÁLISIS COMPARATIVO ENTRE VEHÍCULOS HÍBRIDOS CON GRAFENO, APLICANDO EL MÉTODO SAPEVO H2

Mauricio Cintra do Prado de Salles Penteado[1], Marcos dos Santos[2], Carlos Francisco Simões Gomes[3]

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ABSTRACT

Since its discovery in 2004, graphene has gained increasing industrial relevance, including applications in the automotive sector. However, an analysis of more than 120 articles indexed in Scopus between 2020 and 2024 shows that most studies focus only on specific and isolated advantageous properties of graphene, without comparing similar parameters across vehicle applications. To address this gap, 15 studies were selected to support a comparative assessment of hybrid vehicles enhanced with graphene-based additives. The objective was to evaluate acquisition cost, fuel consumption and oil consumption using the SAPEVO-H² multicriteria decision method. A hypothetical scenario was modeled for four hybrid vehicles priced between R$120,000 and R$150,000, incorporating 0.1–0.3% graphene (by volume) into the coolant, leading to an estimated 6–8% increase in specific heat under the modeled conditions, and 0.15–0.20% graphene (by mass) into the engine oil, yielding a 33–39% reduction in friction coefficient. The analysis indicated that coolant performance had the highest relevance (44.6%), followed by acquisition cost (33.4%) and engine oil performance (22.0%). Among the alternatives, Vehicle 1 (R$120,000) was identified as the best option, while Vehicle 4 (R$150,000) was the least favorable.

KEYWORDS: Multicriteria decision analysis. Decision-making models. Sapevo-H2. Graphene. Automobile.

RESUMO

Desde sua descoberta, em 2004, o grafeno tem adquirido crescente relevância industrial, incluindo aplicações no setor automotivo. No entanto, uma análise de mais de 120 artigos indexados na Scopus entre 2020 e 2024 demonstra que a maioria dos estudos se concentra apenas em propriedades vantajosas específicas e isoladas do grafeno, sem comparar parâmetros semelhantes em diferentes aplicações veiculares. Para suprir essa lacuna, 15 estudos foram selecionados a fim de subsidiar uma avaliação comparativa de veículos híbridos aprimorados com aditivos à base de grafeno. O objetivo foi avaliar o custo de aquisição, o consumo de combustível e o consumo de óleo, utilizando o método de decisão multicritério SAPEVO-H². Modelou-se um cenário hipotético para quatro veículos híbridos com preços entre R$ 120.000,00 e R$ 150.000,00, incorporando 0,1–0,3% de grafeno (em volume) ao líquido de arrefecimento, o que levou a um aumento estimado de 6–8% no calor específico, sob as condições modeladas, e 0,15–0,20% de grafeno (em massa) ao óleo do motor, resultando em redução de 33–39% no coeficiente de atrito.

[1] Department of Industrial Engineering of Fluminense Federal University / Department of Materials and Metallurgical Engineering of the Polythecnical School of the University of São Paulo. São Paulo – SP, Brazil.
[2] Department of Industrial Engineering of Fluminense Federal University. Rio de Janeiro – RJ, Brazil.
[3] Department of Industrial Engineering of Fluminense Federal University. Rio de Janeiro – RJ, Brazil

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A análise indicou que o desempenho do líquido de arrefecimento apresentou a maior relevância (44,6%), seguido pelo custo de aquisição (33,4%) e pelo desempenho do óleo do motor (22,0%). Dentre as alternativas, o Veículo 1 (R$ 120.000,00) foi identificado como a melhor opção, enquanto o Veículo 4 (R$ 150.000,00) foi o menos favorável.

PALAVRAS-CHAVE: Análise de decisão multicritério. Modelos de tomada de decisão. Sapevo-H2. Grafeno. Automóvel.

RESUMEN
Desde su descubrimiento en 2004, el grafeno ha adquirido una creciente relevancia industrial, incluyendo aplicaciones en el sector automotriz. Sin embargo, un análisis de más de 120 artículos indexados en Scopus entre 2020 y 2024 muestra que la mayoría de los estudios se centran únicamente en propiedades específicas y ventajosas aisladas del grafeno, sin comparar parámetros similares en diferentes aplicaciones vehiculares. Para abordar esta deficiencia, se seleccionaron 15 estudios para respaldar una evaluación comparativa de vehículos híbridos mejorados con aditivos a base de grafeno. El objetivo fue evaluar el costo de adquisición, el consumo de combustible y el consumo de aceite mediante el método de decisión multicriterio SAPEVO-H². Se modeló un escenario hipotético para cuatro vehículos híbridos con precios entre R$120.000 y R$150.000, incorporando 0,1-0,3% de grafeno (por volumen) al refrigerante, lo que lleva a un aumento estimado del 6 al 8% en el calor específico en las condiciones modeladas, y 0,15-0,20% de grafeno (por masa) al aceite del motor, lo que produce una reducción del 33-39% en el coeficiente de fricción. El análisis indicó que el rendimiento del refrigerante tuvo la mayor relevancia (44,6%), seguido del costo de adquisición (33,4%) y el rendimiento del aceite del motor (22,0%). Entre las alternativas, el Vehículo 1 (R$120.000) se identificó como la mejor opción, mientras que el Vehículo 4 (R$150.000) fue el menos favorable.

PALABRAS CLAVE: Análisis de decisiones multicriterio. Modelos de toma de decisiones. Sapevo-H2. Grafeno. Automóvil.

INTRODUCTION

How to structure a multi-criteria model capable of comparing hybrid vehicles with the addition of graphene in automotive fluids, considering cost and technical performance?

The search for solutions that promote greater energy efficiency, environmental sustainability and vehicle safety has driven interest in innovative materials in the automotive sector. Among these materials, graphene has stood out due to its unique physicochemical properties, such as high mechanical strength, lightness, excellent electrical and thermal conductivity, as well as notable durability and resistance to corrosion (Okan *et al.*, 2020). These characteristics make it promising for application in hybrid vehicles, especially in components such as coolant and engine oil, with the potential to reduce fuel consumption and extend the vehicle's useful life.

It is important to mention that the hybrid vehicle market has shown growth in Brazil in recent years. Data from the Brazilian Electric Vehicle Association (ABVE, 2025) shows a significant increase in the number of registrations in January 2022, with a growth of 93% compared to the same month in 2021, reflecting a growing adoption of electric and hybrid vehicles in the country

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(ABVE, 2025). This trend is corroborated by accumulated data from 2024, where the number of light electrified vehicles registered in the first seven months has already surpassed the total from 2023, which until then had been the best year for electromobility in Brazil (ABVE, 2025).

