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Technical paper

A dimensionless life-cycle environmental indicator and a decision-oriented score for assessing vehicle component substitution

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ABSTRACT

This study proposes a novel environmental indicator and a dimensionless score to support the assessment of vehicle component substitution strategies, particularly in lightweight redesign applications. The method was developed to provide a rapid and transparent comparison between a baseline component and a redesigned alternative with equivalent mechanical performance, accounting for the full life cycle contribution of production, use phase, and end-of-life (EoL). The indicator can be applied to any environmental category for which consistent characterization factors are available. In this work, it was tested using Global Warming Potential over 100 years (GWP100), water use, and non-renewable energy resource consumption. A score is calculated as the ratio between the environmental indicators of the redesigned and baseline components, enabling immediate classification into environmental performance classes. The methodology was demonstrated through two case studies, i.e., an automotive bracket–damper system and an aeronautical tablet holder, both redesigned according to Design for Additive Manufacturing principles. Results show that while additive manufacturing generally increases production-phase burdens, mass reduction during operation can significantly offset these impacts, particularly in high-intensity transport systems. In the automotive case, the redesigned component reduced GWP100 and non-renewable energy resource consumption, while water use increased; in the aeronautical case, environmental benefits were obtained across all three categories. A complementary break-even analysis was introduced to identify, when applicable, the minimum operating life required for the redesigned solution to become environmentally advantageous. The proposed method offers a practical, component-oriented complement to full LCA, supporting environmentally informed design decisions during early development stages.

1. Introduction

1.1. Overview

The transport sector is one of the main contributors to global environmental impacts, particularly in terms of GreenHouse Gas (GHG) emissions, energy consumption, and resource depletion [1]. Within this context, the automotive industry has been facing increasing pressure to reduce the environmental footprint of vehicles throughout their entire life cycle [2]. One of the most widely adopted strategies to improve vehicle efficiency is lightweighting, *i.e.*, reducing the mass of vehicles and components while maintaining the same mechanical and functional performance and monitoring the carbon footprint of the manufacturing process. According to Kelly *et al.* Kelly et al., [3], material composition and substitution play a key role in determining vehicle-related environmental impacts. Life-cycle analysis of lightweight material substitution indicates that, while the manufacturing impacts of lighter materials can be higher than those of conventional materials, the use-phase fuel economy benefits associated with reduced vehicle mass often lead to a net reduction in life-cycle GHG emissions. Nevertheless, certain lightweight materials may lead to additional burdens due to energy-intensive manufacturing processes or challenges in end-of-life recycling [4].

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1.2. Literature review

A reduction in vehicle mass generally leads to lower fuel consumption and reduced operational emissions during the use phase. Several studies have demonstrated that a significant share of the energy consumed in road transportation is associated with moving the vehicle's own mass. For example, lightweight design strategies have been shown to decrease energy use during the use phase, particularly when applied to vehicles with high fuel consumption profiles, by directly reducing the energy required to overcome inertia and rolling resistance. Furthermore, analytical models estimating fuel savings per unit mass reduction confirm that lighter vehicles can achieve meaningful decreases in fuel consumption and resulting CO_2 emissions [5]. Lewis *et al.* Lewis et al., [6] showed that roughly half of the energy spent in wheeled transportation is used to move vehicle mass, and even more in the case of aircraft. For this reason, mass reduction is often considered a key lever for improving environmental performance. However, lightweighting strategies typically involve the substitution of conventional metallic components (*e.g.,* steel) with lighter materials such as aluminum and magnesium alloys, polymers, or composites, which may have higher environmental burdens in the production and end-of-life phases [7,8]. Moreover, lightweighting alters the ratio between sprung and unsprung masses, thereby modifying the vehicle's dynamic response and influencing the vibration levels transmitted to the cabin, overall energy consumption, and consequently CO_2 [9].

Design for Additive Manufacturing (DfAM) principles can further enhance the environmental performance of lightweight components by enabling size, shape, and topology optimization leading to geometric model complexity that is not achievable with conventional manufacturing [10]. Other additive manufacturing (AM) unique capabilities, such as material and functional complexity, can also be integrated into a sustainable design workflow. By tailoring component design to additive processes, DfAM allows reductions in material use and improved functional integration, which can amplify the use-phase benefits associated with weight reduction while potentially mitigating production-phase impacts [11–15].

Life Cycle Assessment (LCA) is the reference methodology for evaluating the environmental performance of manufacturing and design choices and has been widely applied to vehicles and automotive components, as well as in many other fields [16–19]. Several studies have compared conventional and lightweight manufacturing solutions. For instance, LCAs of metal AM versus conventional production for automotive parts indicate that, although lightweight designs can lower use-phase impacts through mass reduction, the higher energy requirements of additive processes can offset these benefits depending on the material and process conditions [20]. Similar trade-offs between lightweighting and life cycle impacts have been reported in comparative studies of redesigned automotive components produced by additive and traditional methods [21]. Furthermore, broader reviews of LCA in AM indicate that production-phase impacts may outweigh use-phase gains unless energy use and material recovery are optimized. These findings underscore the importance of evaluating the full life cycle when assessing lightweight strategies in transport systems.

While LCA quantifies environmental impacts, other approaches in the literature consider a wider set of factors to support design decisions. These methods integrate multiple parameters beyond emissions alone, including mass, energy use, and operating conditions. Several studies have therefore proposed indicators or frameworks to compare alternative component solutions. For instance, Schmidt and Taylor [22] introduced Ford of Europe's Product Sustainability Index (PSI), which integrates environmental, social, and economic indicators to evaluate vehicle concepts. The PSI includes environmental indicators based on life-cycle performance (*e.g.,* global warming and air quality potentials), as well as social and economic metrics such as mobility capability, safety, and life-cycle cost of ownership, offering a multidimensional sustainability perspective.

