Accelerating lightweight Structural Design in Automotive Engineering through PLR TRIZ -KBE and AI-driven Generative Design

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Abstract. This study introduces a systematic workflow that combines Patent Literature Review TRIZ (**PLR-TRIZ**), Knowledge-Based Engineering (**KBE**), and generative design to optimize compressor brackets for electric vehicles. By extracting inventive principles from global patents and embedding them into automated design rules, the methodology enables rapid exploration of innovative, manufacturable, and patentable solutions. **Generative design** algorithms, guided by multi-physics constraints and material selection using the Ashby index, produced over 26 design variants. The optimized bracket achieved a 66% reduction in mass, a 22% increase in first natural frequency, and a 22% decrease in material cost compared to the legacy design. Finite element analysis confirmed that all critical criteria—static strength, vibration resistance, fatigue life, and thermal stability—were satisfied, with safety factors above two. The workflow is fully automated and scalable, supporting eco-design and industrial innovation. Unlike classical optimization approaches, this method integrates inventive problem-solving, automated rule-based design, and advanced computational exploration, resulting in solutions that are both high-performing and industrially feasible. Beyond automotive brackets, the methodology applies to the aerospace, energy, rail, marine, and medical sectors, enabling the development of lightweight, robust, and sustainable components. These findings highlight the potential for accelerating innovation and deployment in advanced engineering.

Keywords: PLR TRIZ, KBE, Generative Design, Topology optimization, EV, Lightweight.

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1. Introduction

The design of complex automotive components, such as compressor brackets for electric vehicles, requires systematic approaches to address multiple and often conflicting requirements, including weight reduction, structural rigidity, manufacturability, and functional integration. Conventional design methods are limited in their ability to resolve these contradictions efficiently, especially under constraints of rapid development and intellectual property [1]

Recent advances in Patent Literature Review TRIZ (PLR-TRIZ) provide a systematic framework for extracting inventive principles from patent databases and identifying technological contradictions, which can be leveraged to generate innovative solutions. Knowledge-Based Engineering (KBE) enables the capture and reuse of engineering knowledge, automating routine design tasks and supporting multidisciplinary integration, which can reduce development time and cost by up to 80% in recurrent design tasks[2], [3]. Generative design, powered by computational tools, allows engineers to explore a vast solution space, optimizing for multiple objectives such as mass, stiffness, and manufacturability. This approach has demonstrated significant improvements in the design of brackets and other structural components, leading to enhanced performance and reduced material usage [4], [5].

By coupling PLR-TRIZ, KBE, and generative design, it is possible to rapidly develop lightweight, high-performance compressor brackets that meet stringent industry standards and are validated both numerically and experimentally.

2. Methodology

This study follows a structured process that combines PLR-TRIZ, Knowledge-Based Engineering (KBE), and generative design to develop and validate innovative compressor brackets.

First, a patent literature review is conducted using the PLR-TRIZ method. For example, by searching Espace net, WIPO, USPTO, etc, with the keywords “compressor bracket” and “lightweight support,” we found several patents that address the challenge of reducing weight without sacrificing rigidity [6]. Using TRIZ, we identified inventive principles such as segmentation—dividing the bracket into functional zones to optimize each area separately [7], [8].For instance, one patent described a modular bracket where the mounting and vibration-damping functions are separated, making the design both lighter and more robust.

Next, these inventive principles are translated into practical design rules using a KBE system. For example, the segmentation principle is implemented in CATIA as a rule that automatically creates separate geometric zones for mounting and for cable routingClick or tap here to enter text.. Another rule ensures that the minimum wall thickness is always respected, which is critical for manufacturability:

$$e_{min} \geq 3\,mm \tag{1}$$

where e_{min} is the minimum wall thickness required for die casting.

Performance constraints are also encoded, such as the first natural frequency (2):

$$f_1 \; > 210\,Hz \tag{2}$$

where f_1 is the first eigenfrequency, ensuring vibration resistance.

Thanks to KBE, the software can quickly generate dozens of bracket variants that all follow these rules[9].

After that, generative design tools are used to explore a wide range of possible shapes. For example, by setting objectives such as “minimize mass” and “maximize first vibration mode,” the software generates hundreds of bracket geometries. In one case, the generative design proposed a biomimetic structure inspired by bone, which reduced the bracket’s weight by 30% compared to the original design.