The data also shows that the fleet of electrified vehicles in Brazil, since 2012, has surpassed the mark of 300 thousand units, demonstrating the expansion of this market. The fact that July 2024 recorded the best sales of the year and the total number of plug-in vehicles represents a significant portion of the fleet (152,493 vehicles) highlights the popularity and acceptance of these technologies in the country (ABVE, 2025).

To meet growing consumer demands for greener, more efficient and safer vehicles, it is essential to understand how graphene manufacturing techniques impact the quality, sustainability and cost of these vehicles. Reducing vehicle weight has proven to be one of the most promising ways to achieve this goal, as just a 10% weight reduction can improve fuel economy by 6–8% and reduce CO_2 emissions by 15–20 g/km (Okan *et al.*, 2020).

However, when evaluating the feasibility of using graphene in the automotive sector, one must consider not only its technical benefits, but also the still current obstacles for its production on an industrial scale. In this regard, it becomes necessary to apply decision support methods capable of dealing with multiple criteria and technological alternatives, promoting better-informed choices by automakers and other agents in the sector.

In this scenario, the importance of employing robust systemic analysis tools to structure the decision-making process stands out. According to Silva (Silva *et al.*, 2018), many problems encountered in reality fit the definition of multi-criteria decision making. People find their individual preferences while being present in evaluative judgments in multi-criteria decision-making problems. Based on the author, it is possible to state that it may not be difficult to decide when there are few criteria or few alternatives. However, as the subject becomes more complex, people's information processing capacity is restricted, decision-making becomes more difficult and help may be needed. In these cases, rather than trying to integrate a lot of knowledge and decide, applying simple rules and procedures and evaluating the problem gradually will make the decision easier.

In order to understand the different actors, objectives and contexts involved in the introduction of graphene in hybrid vehicles, the CATWOE methodology is used, widely used in the soft systemic approach. Involved expectations and variables can be analysed through the following deployment:

a) C (Clients) – End customers are consumers interested in purchasing hybrid vehicles improved with graphene.

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b) A (Actors) – The actors include engineers and vehicle evaluators, with emphasis on the head of vehicle evaluation.

c) T (Transformation) – The desired transformation is the incorporation of graphene into the coolant and engine oil, aiming for better energy performance and reduced operating costs.

d) W (Worldview) – The worldview is based on reducing pollution, increasing vehicle safety and promoting sustainability.

e) O (Owner) – The person responsible for the process is the head of vehicle evaluation, who leads decision-making.

f) E (Environment) – The environment involves the context of new technologies applied to sustainable mobility and their social and environmental impacts.

From the definition of this scenario, it becomes relevant to highlight the beneficial properties of graphene for the automotive industry: (i) its lightness and structural strength allow the reduction of vehicle weight, increasing energy efficiency; (ii) its high electrical and thermal conductivity fosters improvements in cooling systems and batteries; (iii) its application in safety materials, such as brake systems and bodies, increases occupant protection; (iv) its durability and corrosion resistance extend the service life of automotive parts, reducing maintenance costs; (v) its contribution to sustainability arises from the reduction of greenhouse gas emissions and less disposal of materials.

However, the adoption of graphene on a large scale faces technical and economic challenges, especially in relation to the feasibility of its production and application in different vehicle components. In this regard, it is necessary to adopt a structured approach to decision support that allows the available alternatives to be comparatively evaluated, based on multiple relevant criteria and decision-makers' value judgments.

The decision method "*Simple Aggregation of Preferences Expressed by Ordinal Vectors – Hybrid and Hierarchical (Sapevo-H^2)*" is applied in this paper, of which use is justified by its important advantages: (i) ease of use through accessible software; (ii) possibility of asynchronous and geographically independent participation of decision-makers; (iii) compatibility with qualitative and subjective judgments; and (iv) ability to generate classification rankings of alternatives based on the relative importance of the criteria. Timelessness and spatial independence are especially advantageous, allowing evaluators to make decisions at different times and locations.

The Sapevo-H^2 method structures, in this paper, decision making through three levels: first-level objectives, which guide the evaluation; second-level acceptance criteria, which derive from the objectives and guide value judgments; and last-level alternatives, quantitative and comparable to each other. The results may vary depending on the opinions of decision makers,

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but the method stands out for saving time and resources in obtaining conclusive answers. When the decision criteria are eminently quantitative and do not involve value judgments, other methods, such as the MPSI-Mara or CROWN, may be more appropriate — although they are not within the scope of this article.

The Sapevo-H^2, in this study, was applied to carry out a comparative evaluation between hybrid vehicles, considering the addition of graphene in the coolant and engine oil, aiming at minimizing the acquisition cost, fuel consumption and oil consumption. Therefore, this article seeks to contribute to the technical literature by proposing a structured assessment model for the adoption of emerging technologies in the automotive sector, considering aspects of cost, performance and sustainability.

1. METHODOLOGY

The current study was conducted in two main stages. The first consisted of a systematic survey of scientific articles available in the Scopus database, aiming at identifying the effects of adding graphene to automotive fluids, specifically coolant and engine oil. To select the articles, researches published in the last five years (2019 to 2024) were considered, through the following keywords: Sapevo-H^2, Graphene, Automobile. This strategy sought to ensure the relevance and timeliness of the sources, in addition to covering both literature in Portuguese and English.

This study is focused on investigating the qualitative and quantitative approach, as it combines numerical analysis of data extracted from the literature with the subjective and structured assessment of preferences, by means of the SAPEVO-H² method. The study is also exploratory and applied in nature, as it explores the potential benefits of using graphene in automotive fluids, and applies a robust methodology to support decisions in complex scenarios. Therefore, the method allowed the integration of qualitative and quantitative data, through a hierarchical structure that involved both objective variables and criteria derived from perceptions and priorities, contributing to the comprehensive evaluation of alternatives.

To comparatively propose the evaluation in this study, a hypothetical scenario was developed, among 4 hybrid vehicles, at the acquisition cost from R$ 120,000.00 to R$ 150,000.00, by adding 0.1% to 0.3% of graphene, by volume, in the coolant (generating 6% to 8% increase in specific heat), and 0.15% to 0.20% of graphene, in mass (generating a 33% to 39% reduction in the coefficient of friction), in engine oil. The acronyms "*VehCost*", for the 1st Level Objective Variable, and "*Cost*", for the 2nd Level Criteria, were respectively established.