Ungureanu *et al.* Ungureanu et al., [23] developed a comprehensive sustainability scoring method for automotive applications in aluminum alloy. Their approach is based on multiple elements, including environmental impact, functionality, manufacturability, recyclability, resource use, and societal effects. These approaches are valuable in providing a holistic sustainability perspective, but they require extensive data and are not always easily applicable in early design stages or for quick component-level comparisons. More general environmental indices have also been proposed for production systems and transport infrastructures, often focusing on aggregated sustainability performance at the system level [24–27].

1.3. Aim of the work

A key limitation emerging from literature is the lack of simple, transparent, and component-oriented indicators that allow designers and engineers to quickly compare a reference part with an alternative redesigned component, which may result from a change in materials, technology, or from an optimization, and which we define in this work as the redesigned component. The paper addresses this gap by proposing a new environmental indicator specifically tailored to the substitution of vehicle components.

The ratio of two indicators, referring to the baseline and the redesigned component, condenses into a single score the benefit (or penalty) associated with the substitution of the original (baseline) component with the redesigned. The indicator covers the entire life cycle, from the production of the component through operational emissions attributable to its mass over the vehicle lifetime to End-of-Life (EoL) impacts. The method enables a direct comparison between a reference component (*e.g.,* a steel part) and an optimized lightweight alternative (*e.g.,* aluminum alloy, composite, or additively manufactured part) with equivalent mechanical and functional performance. By expressing the result as a dimensionless score and assigning environmental classes, the approach allows designers to rapidly assess whether a substitution is environmentally advantageous, neutral, or disadvantageous. In this sense, the proposed index complements existing LCA-based and multi-criteria sustainability tools by offering a pragmatic, design-oriented metric that supports environmentally informed decisions in vehicle lightweighting and component optimization. The novelty of the proposed approach therefore lies in the component-level comparative formulation and in the normalization of life-cycle impacts into a decision-oriented score. The proposed methodology is not specific to additive manufacturing. The 2 AM-based case studies were selected because lightweight redesign through AM can generate a particularly pronounced trade-off between reduced component mass and increased manufacturing burdens, thus providing representative examples for demonstrating the capability of the proposed framework to capture competing life-cycle effects.

To demonstrate the proposed method, two case studies are presented:

1. Case study 1: automotive bracket–damper system installed on a limited-production hybrid hypercar;
2. Case study 2: aeronautical cockpit tablet holder installed on a helicopter used for aerial work.

2. Materials and methods

2.1. Environmental indicators

The methodological framework introduced in this work enables the computation of a dimensionless score, enabling classification of the redesigned component into a predefined environmental class, thus supporting design and decision-making processes.

The methodology integrates impacts arising from:

1. production phase, including raw material extraction, transport and manufacturing processes;
2. use phase, accounting for the variation of vehicle emissions associated with the change of component mass;
3. EoL phase, including recycling, disposal, or recovery.

Regarding point (2), the use phase accounts for the cumulative operational emissions attributable to the component mass over its service life. The operational parameter depends on the transport mode considered. For road and rail vehicles, it is typically expressed as the total distance travelled (*e.g.,* kilometers), whereas for aircraft and helicopters, it corresponds to the accumulated flight time (*e.g.,* hours) and take-off / landing cycles. For ships, the reference parameter is generally the operational lifetime, expressed in years of service.

The approach is applicable to any environmental impact category, such as climate change (kg CO_2-eq), particulate matter formation (kg PM_{10}-eq), water use (m^3), and others.

For each component, the proposed environmental indicator E is defined as:

$$E = e_{prod} + e_v + e_{EoL} \tag{1}$$

with:

$$e_v = \frac{M}{M_T} \cdot \varepsilon_v \cdot v \tag{2}$$

where:

- e_{prod} is the impact associated with the production of the component, including upstream;
- M is the mass of the component;
- M_T is the total vehicle mass;
- ε_v is the vehicle-specific emission factor per travelled distance or operating hours;
- v is the vehicle lifetime (in terms of distance or working hours);
- $e_{EoL,i}$ represents the EoL impact of the component.

The indicator defined above takes into account, as previously mentioned, the production phase of the component (from raw material extraction to the final product), the vehicle emissions associated with transporting the component mass during operation, and the impacts related to its end-of-life treatment once its service life has ended. Indeed, during vehicle operation, the component does not directly generate emissions, nor does it require any energy input to perform its function. However, it is important to consider that, as highlighted in the literature [6], a significant share of vehicle emissions is associated with the mass being transported. Therefore, reducing the mass of a component leads to a decrease in the environmental impact related to its transport over the entire vehicle lifetime. Accordingly, the use-phase formulation assumes a linear attribution of the vehicle operational impact to the component-to-vehicle mass ratio and to the operating life. It should also be noted that the total vehicle mass (M_T) is assumed to remain constant. This approximation is considered valid when the mass of the component is negligible compared to the total mass of the vehicle.