To further illustrate the effectiveness of this approach, we refer to the case study by [10], which applied generative design to an automotive engine mounting bracket. In this study, the initial 3D model defined the design space, operating conditions, and objectives such as rigidity, lightweighting, fatigue resistance, and sustainability. The generative design process produced solutions that not only reduced the bracket’s weight by 30% compared to traditional design but also improved rigidity and strength. Moreover, the cumulative weight reduction across multiple brackets led to a decrease in CO_2 emissions by 3.5 g/km and an increase in vehicle range by 2.8 km. This case demonstrates how generative design can simultaneously address structural, functional, and environmental objectives in automotive engineering.

Material selection is also optimized: for instance, the Ashby index is used to choose an aluminium alloy that offers the best compromise between strength and castability:

$$Performance\ Index = \frac{E^{\frac{1}{3}}}{\rho} \tag{3}$$

where E is Young’s modulus and ρ is density [11].

Topology optimization is formulated as: $min\,_x m(x)$ subject to

$$K(x)u = F\ , \sigma_{max}(x) \leq \sigma_{allow} \tag{4}$$

where $m(x)$ is the mass, $K(x)$ the stiffness matrix, u the displacement vector, F the load vector, and σ_{allow} the allowable stress [12].

Once promising designs are identified, each one is tested using multi-physics simulations. For example, finite element analysis (FEA) (5) is used to check that the bracket can withstand the compressor's weight and vibrations without exceeding stress limits. The Von Mises stress is calculated as:

$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]\sigma_{allow}} \quad (5)$$

where σ_1, σ_2, σ_3 are principal stresses.

Fatigue is checked using the Goodman criterion (6):

$$\frac{\sigma_a}{\sigma_{-1}} + \frac{\sigma_m}{\sigma_{UTS}} \leq 1\sigma_{allow} \quad (6)$$

where σ_a is the alternating stress, σ_m the mean stress, σ_{-1} is the fatigue limit, and σ_{UTS} the ultimate tensile strength.

Manufacturability is checked by simulating the casting process, ensuring there are no undercuts or thin sections that would cause defects. Patentability is also verified by comparing the final solutions to existing patents to ensure novelty.

Finally, the best solution is selected based on all technical and innovation criteria, and the entire process is documented for transparency and future reuse.

2.1. Workflow Diagram of the Method

The diagram below illustrates the workflow of this method.

Fig. 1 Workflow Diagram of the Method

2.2. Shape and technical specifications:

To provide a concrete illustration of this method, we studied the compressor support presented below.

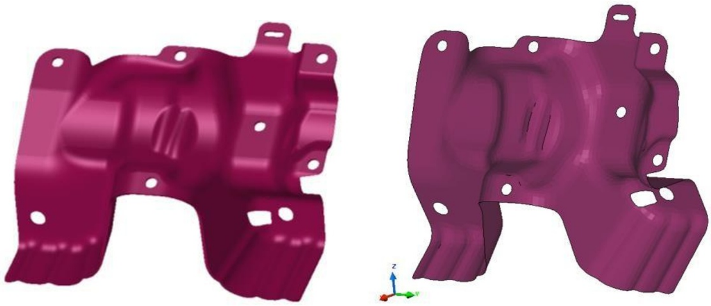

Fig. 2 The legacy compressor support

The support has a mass of 1.963 kg. It is made of S235J steel, and its first natural frequency is 192 Hz. This support is integrated within the housing of the electric motor, the electric compressor, as well as the electrical harnesses.