The Sapevo-H^2 method was used to perform the analysis. This method was proposed by Moreira (Moreira *et al.*, 2023) *et al.*, characterized as an advanced approach to supporting multi-criteria decisions aimed at complex scenarios. The methodology allowed evaluating alternatives

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based on multiple criteria and perceptions, integrating hierarchically structured objectives and analyzing qualitative and quantitative data. As a practical application, the study analyzed defense strategies against remotely piloted aircraft systems (anti-RPAS) for the Brazilian Navy, using causal maps and the SODA methodology to structure the problem. The model generated rankings of the technologies evaluated based on subjective information, highlighting their potential for strategic decisions.

As the number of possible vehicle combinations between the Acquisition Cost (from R$ 120,000 to R$ 150,000), the Percentage Increase in the Specific Heat of the Coolant (from 6% to 8%), and the Reduction in the Coefficient of Friction of the Engine Oil (from 33% to 39%) would be very large, a simplification of the illustration of the Sapevo-H2 method was adopted, by limiting it to 4 hypothetical vehicles, 4 combinations of Coolant Specific Heat Percentage Increase, and 4 combinations of Engine Oil Friction Coefficient Reduction.

2. RESULTS

From the bibliographical survey carried out, it was verified that graphene has been developed exponentially since the discovery of its most diverse and advantageous properties in 2004, and has recently found application in industry, including the automotive industry. However, more than 120 articles found on automotive graphene in the Scopus database, from 2020 to 2024, focused on listing advantageously specific properties, arising from specific production processes, on one or more parameters, individually, without having made comparisons between similar parameters, in vehicles. Therefore, by aiming at listing and comparing two similar specific properties, originating from specific manufacturing processes, 15, out of 120 found articles, were filtered.

The selection of 15 scientific articles, in the Scopus database, showed that the percentage of addition of graphene, by volume, in the range of 0.1% to 0.3%, in the coolant, caused the value of the specific heat of the coolant to increase from 6% to 8% (in J/KgK). The logic resulting from this procedure lies in the fact that the addition of graphene increases the calorific value of the coolant, and, therefore, a greater reduction in fuel consumption in the engine. The acronyms "*FuelConsumption*", for the 1st Level Objective Variable, and "*MaxCoolingPImpr*", for the 2nd Level Criterion, were respectively established. Thus, the objective is to maximize the percentage of graphene addition in the coolant.

The results also showed that the percentage of addition of graphene, in the engine oil, in the range of 0.15% to 0.20%, by mass, in the engine oil, resulted in a reduction in the coefficient of friction of the engine oil, in the range of 33% to 39%. The logic lies in the fact that the addition of graphene to engine oil means that this reduction in the coefficient of friction also results in a

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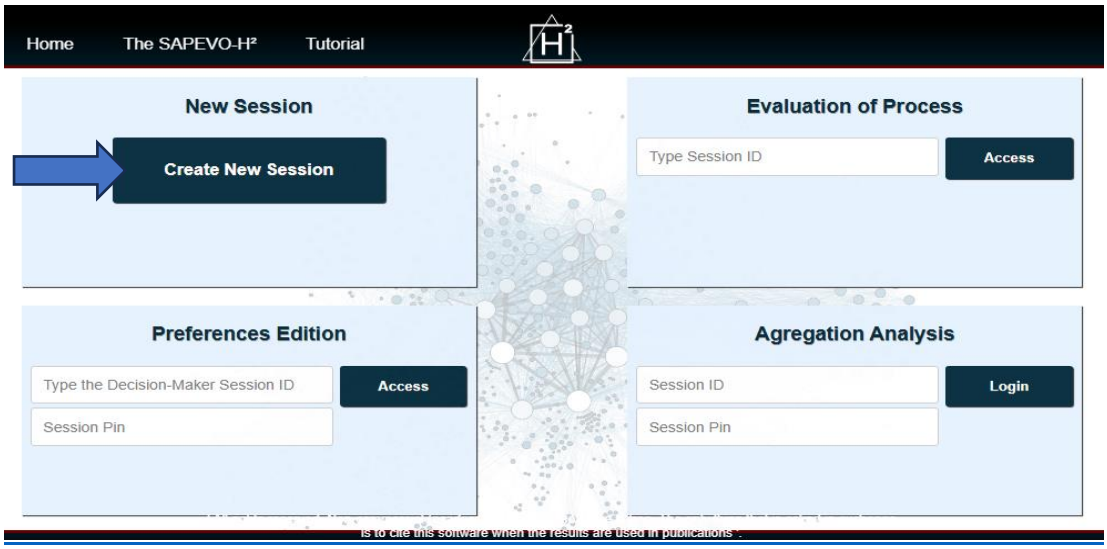
reduction in engine oil consumption. The acronyms "*OilConsumption*", for the 1st Level Objective Variable, and "*MaxFricPRed*", for the 2nd Level Criterion, were respectively established.

From the construction of the hypothetical scenario, the application of the SAPEVO-H² method began with access to the official platform (https://www.sapevo-h2.com/home.php), where a new session was created to insert the variables and alternatives analyzed (Figure 1).

Figure 1. Initial filling of the Fields on the Sapevo-H^2 site



Source : https://www.sapevo-h2.com/home.php

In the "*Session Data*" tab, a hierarchical structure was defined consisting of three levels, with three qualitative variables at the first level and no quantitative variables, according to the parameters established for the first decision maker *(D-A)* (Figure 2).