The proposed environmental score is defined as the ratio between the defined indicator of the redesigned component and that of the baseline component:

$$score = \frac{E_{red}}{E_{base}} = \frac{\left(e_{prod} + \frac{M}{M_T} \cdot \varepsilon_v \cdot v + e_{EoL}\right)_{red}}{\left(e_{prod} + \frac{M}{M_T} \cdot \varepsilon_v \cdot v + e_{EoL}\right)_{base}} \tag{3}$$

The rationale of the proposed formulation is to provide a direct component-level comparison between two functionally equivalent alternatives evaluated within the same system boundaries and environmental impact category. The environmental indicator retains the life-cycle contributions associated with production, use, and EoL, while the dimensionless score normalizes the redesigned solution with respect to the baseline component. This normalization provides a direct decision-oriented measure of the environmental consequence of component substitution without introducing additional weighting factors or aggregating heterogeneous impact categories. The comparison is therefore performed independently for each environmental category, preserving the information provided by the underlying environmental assessment. Furthermore, the ratio formulation is reciprocal, since reversing the baseline and redesigned alternatives results in the reciprocal score, thus ensuring consistency of the comparison in both substitution directions.

The score is also dimensionless because it is the ratio of two indicators within the same impact category. This property makes the methodology independent of the unit of measurement and directly applicable to any environmental impact category.

The interpretation of the score is:

- $score = 1$: no difference between redesigned and baseline;
- $score < 1$: environmental benefit of the redesigned;
- $score > 1$: environmental penalty of the redesigned.

To support practical interpretation, the score is mapped into five environmental classes, from A to E, using two threshold values a and b with $1 < a < b$, and their reciprocals $1/a > 1/b > 1$. The scale is symmetric around score $= 1$, corresponding to a neutral substitution (Class C), analogously to energy efficiency labelling schemes (Fig. 1).

Table 1 describes the five environmental classes.

This symmetric structure ensures that if the substitution of component A with B yields, for example, Class B, the reverse substitution (B with A) will yield Class D. The assignment of the environmental class requires defining the threshold parameters a and b, which determine the score intervals. In this study, the values $a = 1.5$ and $b = 3$ were selected. These thresholds were chosen to reflect progressively significant variations in environmental performance relative to the reference component. In particular, a score between 1/1.5 and 1.5, corresponding to a variation ranging approximately from a 33% reduction to a 50% increase relative to the reference component, is considered moderate and corresponds to Class C, which includes the neutral condition (score = 1). Larger deviations indicate increasingly significant improvements or deteriorations, with Class A corresponding to reductions of approximately 67% or more and Class E to increases of approximately 200% or more.

Although the choice of a and b is inherently conventional, these parameters are not intended to represent universal industrial lightweighting benchmarks. The quantitative output of the proposed methodology is the dimensionless score, while the environmental classes provide an additional decision-oriented interpretation layer. The threshold values can be defined according to company-specific targets, sector requirements, regulatory criteria, or other decision-making needs.

Moreover, to account for components that are replaced during the vehicle lifetime, two coefficients are introduced:

- α: number of reference components used;
- β: number of redesigned components used.

The score becomes:

$$score = \frac{\beta \cdot E_{red}}{\alpha \cdot E_{base}} \tag{4}$$

When multiple components are substituted simultaneously, the global score is calculated as, which represents the most general formulation:

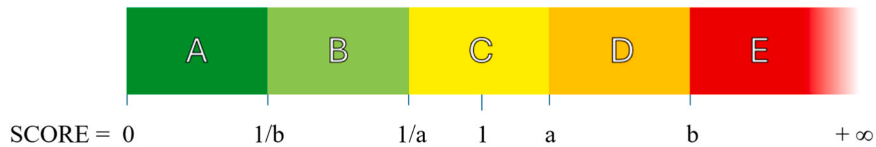

Fig. 1. Environmental classes.

Table 1
Description of the five environmental classes.

Class	Score range	Interpretation
A	$0 < score \leq 1/b$	High environmental benefit
B	$1/b < score \leq 1/a$	Moderate environmental benefit
C	$1/a < score < a$	Neutral substitution
D	$a \leq score < b$	Moderate environmental penalty
E	$score \geq b$	High environmental penalty

$$score = \frac{\sum_{i=1}^{n_{rev}} \beta_i \, E_{red,i}}{\sum_{j=1}^{n_{base}} \alpha_j E_{base,j}} \tag{5}$$

3. Case studies

3.1. LCA methodology

To assess whether a redesigned component manufactured via AM is environmentally advantageous compared with its conventionally produced baseline counterpart, two case studies from different sectors were investigated, *i.e.,* an automotive bracket–damper system (Case study 1) installed on a limited-production hybrid hypercar and an aeronautical cockpit tablet holder (Case study 2) installed on a helicopter largely used in the civil field for aerial work and transportation. In both cases, a consistent workflow was adopted. Starting from the existing component in its baseline configuration, reverse engineering and CAD modelling were carried out, followed by the definition of design assumptions and functional constraints to obtain an AM-optimized geometric model that meets the same requirements. Bills of materials were then compiled by accounting for materials, masses, and parts, together with manufacturing-related parameters such as processes, energy, material consumption, and production waste, in order to build the life cycle inventory required for the environmental assessment.

The environmental evaluation was performed using the LCA methodology in accordance with ISO 14040 and ISO 14044. The study was structured into goal and scope definition, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and interpretation. Consistent with the indicator developed within the project, the assessment considered life cycle contributions attributable to production (raw material, semi-finished product production, transports, and manufacturing processes), use phase (additional operational emissions attributable to the component mass over its service life), and end-of-life treatment, including component disposal, thus adopting a cradle-to-grave approach [28].