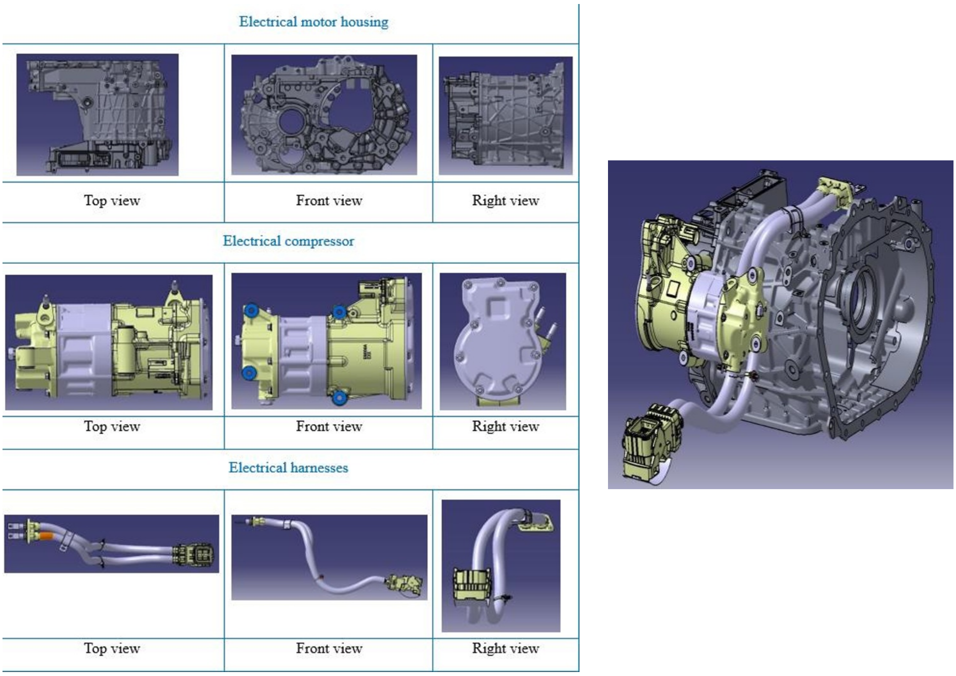

Fig. 3 General isometric view of the environment

Table 1 shows the main roles and goals that compressor support is expected to meet throughout its service life.

Table. 1 Technical specifications and goals

Criterion	Levels
Support the mechanical load	0 degrees of freedom and Support 8.7 kg
Clash	0
Minimum distance	> 5 mm
Weight	Reduce the bracket mass by at least 40%
First modal frequency	> 210 Hz
Price	Optimize the cost as much as possible

Before starting generative design, it was essential to determine and model the functional areas, as well as decide which interfaces should be kept or removed.

The figure below shows the design of the support operational areas.

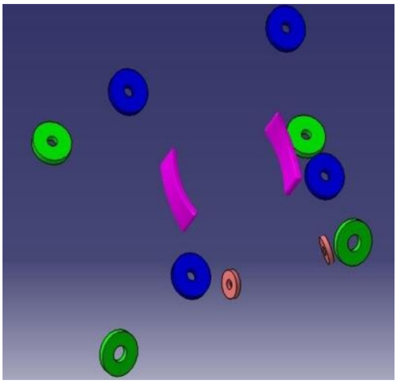

Fig. 4 Design of functional bracket areas

2.3. Load evaluation:

The next step is to evaluate the different load cases that need to be considered when generating the 3D models. Table 2 shows the different load cases applied to the support:

Table. 2 Applied load cases.

Load case	**1**	**2**	**3**
Coordinates of its point of application (m)	$\begin{cases} X = -129.81 \\ Y = +232.802 \\ Z = +49.052 \end{cases}$		
Direction	-Z	-Y	-Y
Value (N)	80.7	80.7	139.51

2.4. The selection of materials:

The selection of materials is based on performance indices that objectively assess their ability to meet specific requirements, considering the function, objectives, constraints, and free variables. Each combination of these elements produces a performance index.
To create a support that is both **light** and **rigid** during **bending**, the performance index must be maximised.

$$IP_1 = E^{\frac{1}{3}}/\rho\, \sigma_{allow} \tag{7}$$

ρ denotes the mass density; E represents Young's modulus.

When this index is plotted on a logarithmic scale, the resulting curve shows:

$$\ln(E) = 3 * \ln(\rho) + Cte\sigma_{allow} \tag{8}$$

To create a support that is both lightweight and resistant to bending, maximising the performance index is essential.

$$IP_2 = \sigma_Z^{\frac{1}{2}}/\rho \tag{9}$$

 https://doi.org/10.1051/e3sconf/202568000111

σ_z corresponds to the elastic limit of the material.

When this index is plotted on a logarithmic scale, the resulting curve shows:

$$\ln(\sigma_z) = 2 * \ln(\rho) + Cte \qquad (10)$$

For a structure to be **economical** and **resist tension or compression** effectively, it's important to maximise this performance index.

$$IP_3 = \frac{\sigma_Z}{C_m * \rho} \qquad (11)$$

C_m represents the cost per kg

When this index is plotted on a logarithmic scale, the resulting curve shows:

$$\ln(\sigma_z) = 3 * \ln(C_m) + \ln(\rho) + Cte \qquad (12)$$

After defining the performance indices, **Ashby diagrams** should be created and the selection lines drawn as shown in figures 5, 6 and 7. These charts compare and help in selecting materials based on their properties.

Below are the various Ashby diagrams developed from the performance indices by using the **GRANTA Edupack V2024** tool.