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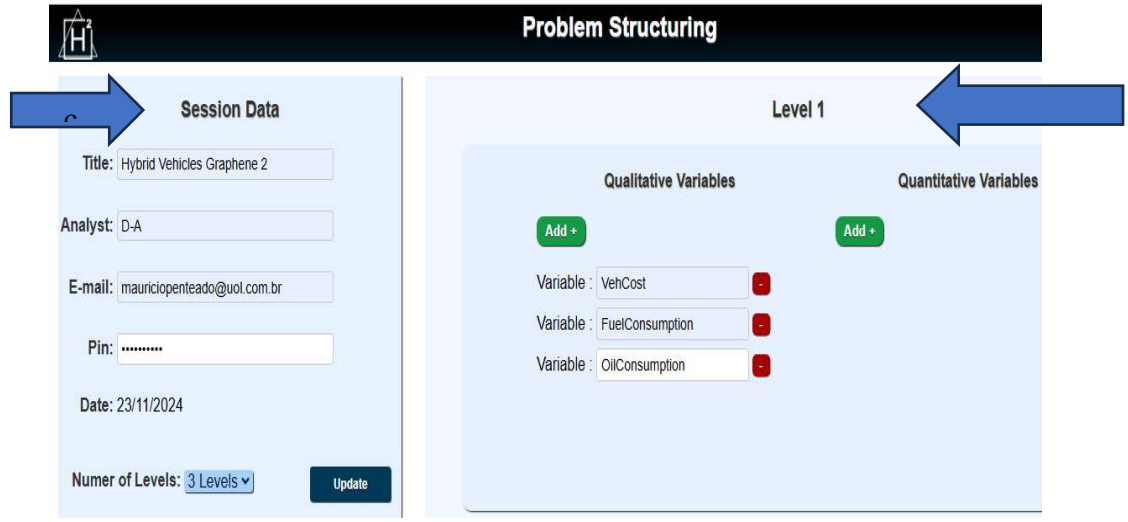
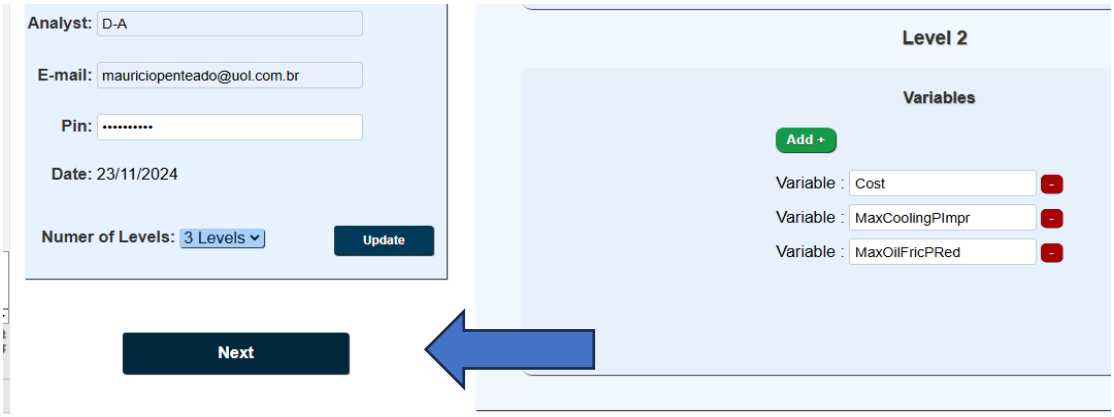
Figure 2. Filling in the Fields referring to Level 1



Source: https://www.sapevo-h2.com/home.php

At *Level 2*, the variables were introduced: *Cost* (Vehicle Acquisition Cost), *MaxCoolingPImp* (Maximum Cooling Potential Improvement, with the addition of graphene) and *MaxOilFricPRed* (Maximum Engine Oil Friction Coefficient Potential Reduction, ith the addition of graphene)(Figure 3).

Figure 3. Filling in the Fields referring to Level 2



Source: https://www.sapevo-h2.com/home.php

After this configuration, the platform automatically generated the subsequent screen for *Level 3*, in which the four hypothetical vehicle alternatives were registered, previously defined with different combinations of the analyzed parameters (Figure 4).

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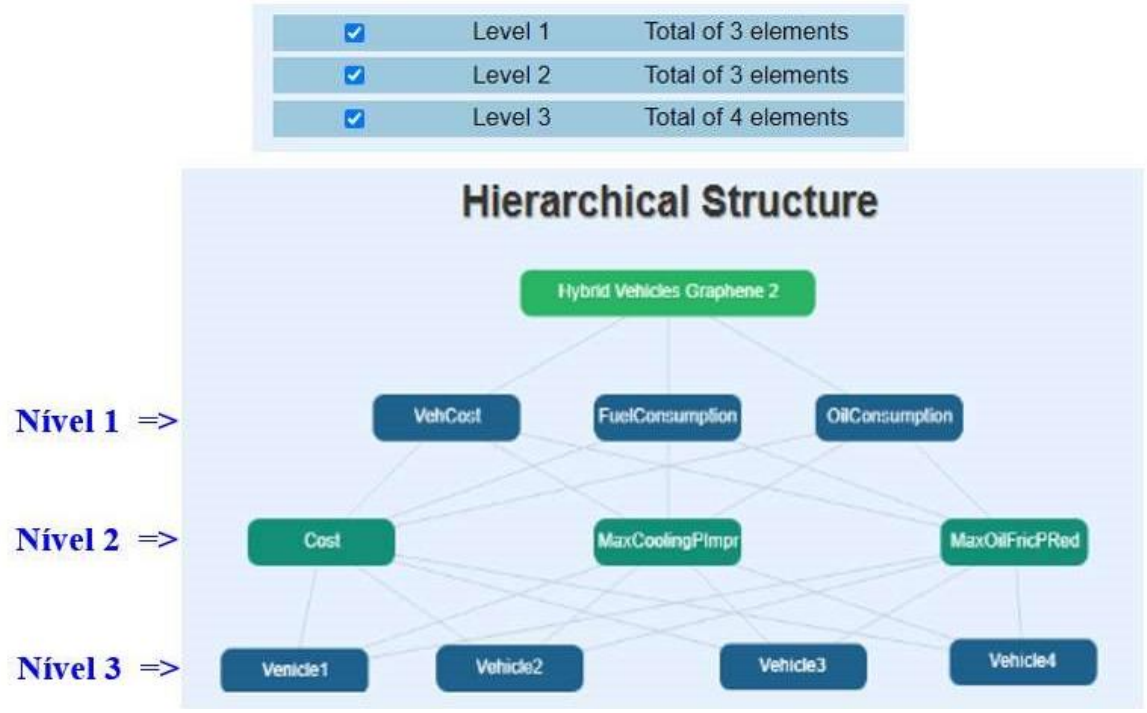
Figure 4. Hierarchical Structure



Source: https://www.sapevo-h2.com/home.php

Next, the variables were qualitatively assessed by the *D-A* decision maker, at *Levels 1* and *2*, assigning relative preferences based on subjective judgments (Figure 5). Subsequently, a quantitative assessment was carried out, also by decision maker *D-A*, at *Level 2*, based on the insertion of objective data previously extracted from the scientific literature on the effects of graphene in automotive fluids (Figure 6).