LCA modelling was implemented in OpenLCA v2.5 [29] using the Ecoinvent v3.10 database [30]. The impact category indicators considered in this study include the 100-year Global Warming Potential (GWP100), expressed in kg CO_2-eq, together with water use (m^3) and non-renewable energy resource consumption (MJ). These indicators are consistently evaluated for both the baseline and the redesigned component.

The impact categories selected in this study (GWP100, water use, and non-renewable energy resource consumption) are among the most widely used indicators in environmental assessments and are considered representative of key environmental pressures associated with industrial systems and transport applications. In particular, GWP100 captures the contribution to climate change, which is a primary concern in the transport sector. Water use reflects the pressure on freshwater resources, which is increasingly critical in the context of global resource scarcity. Non-renewable energy resource consumption accounts for the depletion of finite energy resources, such as fossil fuels, and is closely linked to both environmental impact and long-term sustainability considerations. Together, these categories provide a comprehensive, yet manageable representation of the main environmental implications associated with material substitution and lightweighting strategies. Nevertheless, the proposed methodology is fully general and can be applied to any environmental impact category for which consistent characterization factors are available. Additional categories, such as particulate matter formation, acidification, or mineral resource depletion, can therefore be incorporated depending on the specific goal and scope of the analysis.

For both case studies, the MEX manufacturing stage of the redesigned components was modelled considering the FUNMAT HT system. No direct water consumption was associated with the printing process; therefore, the water-use impact of the manufacturing stage arises from the upstream impacts related to the electricity consumed during printing, modelled using the Ecoinvent 3.10 dataset “market for electricity, low voltage” for the Italian electricity mix (IT).

3.2. Case study 1

In the automotive case study, a structural bracket equipped with elastomeric dampers was selected (Fig. 2). The assembly is used to fasten a compressor to the vehicle while isolating the chassis from vibrations, thereby reducing the likelihood of noise being perceived inside the cabin under specific operating conditions. The baseline component is currently manufactured by sheet-metal stamping.

The redesign was developed, using the DfAM guidelines, starting from the baseline component by imposing geometric and functional interchangeability as a key constraint. Accordingly, the interfaces to the chassis and the compressor, the overall envelope, and the compressor's relative position with respect to the chassis were preserved. The optimized solution was conceived for material extrusion (MEX) AM, using ULTEM 9085 and Thermoplastic PolyUrethane (TPU) Shore 80 A filaments.

The optimization aimed at minimizing mass while satisfying structural requirements. The constraints were defined in terms of the global stiffness of the assembly, the local stiffness of the dampers (i.e., radial and axial), and the modal and frequency response at the bracket's

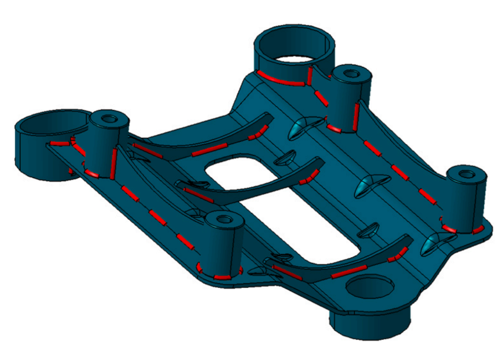

Fig. 2. Reference geometry for the automotive case study.

anchoring points to the vehicle chassis. The local stiffness was evaluated by correlating the applied load and the resulting displacement according to Hooke's law. With regard to the modal response, the natural frequencies of the component were required to remain above specified threshold values, while the maximum displacement of the bracket was evaluated under frequency loading conditions.

The optimized damper was designed as a three-part assembly comprising a ULTEM 9085 base with a threaded interface to the chassis, a central damping section made of TPU Shore 80 A manufactured as a lattice structure, and an upper ULTEM 9085 part that can also be produced as a single piece integrated with the compressor-connection geometry (Fig. 3).

The assembly of the three parts was designed to be achieved through structural adhesive bonding. This choice was aimed at avoiding assembly preloads, reducing both mass and part count, and limiting the overall envelope. The axisymmetric layout further simplifies installation and makes the system independent of mounting orientation. In addition, a fail-safe mechanism was introduced by placing a washer, either printed in or integrated with the ULTEM component, between the screw head and the damper to retain the bracket and compressor in the event of failure of the lattice section. The bill of materials and the mass-related inventory parameters adopted for the reference and the optimized configurations are reported in Table 2.

The mass values reported are used exclusively as inventory inputs for modelling the manufacturing stage of the two configurations, whereas the assessment of environmental convenience is presented separately in the next section.

For the baseline multi-material bracket, manual disassembly prior to EoL treatment was assumed, allowing the steel, aluminum, and TPU components to be separated and subsequently modelled independently according to their respective end-of-life scenarios.

3.3. *Case study 2*

In the second case study, an aeronautical component installed inside the cabin was investigated. The selected component is a tablet holder, originally manufactured using metallic materials, namely AISI 304 stainless steel and Ergal 7075-T6 aluminum alloy. The baseline tablet holder has been modelled in detail in CAD, based on a commercial item available on the market (Fig. 4).

A dimensional survey was carried out on an available sample, and CAD models of the individual parts and of the overall assembly were reconstructed. Part masses were then estimated to define the manufacturing life cycle inventory. For the baseline configuration, a subtractive manufacturing route based on five-axis CNC machining was assumed, consistent with the component typology and the manufacturing indications for the product. Starting from the baseline product, a redesigned version was developed following the DfAM guidelines to achieve comparable functional performance through a different functional architecture. Spherical joints and threaded collars were introduced to provide the degrees of freedom required for tablet orientation, and the higher-mass components were subjected to topology optimization. ULTEM 9085 was selected as the design material for the additively manufactured parts, in line with cabin applications, because this material can be used inside aircraft and helicopters in flight, as it meets the European Aviation Agency for Safety (EASA) requirements for flammability, toxicity, and smoke. The bills of materials and the corresponding mass-related inventory parameters for both the baseline and the AM-oriented configurations are reported in Table 3.