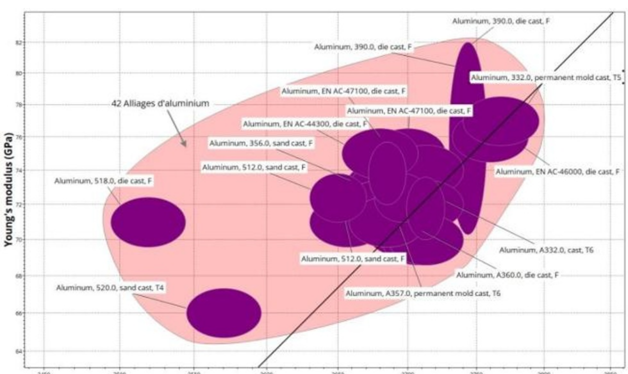

Fig. 5 Ashby's chart showing the relationship between E and ρ.

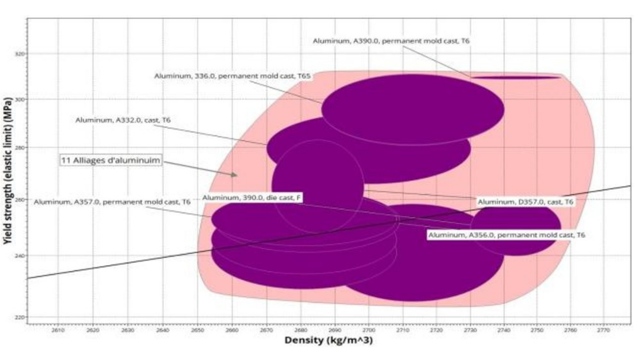

Fig. 6 Ashby's chart showing the relationship between σ and ρ.

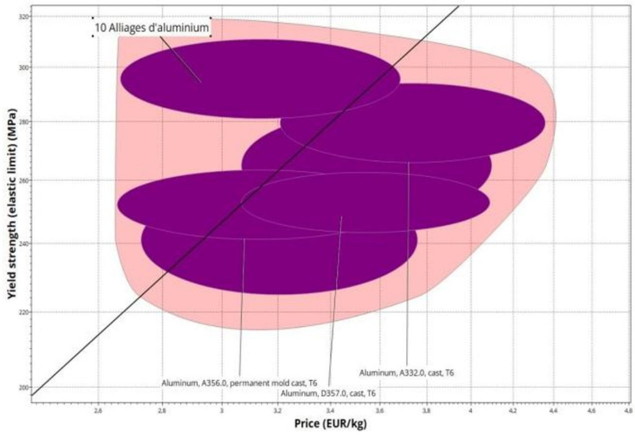

Fig. 7 Ashby's chart showing the relationship between stress σ and unit cost.

The " AlMg7Si alloy, permanent mold" candidate offers the lowest cost. This high-performance alloy, commonly used in die casting, is designated in the automotive industry by the European standard EN 1780-1 (EN AC-42000). Table 3 presents the technical characteristics of the selected material.

Table. 3 Characteristics of the Selected Material

Characteristics	Margin
Unit price	2.66 to 3.68 €/Kg
Density	2660 to 2710 Kg/m^3
Young's modulus	71.5 to 74.5 GPa
Yield strength	241 to 263 MPa
Thermal conductivity	149 to 155 W/m.C°
Electrical resistivity	4.2 to 4.6 Ω.cm

2.5. Generative design

Fusion 360 software was used for generating 3D models, resulting in twenty candidate models that meet the design objectives, as shown in Figure 8.