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Figure 5. Qualitative Assessment, by Decision Maker D-A, at Level 1 and Level 2

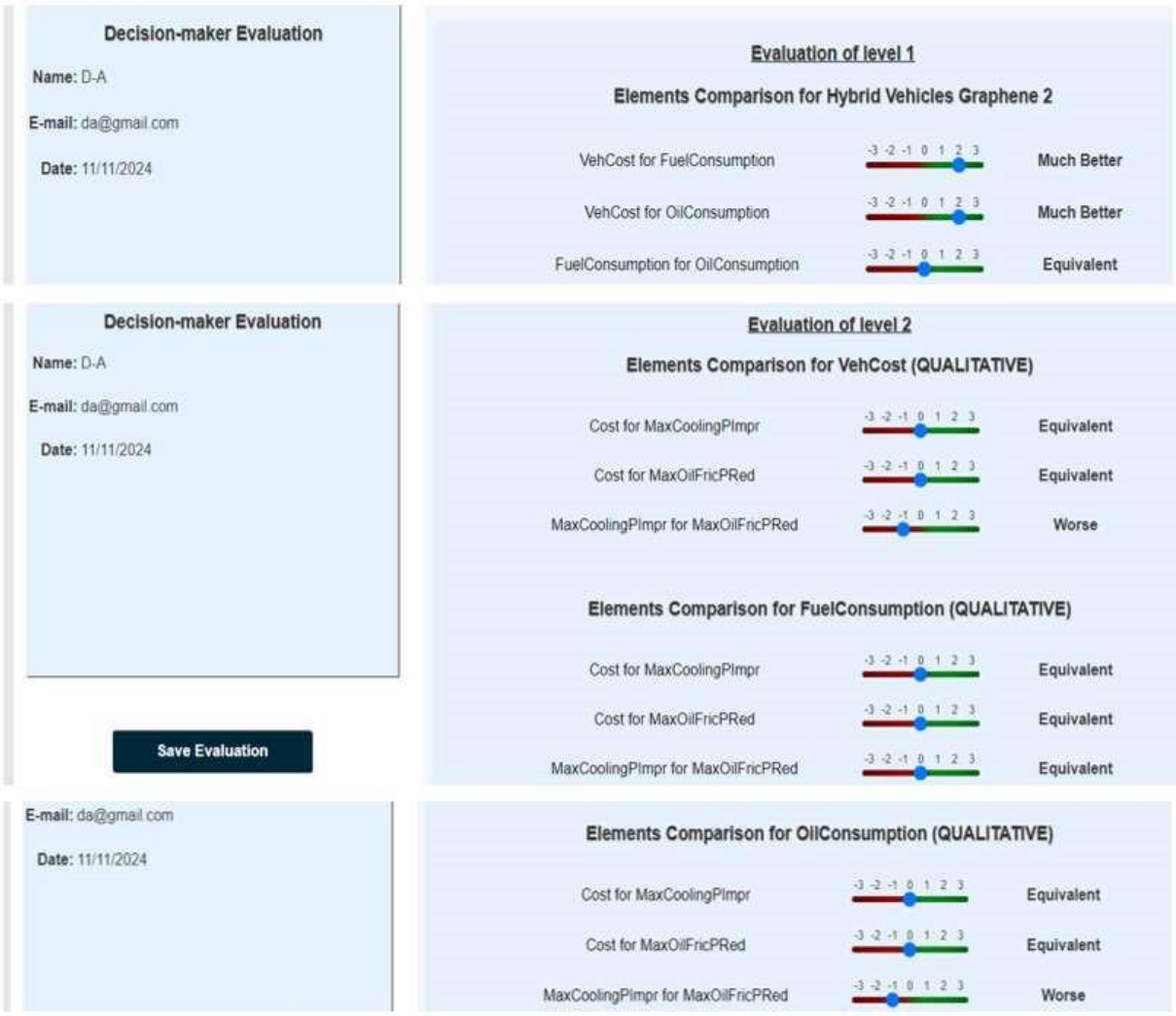

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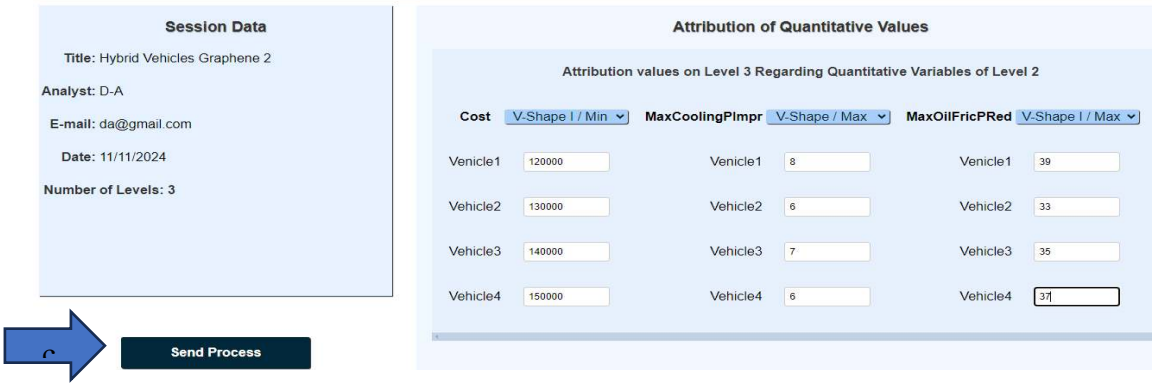
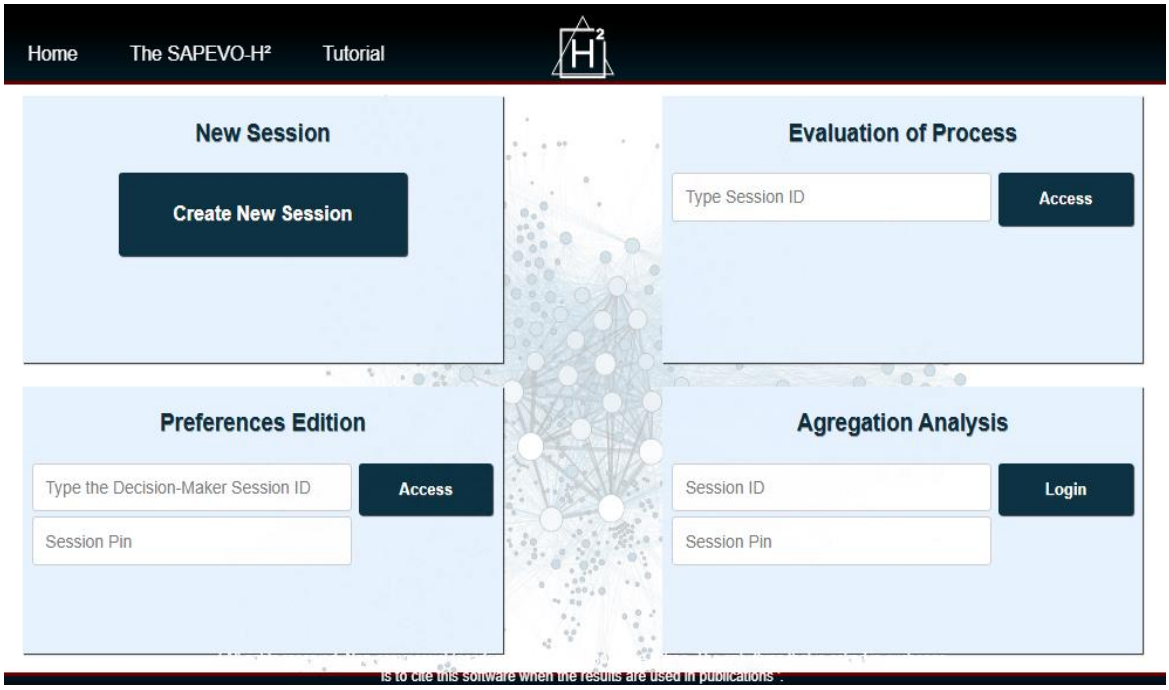
Figure 6. Quantitative Assessment, by Decision Maker D-A, at Level 2, and sending data: Send Process