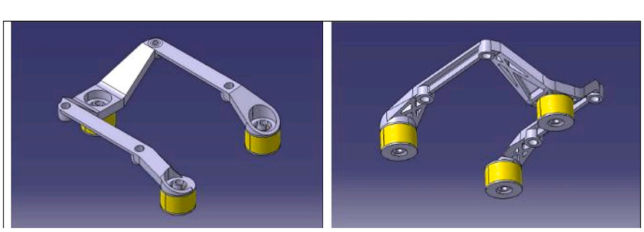

Fig. 3. Optimized configuration designed for MEX manufacturing.

Table 2
Bill of materials and inventory parameters for the automotive case study, baseline and optimized configurations.

	Baseline	Redesigned
Material	Aluminum alloy, TPU, Steel	TPU and ULTEM 9085
Mass [kg]	0.466	0.160

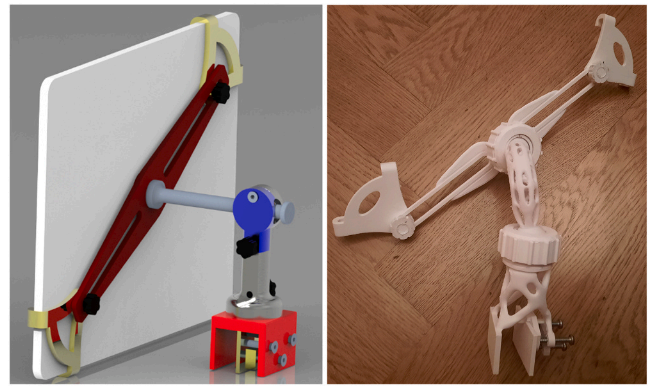

Fig. 4. Baseline tablet-holder configuration (left), prototype optimized in PETG (right).

To obtain a more realistic inventory for additive manufacturing, typical process-specific operations and auxiliary consumptions were accounted for. The need for a brim to prevent part detachment during printing and the use of support structures for overhang regions were included, resulting in an increase in the total material processed relative to the net mass of the finished parts (Fig. 5). For process control, the inclusion of test specimens was considered, with a recommendation of three specimens per build oriented along the X, Y, and Z directions. Post-processing activities included manual removal of supports and the management of brim and support waste.

4. Results and discussions

4.1. *Environmental assessment*

Following the environmental assessment of raw material production, component manufacturing, and EoL treatment, performed using the above-mentioned software and database, it was possible to quantify, for each component and for each life cycle phase, the corresponding environmental impact in terms of GWP100, non-renewable energy resource consumption, and water use. The results are reported in Table 4. It should be noted that, for the investigated case studies, the assumption of a constant total vehicle mass can be considered valid. In Case Study 1, the component mass reduction is 0.306 kg relative to a total vehicle mass of 1525 kg, corresponding to approximately 0.020%. In Case Study 2, the mass reduction is 0.447 kg relative to a total vehicle mass of 2000 kg, corresponding to approximately 0.022%. The effect of component substitution on M_T is therefore negligible in both cases.

Table 3
Bill of materials and mass-related inventory parameters for the tablet holder in the baseline and AM-oriented configurations.

	Baseline	Redesigned
Material	Ergal, ABS, AISI 304	ULTEM 9085
Mass [kg]	0.623	0.176

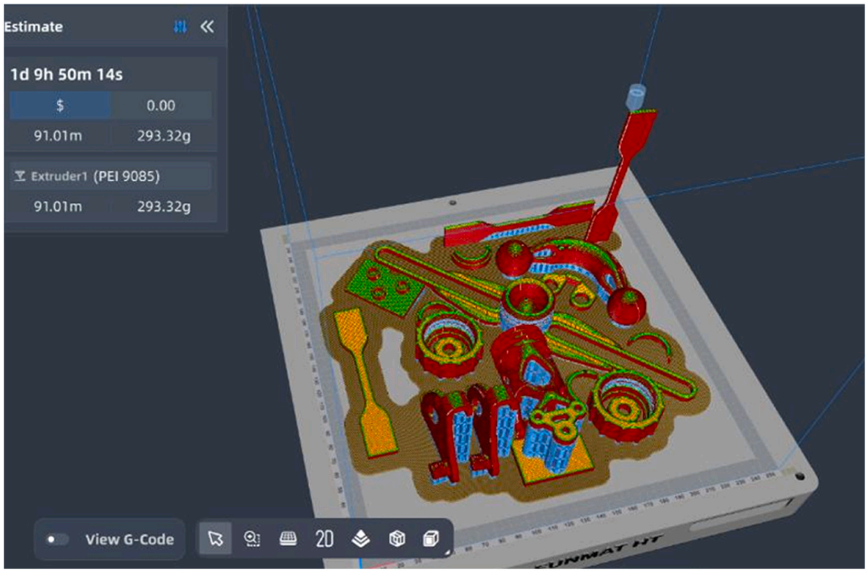

Fig. 5. ULTEM 9085 build-plate layout showing brim and support structures, and the estimated build time and total material usage.

Table 4
GWP100 in kg CO_2-eq.