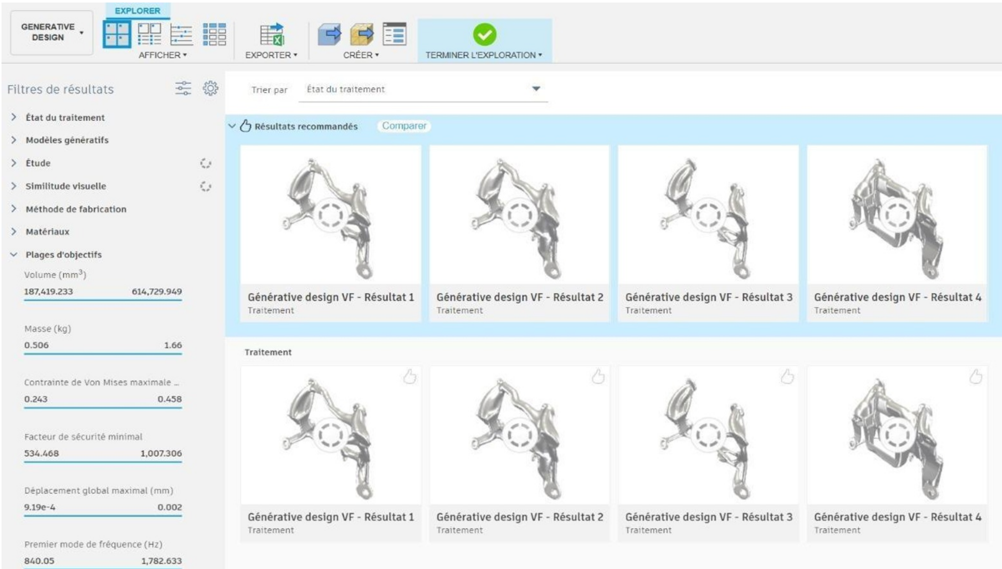

Fig. 8 Displaying the results on the page.

Once we obtained consistent results, we conducted a quick comparison of the available solutions and selected one based on several factors: material, manufacturing method, mass, volume, safety factor, and Von Mises stress.

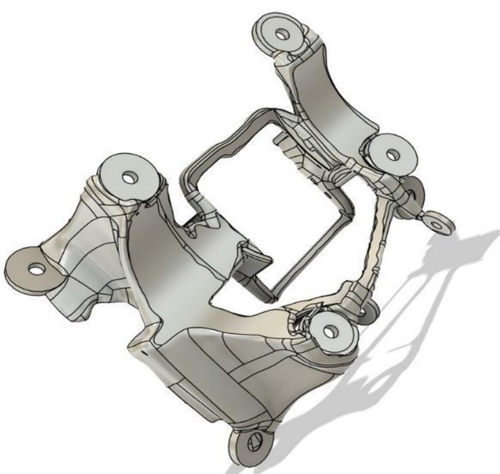

Fig. 9 Selected solution.

As shown, this solution has unfeasible shapes or material discontinuities. A corrective model must be designed to simplify the outcome, ensure manufacturability, and validate that it meets client requirements. Geometric adjustments and targeted reinforcements should minimise added material to reduce mass and improve efficiency. Figure 10 presents the new design of the compressor bracket.

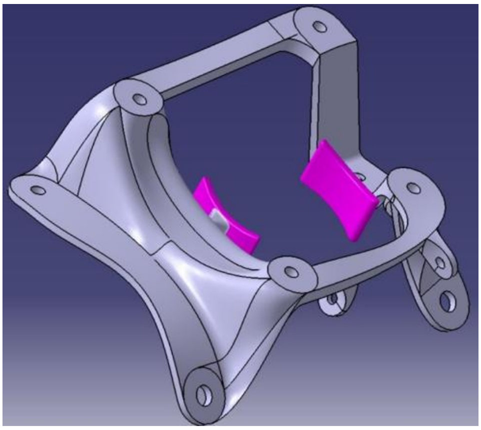

Fig. 10 New design of the bracket

3. Results

After designing, the most notable results are:

3.1. Key Outcomes of PLR-TRIZ Application

The systematic analysis of patent literature using PLR-TRIZ enabled the identification of major technical contradictions for the compressor bracket:

- **Mass vs. Rigidity**: Addressed by applying segmentation (TRIZ Principle 1) and geometric transformation (Principle 14), resulting in locally optimized sections that maintain stiffness while reducing weight.
- **Geometric Complexity vs. Manufacturability**: Solutions compatible with die casting were prioritized, avoiding undercuts and ensuring minimum wall thickness.
- **Functional Integration vs. Packaging**: The integration of secondary functions (e.g., cable routing, vibration damping) was achieved without increasing the overall size, thanks to segmentation and dynamization (Principle 15).

3.2. KBE-Driven Variant Generation

By formalizing TRIZ principles into KBE rules, the design process was automated and robust.

- **Automatic Variant Generation**: Over 26 bracket variants were generated, all compliant with manufacturability, packaging, and performance constraints.
- **Multi-criteria Filtering**: Each variant was automatically evaluated for mass, first natural frequency, maximum stress, casting compatibility, and ease of assembly.