Source: https://www.sapevo-h2.com/home.php

After sending this information, the same process was replicated for *decision makers D-B and D-C*, ensuring multiple perspectives when judging the variables. Finally, the evaluations of the three decision makers were integrated, by using the "*Aggregation Analysis*" command, allowing consolidated results to be obtained (Figure 7).

Figure 7. **Aggregation of data generated by decision makers D-A, D-B e D-C**



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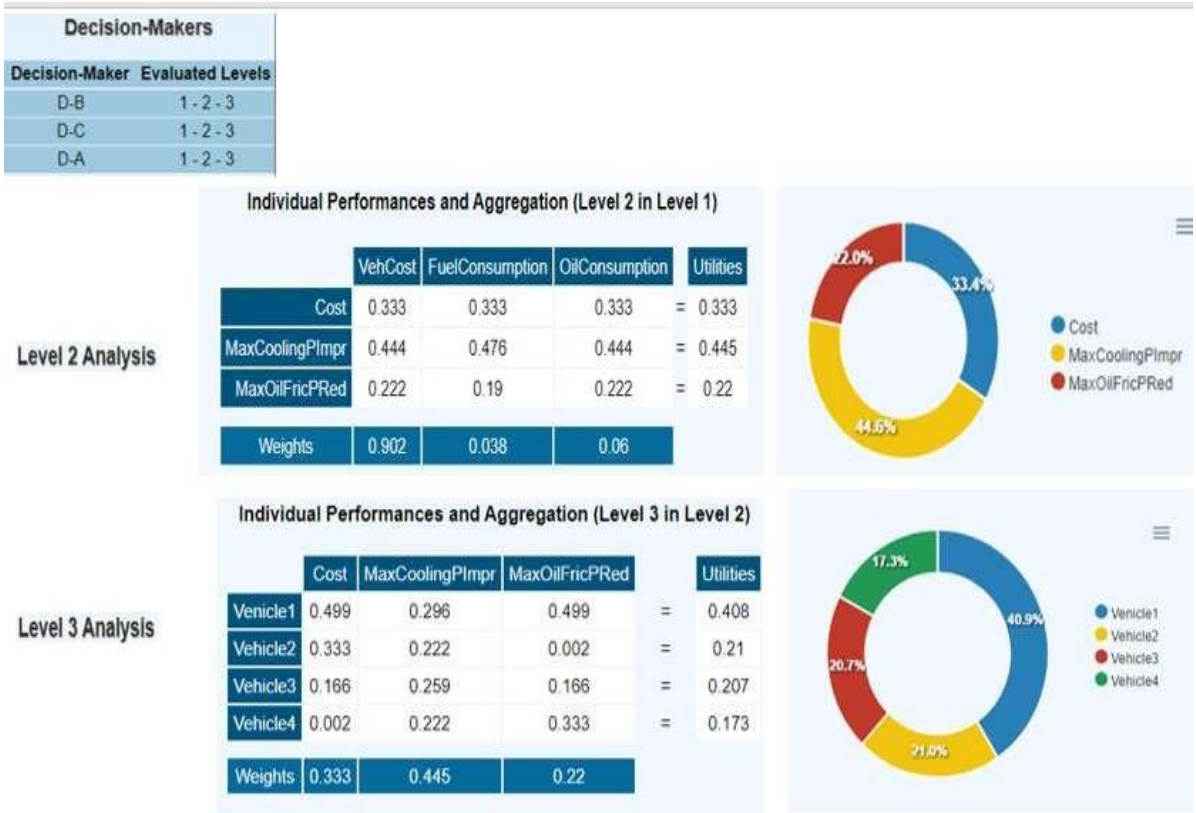
After applying the method, at *Level 2* of analysis, which corresponds to the aggregation between levels 1 and 2, the results indicated that the most relevant variable was the addition of graphene to the coolant, which obtained a degree of importance of 44.5%, standing out as the most valued criterion by decision-makers in the comparison between thermal performance, cost and friction.

Secondly, the vehicle acquisition cost had a degree of importance of 33.3%, followed by the addition of graphene to engine oil, with 22.0%. These data reveal that, in the aggregate judgment, the effects of graphene on the thermal performance of the cooling system were considered more relevant than the benefits on engine lubrication and the acquisition cost itself.

However, when observing the weights attributed to *Level 1*, an inversion of priorities is observed. The vehicle acquisition cost emerges as the most influential criteria, with 90.2% of the total weight, revealing a strong predominance of the economic variable in the global perception of decision makers. Technological variables assume less relevance at this level: the addition of graphene to the engine oil represented a weight of 6.0%, and the addition to the coolant, 3.8%. The results verified by applying the Sapevo-H^2 method are presented in Figure 8.

Figure 8. Results of the comparative analysis with the Sapevo-H2 method



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This discrepancy between the weights attributed at the general level and in the specific analysis of technological criteria highlights the complexity of the decision-making process, in which the economic factor tends to exert a significant influence on the final choice, even when the technical benefits are widely recognized.