Phase		Case study 1 Baseline	Case study 1 Redesigned	Case study 2 Baseline	Case study 2 Redesigned
Production	Material production	2.25	0.99	6.87	1.09
	Piece production	1.54	6.88	2.12	7.45
	$e_{prod} = Material + Piece$	3.79	7.87	8.99	8.54
EoL	e_{EOL}	0.25	0.38	0.10	0.39
Prod + EoL		**4.03**	**8.26**	**9.09**	**8.93**
Life	M_T	1525 [kg]		2000 [kg]	
	ν	$2{\cdot}10^5$ [km]		$2{\cdot}10^4$ [h]	
	ε_ν	0.307 [kg (CO_2)/km]		461.2 [kg (CO_2)/h]	
	e_ν	**18.76**	**6.44**	**2873.26**	**756.36**
E		**22.79**	**14.69**	**2882.35**	**765.29**

From Table 4, a consistent pattern emerges across both case studies when separately examining production, end-of-life, and use-phase contributions. Considering the production phase alone, the baseline components show higher impacts during raw material production because of their greater mass and larger material demand, whereas the redesigned components exhibit significantly higher impacts during manufacturing. This reflects the typical trade-off associated with additive manufacturing: material savings reduce upstream burdens, but the higher process energy demand increases manufacturing-related emissions. In both case studies, this shift is clearly visible. For example, in Case Study 1, material production decreases from 2.25 to 0.99 kg CO_2-eq in the redesigned solution, while piece production increases from 1.54 to 6.88 kg CO_2-eq. Similarly, in Case Study 2, raw material production drops from 6.87 to 1.09 kg CO_2-eq, whereas manufacturing emissions rise from 2.12 to 7.45 kg CO_2-eq.

When production and end-of-life are combined, the redesigned component in Case Study 1 has a substantially higher impact than the baseline (8.26 vs. 4.03 kg CO_2-eq), indicating that, if only component manufacturing and disposal are considered, redesign through AM would appear environmentally disadvantageous. In Case Study 2, the production and EoL impacts are instead nearly equivalent (8.93 vs. 9.09 kg CO_2-eq), suggesting that material savings almost fully compensate for manufacturing burdens. However, the inclusion of the use phase fundamentally changes the interpretation. The use-phase contribution, represented by e_ν, accounts for the environmental burden associated with transporting the component mass throughout the vehicle lifetime. Since the redesigned components are substantially lighter, their associated operational emissions are significantly reduced. In Case Study 1, use-phase emissions decrease from 18.76 to 6.44 kg CO_2-eq, while in Case Study 2 they decrease dramatically from 2873.26 to 756.36 kg CO_2-eq. These reductions are particularly relevant in applications with high operational intensity, where cumulative transport-related emissions dominate the overall life cycle.

As a result, the total indicator E, which includes production, use, and EoL, reverses the conclusions suggested by production alone. In Case Study 1, despite higher production impacts, the redesigned component achieves a lower total impact (14.69 vs. 22.79 kg CO_2-eq), demonstrating that operational savings are sufficient to compensate for manufacturing burdens. This effect is even more pronounced in Case Study 2, where the redesigned component reduces total emissions from 2882.35 to 765.29 kg CO_2-eq, highlighting the decisive role of mass reduction in high-use transport systems such as aeronautics. Overall, Table 4 demonstrates that evaluating production alone would underestimate the environmental benefits of lightweight redesign. While additive manufacturing may increase manufacturing emissions, the reduction in transported mass during operation can generate substantial life-cycle advantages, particularly when vehicle lifetime and operational energy demand are high. This confirms the necessity of integrating production, use, and end-of-life into a unified indicator to properly assess the true environmental convenience of component substitution.

Table 5 presents the results for non-renewable energy resource consumption and reveals patterns that are broadly consistent with those observed for GWP100, while also highlighting some category-specific differences.

Table 5
Non-renewable energy resource consumption in MJ.

Phase		Case study 1		Case study 2	
		Baseline	**Redesigned**	**Baseline**	**Redesigned**
Production	Material production	26.76	20.05	68.36	21.62
	Piece production	17.16	110.09	23.31	119.11
	$e_{prod} = Material + Piece$	43.92	130.14	91.67	140.73
EoL	e_{EOL}	0.16	0.07	0.20	0.08
Prod + EoL		**44.08**	**130.21**	**91.87**	**140.81**
Life	M_T	1525 [kg]		2000 [kg]	
	v	$2 \cdot 10^5$ [km]		$2 \cdot 10^4$ [h]	
	ε_v	3.97 [MJ/km]		5979.25 [MJ/h]	
	e_v	**242.45**	**83.25**	**37,250.75**	**9805.98**
E		**286.53**	**213.46**	**37,342.62**	**9946.79**

When considering the production phase alone, the redesigned components again show lower impacts in raw material production but significantly higher impacts in piece manufacturing. In both case studies, the baseline components require more non-renewable energy for material production because of the larger quantity of primary material involved. In Case Study 1, material production decreases from 26.76 MJ for the baseline component to 20.05 MJ for the redesigned one, while in Case Study 2 the reduction is even more pronounced, from 68.36 MJ to 21.62 MJ. This confirms that lightweight redesign can effectively reduce the upstream energy demand associated with material extraction and processing. However, these benefits are offset by the manufacturing phase. Additive manufacturing of the redesigned components requires substantially more non-renewable energy than conventional production. In Case Study 1, piece production increases dramatically from 17.16 MJ to 110.09 MJ, while in Case Study 2 it rises from 23.31 MJ to 119.11 MJ. This indicates that, from an energy resource perspective, AM currently imposes a considerable process-related burden, likely due to machine energy demand, processing time, and auxiliary operations. When combining production and EoL, the redesigned component is clearly more energy intensive in both case studies. In Case Study 1, total production plus EoL consumption increases from 44.08 MJ for the baseline to 130.21 MJ for the redesigned component. Similarly, in Case Study 2, values increase from 91.87 MJ to 140.81 MJ. Therefore, if only production and disposal phases are considered, the redesigned solutions would appear environmentally disadvantageous from the standpoint of non-renewable energy use.