Example of KBE rules applied:

- Minimum wall thickness: $e_{min} \geq 3\ mm$
- First natural frequency: $f_1 \ > 210\ Hz$
- Maximum mass: $m < 0.7\ kg$

3.3. Generative Design and Topology Optimization

Generative design combined with topology optimization facilitates the exploration of a broad range of solutions using AlMg7Si alloy as the chosen material. The optimal solution demonstrates the following performance characteristics:

- **Mass reduction**: 66% (from 1.96 kg to 0.66 kg)
- **First natural frequency**: Increased from 192 Hz (legacy) to 234 Hz (optimized)
- **Material cost**: Reduced by 22%
- **All FEA and thermal constraints met.**

3.4. Multi-Physics Validation

- **Static FEA**: All Von Mises stresses were below the yield strength, with a safety factor above 2. (see Figures from Fig. 12 to Fig. 17 in Appendix I)
- **Modal Analysis**: The first natural frequency exceeded 210 Hz, eliminating resonance risk (Figure 18 in Appendix II)
- **Fatigue**: The Goodman criterion (6) was satisfied, ensuring infinite theoretical life under expected loading cycles (Figure 19 in Appendix II)
- **Manufacturability**: The final geometry was validated for die casting (thickness, draft angles, no undercuts).

3.5. Patentability:

The solution is currently under review for a patent application with some adjustments. It meets the patentability criteria, notably novelty, inventive step, and industrial applicability.

3.6. Comparative Performance Chart

The radar chart below compares legacy and optimized brackets on key performance metrics after normalizing values.

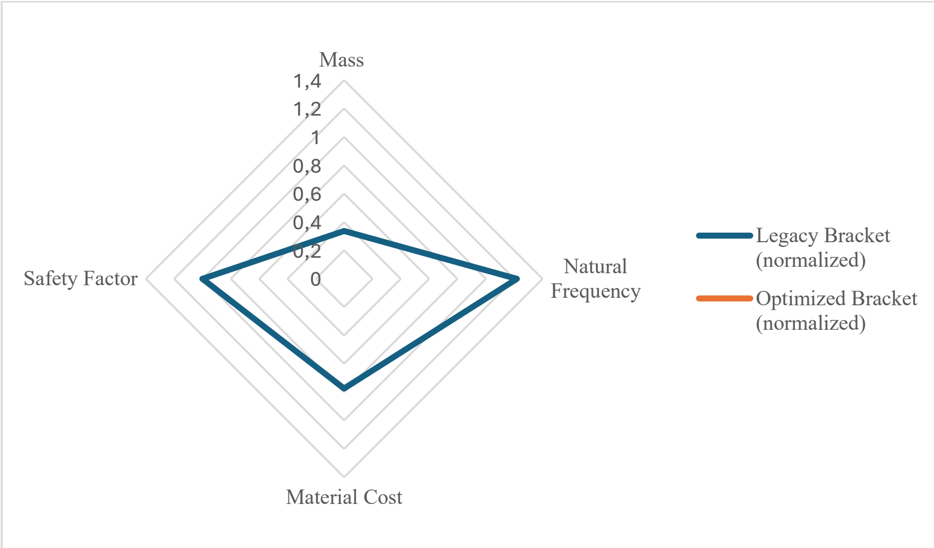

Fig. 11 Comparative Performance Chart

3.7. Best Findings

- The optimized bracket is significantly lighter and less expensive, while being more robust and better suited to withstand vibrations.
- The design process is fully automated and reproducible, allowing rapid exploration of innovative solutions.
- The methodology is generalizable to other automotive components, supporting eco-design and industrial innovation.

4. Discussion

Compared to similar studies, this work presents several unique contributions:

- **Systematic Integration of Innovation and Automation:** Unlike most classical topology optimization or genetic algorithm approaches, this study systematically integrates inventive principles from global patents (PLR-TRIZ) with automated rule-based design (KBE) and advanced generative design. This ensures that all generated solutions are not only optimal in terms of performance but also innovative, manufacturable, and patentable.
- **Multi-Objective and Multi-Physics Optimization:** While many studies focus on a single objective (mass or stiffness), this workflow simultaneously optimizes for mass, vibrational performance, manufacturability, cost, and patentability. The use of the Ashby index for material selection and the systematic application of FEA for static, modal, and fatigue validation go beyond the scope of most published works.
- **Industrial Feasibility and Eco-Design:** The final design is not only lighter and stiffer but also validated for industrial die casting and cost efficiency. The 66% mass

reduction and 22% cost saving directly support eco-design and sustainability goals, which are often overlooked in purely academic optimization studies[13]

- **Automation and Scalability:** The workflow enables the automated generation and evaluation of plenty of design variants, a scale and speed that manual or semi-automated methods cannot match [14]. This makes the approach highly scalable for industrial applications.
- **Patentability and Innovation:** By leveraging PLR-TRIZ, the study ensures that the optimized solution is not only technically superior but also novel in the context of existing intellectual property, a key differentiator for industrial innovation.