Finally, at *Level 3* of analysis, which aggregates all hierarchical layers and generates the final ordering of alternatives, the SAPEVO-H² method indicated that *Vehicle 1* was the alternative with the highest added value, with an overall weight of 40.8%, being, therefore, the option most aligned with the decision makers' criteria and preferences. Then, *Vehicle 2* obtained 21.0%, *Vehicle 3*, 20.7%, and *Vehicle 4*, 17.3%. The predominance of *Vehicle 1* suggests that its combination of competitive cost and technical performance associated with the use of graphene in automotive fluids offered the best balance between the analyzed criteria.

These results illustrate the effectiveness of the SAPEVO-H² method in structuring complex decisions involving multiple levels and criteria, allowing the visualization of tradeoffs between cost and performance, and providing robust decision support based on multicriteria judgments. Furthermore, the applicability of the method is highlighted in scenarios with uncertainty and multiple decision-makers, characteristic of real decision-making environments in the automotive sector.

3. DISCUSSION

The results obtained through the literature review and the application of the SAPEVO-H² multi-criteria method highlight the growing interest of the scientific community and the automotive sector in the application of graphene in vehicle fluids, with a view to improving technical performance and reducing fuel and oil consumption. This scenario is consistent with the exponential evolution of research into graphene since 2004, driven by its exceptional properties, such as high thermal and electrical conductivity, mechanical resistance, chemical stability and lightness (Kausar, 2022).

In the current research, it was identified that the addition of graphene to the coolant, in concentrations between 0.1% and 0.3% by volume, provided an increase in specific heat between 6% and 8%, consequently promoting better thermal performance of the engine and reducing fuel consumption. These outcomes directly cope with the results obtained by Hao (Hao *et al.*, 2023), who investigated nanofluids with graphene nanoplatelets (GnP) in automotive radiators and observed improvements of up to 275% in heat transfer, especially at high powers and flow rates.

The research by Hao (Hao *et al.*, 2023) evaluated the thermophysical properties of these nanofluids at different concentrations and temperatures, by verifying that convective heat transfer performance improves with increasing nanoparticle concentration, heating power, air flow rate and Reynolds Number. The greatest increase in thermal performance was 275%, obtained with 0.3

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vol.% of GnP (graphene nanoplates) at the highest heating power. The research concludes that the presence of nanoparticles is the most relevant factor in improving thermal exchange in the radiator, followed by heating power, air speed and Reynolds number. These data confirm the effectiveness of graphene as a thermal conductive agent in vehicle systems.

The analysis also revealed that the addition of graphene to engine oil, in the range of 0.15% to 0.20% by mass, resulted in reductions of 33% to 39% in the coefficient of friction, directly impacting energy efficiency and lower lubricating oil consumption. These results are supported by Kogovšek and Kalin (Kogovšek & Kalin, 2023), who analyzed graphene platelets in different lubrication regimes and demonstrated the superiority of the material in relation to conventional additives, especially in the limit and mixed regimes, thanks to the formation of stable and effective tribofilms.

The authors carried out tests with steel/steel and DLC/DLC (diamond-like carbon) contacts, at temperatures of 25°C and 100°C, covering all lubrication regimes (limit, mixing and hydrodynamic) and considering the running-in effect. The results showed that graphene platelets provided the lowest friction in the limiting (BL) and mixed (ML) regimes, due to the formation of graphene tribofilms that remain effective, regardless of temperature, tribochemical activation and conditions before or after the engine break-in. Specific interactions were also observed between graphene platelets and conventional additives when used together, suggesting combined effects on tribological performance (Kogovšek & Kalin, 2023).

Furthermore, Malik (Malik *et al.*, 2024) highlighted the role of graphene in improving the mechanical properties of kenaf/epoxy composites, relevant for automotive internal parts. To overcome the poor adhesion between fibers and matrix, the authors developed multiphase composites using vacuum infusion molding, with GNPs dispersed evenly via sonication. The addition of 0.2% by weight of GNPs resulted in the best gains, with increases of 30.5% in tensile strength, 61.5% in tensile modulus, 17.6% in flexural strength, 22.7% in flexural modulus, 35.1% in interlaminar shear strength and 17.1% in fracture toughness. There was also an improvement of up to 7% in resistance to water absorption. These advances were attributed to the good dispersion of GNPs and better interaction with the surface of the fibers, making the composites promising for vehicle interior parts, such as panels, partitions and luggage compartments. The increase in tensile strength (30.5%), interlaminar shear (35.1%) and fracture toughness (17.1%) reinforces the structural potential of graphene in automotive applications, although not directly related to fluids, contributing to the expanded understanding of its performance in different vehicle contexts.

On the other hand, Teng (Teng *et al.*, 2021) investigated the use of graphene-based heat dissipation coatings (GNHC), with 0.6% by weight of graphene, to improve the thermal performance of automotive headlights with LED lamps. The study compared three configurations:

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an original lamp (Case 0), the application of GNHC on the joining surfaces between components (Case 1) and the addition of GNHC also to the aluminum radiator (Case 2). Tests showed that under an ambient temperature of 80°C, the luminous efficacy of Cases 1 and 2 increased up to 11.03% and 8.70%, respectively, while the temperature difference in the heat dissipation path dropped up to 6.41%. The results demonstrated that the use of graphene-based coatings in automotive headlights (GNHC) significantly improved luminous efficiency and thermal dissipation by up to 11.03% and 6.41%, respectively. Such data supports the idea that graphene, correctly applied, is a versatile and efficient material in different thermal fronts of the vehicle.

As for the anti-corrosion protection, Xavier and Ramesh (Xavier & Ramesh, 2023) presented a nanocomposite of graphene oxide and cerium carbide that increased the corrosion resistance of carbon steel by more than 42 times, in addition to promoting excellent water repellency and mechanical resistance. The addition of GO/MEAPS-CeC_2 to the epoxy resin significantly increased corrosion resistance, reaching 9698.17 kΩ·cm² after 480 hours in seawater — more than 42 times greater than that of pure epoxy. The nanocomposite also showed low release of ferrous ions, high water repellency (WCA of 149°), good mechanical resistance (adhesion of 13.8 MPa) and formed an inert crystalline layer that prevents the penetration of corrosive ions. This result highlights the applicability of graphene in aggressive automotive environments, such as those exposed to salt spray or constant humidity.

Regarding the current study, the application of the SAPEVO-H² method revealed that, in the *Level 2* analysis, the addition of graphene to the coolant ("*MaxCoolingPImpr*" criteria) was considered the most relevant factor (*44.5%*), surpassing the *vehicle acquisition cost* (*33.3%*) and the *addition of graphene to the engine oil* (*22.0%*). This suggests a more intense appreciation of thermal performance in the technical judgment of decision makers.