The inclusion of the use phase again substantially alters the interpretation. In Case Study 1, the use-phase energy demand attributable to the transported component mass decreases from 242.45 MJ for the baseline to 83.25 MJ for the redesigned component. This reduction is sufficient to compensate for the higher manufacturing burden, leading to a decrease in total life-cycle non-renewable energy consumption from 286.53 MJ to 213.46 MJ. In Case Study 2, the use-phase energy demand drops from 37,250.75 MJ for the baseline component to 9805.98 MJ for the redesigned one. Because of the extremely high operational energy demand associated with aeronautical applications, this reduction overwhelmingly compensates for the increased manufacturing burden. As a result, total life-cycle non-renewable energy consumption is dramatically reduced, from 37,342.62 MJ for the baseline to 9946.79 MJ for the redesigned component.

These data demonstrate that the environmental convenience of lightweight redesign from a non-renewable energy perspective is highly context-dependent. While additive manufacturing may impose substantial production-phase energy burdens, the magnitude of operational savings determines whether substitution is ultimately beneficial. In lower-intensity applications, such as Case Study 1, the higher production burden can partially offset the operational gains, limiting the overall benefit, whereas in high-intensity systems such as aeronautics, operational savings can far outweigh manufacturing penalties. This confirms that energy-based environmental assessments, like GWP100 evaluations, require a full life-cycle perspective to avoid misleading conclusions based solely on production data.

Table 6 reports the results for water use and provides further insight into how lightweight redesign influences environmental performance across different resource categories. Although the general structure of the results is similar to that observed for GWP100 and non-renewable energy consumption, water use reveals additional nuances related to process-specific burdens.

As in the previous impact categories, the baseline components show higher impacts during raw material production due to the larger quantity of material required. In both case studies, the redesigned components significantly reduce water use associated with material production. In Case Study 1, raw material water consumption decreases from 0.67 m^3 for the baseline component to 0.31 m^3 for the redesigned one, while in Case Study 2 the reduction is even more substantial, from 1.72 m^3 to 0.31 m^3 . These reductions confirm that lightweighting and material minimization can effectively decrease the upstream burden on freshwater resources. However, the manufacturing phase again shifts the environmental burden toward the redesigned AM solutions. In Case Study 1, water use during piece production rises from 0.40 m^3 to 4.21 m^3 , while in Case Study 2 it increases from 0.55 m^3 to 4.56 m^3 . This sharp increase suggests that additive manufacturing processes, or the associated upstream energy systems supporting them, may be considerably more water intensive than conventional manufacturing routes. When production and EoL are combined, the redesigned component exhibits substantially higher water consumption in both applications. In Case Study 1, total production plus EoL water use increases from 1.09 m^3 for the baseline to 4.55 m^3 for the redesigned component. Similarly, in Case Study 2, it rises from 2.28 m^3 to 4.89 m^3 . Therefore, from a cradle-to-gate plus disposal perspective, the redesigned components appear significantly less favorable in terms of freshwater resource demand. The use phase, however, introduces important differences between the two applications. In Case Study 1, operational water use associated with transporting the lighter redesigned component is only slightly reduced compared with the baseline (0.38 vs. 0.13 m^3). Because the use-phase contribution is relatively small in this automotive scenario, it does not compensate for the much higher water demand of additive manufacturing. Consequently, the total indicator E increases from 1.47 m^3 for the baseline to 4.68 m^3 for the redesigned component, indicating a clear environmental disadvantage from a water-use perspective.

In Case Study 2, the situation changes considerably. The operational water burden decreases from 52.67 m^3 for the baseline to 13.86 m^3 for the redesigned solution. Given the high operational intensity of the aeronautical system, these savings are sufficient to outweigh the higher production burdens, reducing total life-cycle water use from 54.94 m^3 to 18.75 m^3 . This demonstrates that, even for water use, operational savings can dominate the life cycle when service conditions are sufficiently intensive.

Overall, Table 6 confirms that water use can lead to conclusions that differ substantially from those based solely on GWP100. In Case Study 1, the redesigned component is advantageous from a climate perspective

Table 6
Water use in m^3.

Phase		Case study 1		Case study 2	
		Baseline	Redesigned	Baseline	Redesigned
Production	Material production	0.67	0.31	1.72	0.31
	Piece production	0.40	4.21	0.55	4.56
	$e_{prod} = Material + Piece$	1.07	4.52	2.27	4.87
EoL	e_{EOL}	0.02	0.03	0.01	0.03
Prod + EoL		1.09	4.55	2.28	4.89
Life	M_T	1525 [kg]		2000 [kg]	
	v	$2{\cdot}10^5$ [km]		$2{\cdot}10^4$ [h]	
	ε_v	0.01 [m^3/km]		8.45 [m^3/h]	
	e_v	**0.38**	**0.13**	**52.67**	**13.86**
E		**1.47**	**4.68**	**54.94**	**18.75**

but clearly unfavorable in terms of water consumption, showing that reliance on a single impact category may provide an incomplete or potentially misleading assessment. In Case Study 2, the redesigned solution performs better across all categories due to the dominant effect of use-phase savings. These results reinforce the importance of multi-category environmental assessment and demonstrate the flexibility of the proposed indicator in capturing different dimensions of sustainability depending on the selected impact category.