While the digital workflow is robust, physical prototyping and experimental validation remain necessary to confirm real-world performance. Future work could integrate life cycle analysis and recyclability directly into the optimization process, further supporting sustainable engineering.

5. Conclusion

This study has demonstrated the effectiveness of a structured and innovative approach to designing a complex automotive component—the electric vehicle compressor bracket—by integrating Patent Literature Review TRIZ (PLR TRIZ), Knowledge-Based Engineering (KBE), and generative design.

By systematically identifying technical contradictions through patent analysis and translating inventive principles into design rules, the PLR TRIZ method provided a solid foundation for innovation. Coupling this with KBE enabled the automation and formalization of expert knowledge, ensuring that every design variant generated was both feasible and aligned with industrial constraints.

The integration with generative design allowed for the exploration of a wide design space, guided by both engineering logic and creative principles. The result was a highly optimized bracket that achieved significant improvements in weight reduction, vibrational performance, and cost efficiency—all validated through multi-physics simulations.

Beyond the technical achievements, this methodology offers a new way of thinking about engineering design: one that is knowledge-driven, patent-aware, and AI-accelerated. It shortens development cycles, enhances product differentiation, and opens the door to scalable innovation across other components and industries.

In conclusion, the PLR TRIZ–KBE–Generative Design framework is not just a toolset—it is a strategic asset for modern engineering teams seeking to innovate faster, smarter, and with greater confidence.

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Appendix I: **Detailed FEA Static Analysis using ANSYS:** Von Mises stresses.

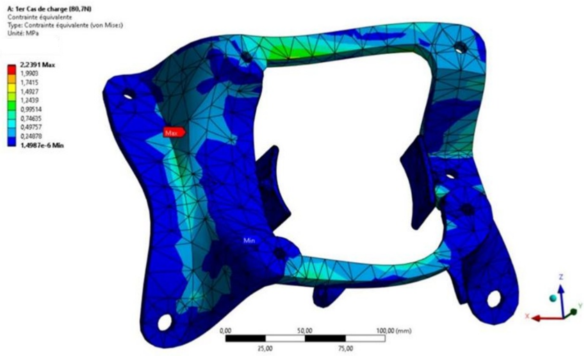


Fig. 12 Von Mises stress for case load 1.

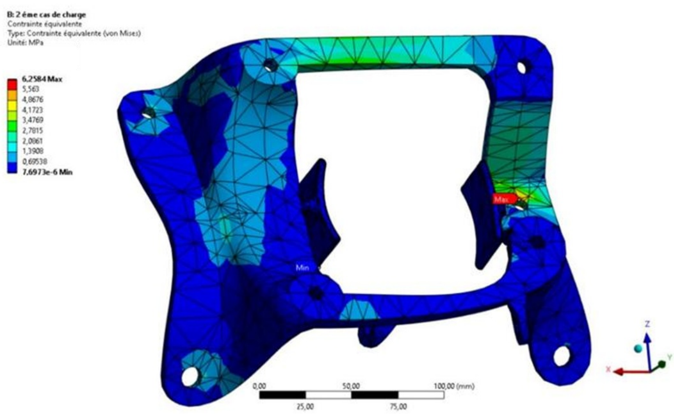


Fig. 13 Von Mises stress for case load 2.

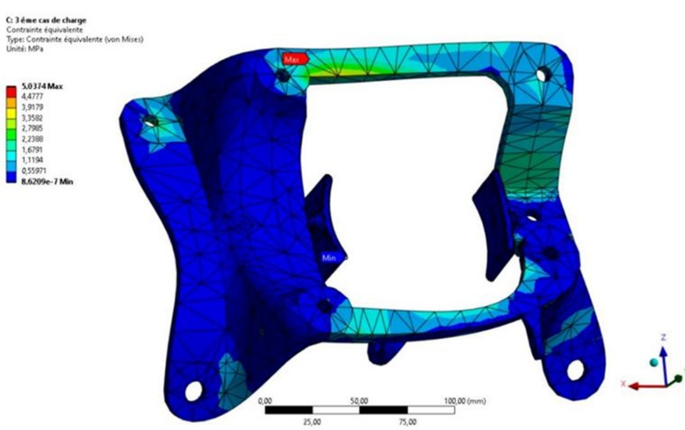


Fig. 14 Von Mises stress for case load 3.