However, at *Level 1*, economic logic prevailed. The *cost of purchasing the vehicle* was *90.2%* important, compared to just *3.8%* for *adding coolant* and *6.0%* for *engine oil*. This inversion highlights the tension between technological innovation and economic viability, a pattern frequently observed in industrial decision-making processes.

At *Level 3*, which integrates all hierarchical criteria, *Vehicle 1* emerged as the best alternative, with *40.8%* of global importance, reflecting the ideal balance between technical performance and cost. This ordering suggests that, even with budget constraints, the strategic application of graphene can maximize added value in automotive products.

Thus, the present discussion, based on both research findings and scientific literature, proves that graphene offers substantial improvements in the thermal, tribological, structural and anti-corrosion performance of vehicles. However, the effective adoption of such technologies will depend on overcoming economic barriers and the efficient integration between innovation, cost

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and reliability, dimensions that SAPEVO-H² managed to structure in a robust, transparent way and aligned with the decision-making context of the automotive industry.

It is important to mention that recent studies have highlighted the potential of graphene-based nanomaterials in automotive applications, mainly in improving thermal, mechanical and tribological properties. Graphene and its derivatives, such as nanoplatelets (GnPs) and Graphene Nanoribbons (GNR), have been widely researched as additives in polymer composites and nanofluids aimed at automotive systems, such as heat exchangers, radiators and structural parts.

As for nanofluids, Reddy and Reddy (Reddy & Reddy, 2021) conducted a detailed numerical analysis of the flow and heat transfer of hybrid nanofluids containing silver and graphene in binary mixtures of water and ethylene glycol. Considering effects such as magnetic field, viscous dissipation, Joule heating and stagnation point, the authors demonstrated that increasing the volume fractions of silver nanoparticles (ϕ1) and graphene (ϕ2) significantly increases the heat transfer rate, highlighting their promising application in automotive cooling systems.

Complementarily, Nogueira (Nogueira, 2020) evaluated the thermal performance of nanofluids with GNR and silicon carbide (SiC) in compact automotive radiators, verifying that GNR has higher heat transfer coefficients than SiC, even at lower concentrations, reinforcing its potential for applications that require high thermal efficiency. Also in the line of thermal performance, Ajuka (Akuja *et al.*, 2022) investigated the generation of entropy in nanofluids with GnPs, concluding that the use of graphene can reduce the total generation of entropy and improve thermo-hydraulic performance in automotive micro and mini channels.

In composites applications, Elmasry (Elmasry *et al.*, 2023) proposed a multiscale model for composites reinforced with glass fibers and graphene nanoplatelets in a Polyamide 6 (PA6) matrix, applied under severe impact conditions, using a generalized homogenization approach (GMT) with viscoplastic constitutive laws. The model provided more accurate predictions of the mechanical behavior of these materials in automotive components, combining lightness and safety.

Still on the topic of composites, Irez (Irez *et al.*, 2020) developed hybrid materials based on recycled rubber, epoxy resin and GnPs. The results demonstrated a significant increase in the stiffness and tenacity of the composites with the addition of graphene, in addition to highlighting the possibility of protection against electrical discharges due to the high conductivity of the material, something relevant for the aeronautical industry and, by extension, the automotive industry. The use of homogenization models such as Halpin–Tsai and finite element analyzes experimentally validated the structural benefits of the material.

Another important focus is tribological properties. Lee (Lee *et al.*, 2022) investigated two methods of incorporating graphene into PA46, a common polymer in automotive parts. The self-adsorption method, which promotes better dispersion of graphene, resulted in nanocomposites

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with a lower coefficient of friction and better mechanical properties, when compared to simple mixing by extrusion.

In general, the researches by Aravindan (Aravindan *et al.*, 2019), Zhang (Zhang *et al.*, 2020), Qureshi (Qureshi; Ootim, 2023) and Maqbool (Maqbool *et al.*, 2022) also significantly contributed to the advancement in this regard, showing that the addition of graphene in nanofluids and polymer composites can increase the wear resistance, thermal efficiency and durability of automotive components, often with small fractions of the material.

Therefore, the literature converges by showing that graphene-based materials offer a unique combination of thermal, mechanical, electrical and tribological properties that make them highly suitable for the development of more efficient, sustainable and safe automotive technologies.

4. CONSIDERATIONS

Technological advances driven by the use of graphene-based nanomaterials have demonstrated great potential for optimizing the performance of automotive components, especially in aspects such as thermal efficiency, mechanical resistance, durability and weight reduction. The literature analyzed shows that the incorporation of graphene nanoplatelets and derivatives into nanofluids and polymer composites contributes significantly to improving heat exchange, reducing friction, greater impact resistance and better structural performance of automotive parts. Such technological innovations point to a promising scenario for the application of these materials in hybrid and electric vehicles, which demand increasingly efficient and sustainable solutions.

The comparative analysis carried out between hybrid vehicles made it possible to identify the most relevant criteria for decision-making when choosing the ideal model, with *coolant being the most important criterion (44.6%)*, followed by *acquisition cost (33.4%)* and *engine oil (22.0%)*. These results reinforce the importance of thermal efficiency as a determining factor in the selection of vehicles most suitable for the consumer, especially in a context of increasing search for sustainability and operational savings.

In this context, the Sapevo-H^2 method proved to be an effective tool for conducting multi-criteria analysis, allowing the incorporation of qualitative preferences and subjective judgments in a structured and transparent way. By enabling comparison between alternatives based on criteria of different nature and weights assigned according to the perception of decision makers, the method contributed to a more rational and well-founded choice, even in a scenario with uncertain or imprecise information. The flexibility of the method in dealing with verbal language, combined with the hierarchical decision structure, favored the careful prioritization of the most relevant attributes for the problem studied.

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The practical application of the multi-criteria methodology resulted in the selection of vehicle 1 as the best alternative, with a cost of R$ 120,000.00, demonstrating the best balance between performance and cost-benefit. On the other hand, vehicle 4 was classified as the least favorable alternative, presenting the highest cost (R$ 150,000.00) and lowest relative performance in the analyzed criteria.

Therefore, the conclusion is that the adoption of graphene-based technologies can represent a decisive competitive advantage in improving components such as cooling and lubrication systems, aspects that directly impact the efficiency and longevity of hybrid vehicles.

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