Appendix II: **Detailed FEA Static Analysis:** Deformations

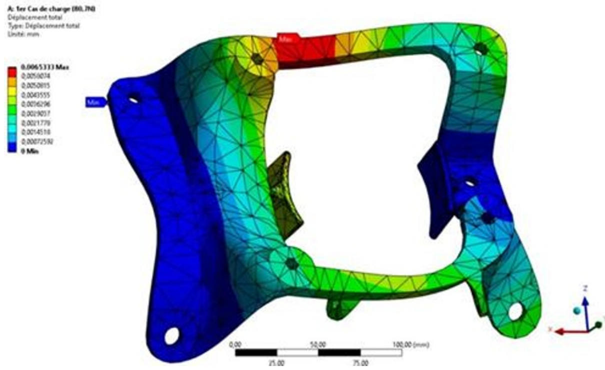


Fig. 15 Deformations related to case load 1.

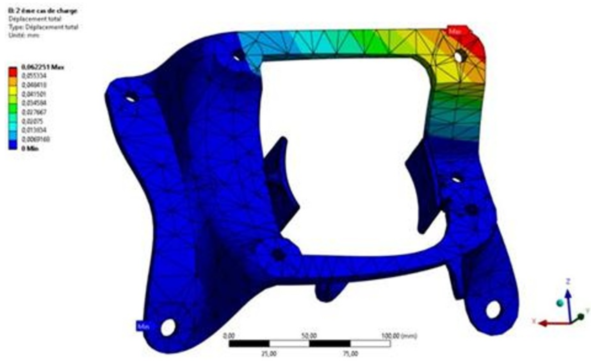


Fig. 16 Deformations related to case load 2.

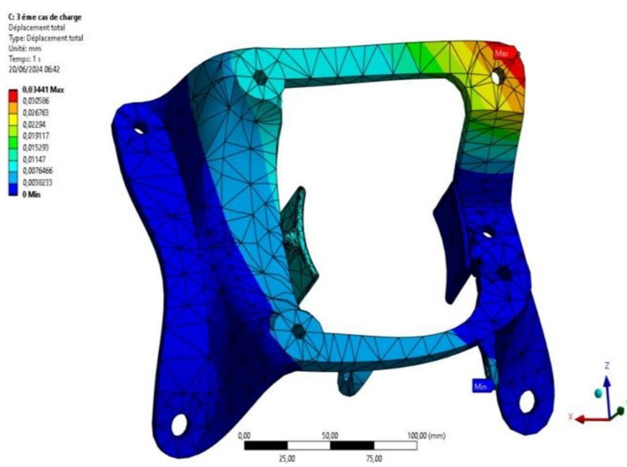
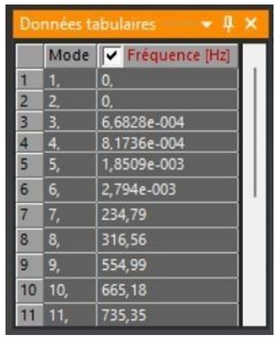


Fig. 17 Deformations related to case load 3.

Appendix III:

Modal Analysis



Données tabulaires

	Mode	Fréquence [Hz]
1	1,	0,
2	2,	0,
3	3,	6,6828e-004
4	4,	8,1736e-004
5	5,	1,8509e-003
6	6,	2,794e-003
7	7,	234,79
8	8,	316,56
9	9,	554,99
10	10,	665,18
11	11,	735,35

Fig. 18 Frequencies of the new design of bracket

Fatigue Analysis:

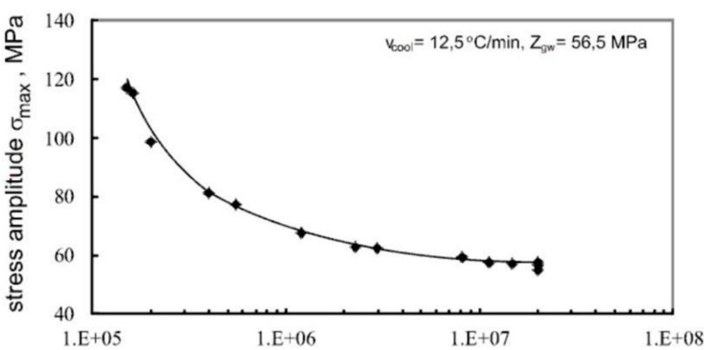


Fig. 19 Wöhler curve for the AlMg7Si alloy