4.2. Indicator and score evaluation

Based on the results obtained above, it is possible to proceed with the evaluation of the indicators (E_{red} and E_{base}) and of the associated *score* for each environmental indicator and for each case study. Since the analysis concerns the substitution of a single component, and the redesigned components were designed to ensure a service life comparable to that of the baseline ones, the score is calculated according to Eq. (3).

Case study 1

By applying Eq. (3), the score related to GWP100 can be calculated as follows:

$$score_{(GWP100)} = \frac{E_{red}}{E_{base}} = \frac{14.69}{22.79} = 0.64 \quad (6)$$

With this score value, the substitution of the component is placed in Class B (Fig. 6).

Similarly, the score values for the other environmental indicators were also calculated. The three resulting scores are reported in Table 7.

This result indicates that, despite the higher production and end-of-life burdens of the redesigned AM component, the reduction in operational emissions associated with lower mass is sufficient to generate a moderate environmental benefit over the full life cycle. In other words, from a climate-change perspective, the redesigned solution is environmentally preferable. However, extending the same analysis to the other environmental categories highlights a more complex scenario. The score for non-renewable energy resource consumption is 0.75, which falls within Class C. This indicates a nearly neutral substitution: although some life-cycle energy savings are achieved through mass reduction, these are partially offset by the significantly higher energy demand of additive manufacturing. Therefore, from an energy resource perspective, the redesigned component does not provide a strong environmental advantage, but neither does it represent a severe penalty. In contrast, the score for water use is 3.18, placing the redesigned component in Class E, which corresponds to a high environmental penalty. This result shows that the increased water demand associated with additive manufacturing and related upstream processes substantially outweighs the operational savings achieved through lightweighting. Consequently, while the redesign improves carbon performance, it performs significantly worse with respect to freshwater resource consumption.

Table 7
Score values for Case Study 1.

Score	Value	Class
$\text{Score}_{(\text{GWP100})}$	0.64	B
$\text{Score}_{(\text{non-renewable energy resource})}$	0.75	C
$\text{Score}_{(\text{water use})}$	3.18	E

These results demonstrate that, in the automotive case study, the environmental convenience of redesign strongly depends on the impact category considered. The proposed score therefore reveals that a substitution considered beneficial under one metric (e.g., GWP100) may be neutral or even clearly disadvantageous under another. This confirms the importance of evaluating multiple environmental dimensions before drawing conclusions regarding sustainability.

Case study 2

By applying Eq. (3), the score can be calculated as follows:

$$score = \frac{E_{red}}{E_{base}} = \frac{765.29}{2,882.36} = 0.27 \quad (7)$$

With this score value, the substitution of the component is placed in Class A (Fig. 7).

Similarly, the score values for the other environmental indicators were also calculated. The three resulting scores are reported in Table 8.

These results indicate a very high environmental benefit, meaning that the redesigned lightweight component dramatically reduces life-cycle greenhouse gas emissions compared with the baseline solution. The large reduction is primarily driven by the substantial decrease in operational burdens, which is particularly relevant in aeronautical applications where transported mass has a disproportionately large effect on lifetime environmental performance.

The same trend is observed for non-renewable energy resource consumption, where the score is also 0.27 (Class A). This confirms that, despite the high energy demand of AM during manufacturing, the

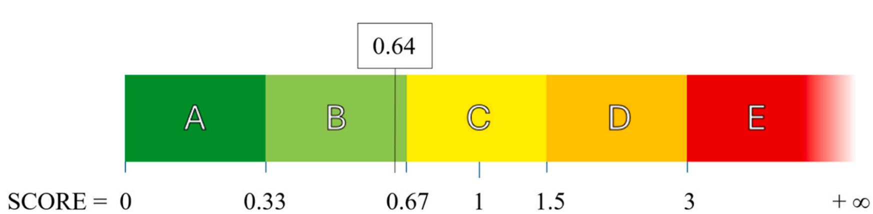

Fig. 6. $\text{Score}_{(\text{GWP100})}$ value for Case study 1 placed in Class B.

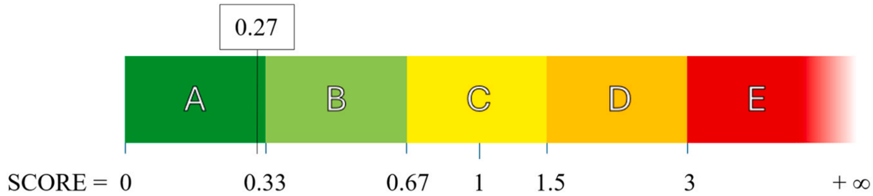

Fig. 7. $Score_{(GWP100)}$ value for Case study 2 placed in Class A.

Table 8
Score values for Case Study 2.

Score	Value	Class
$Score_{(GWP100)}$	0.27	A
$Score_{(non\text{-}renewable\ energy\ resource)}$	0.27	A
$Score_{(water\ use)}$	0.34	B

operational energy savings generated by weight reduction overwhelmingly compensate for production burdens. Therefore, from both climate and fossil energy resource perspectives, the redesigned component is strongly preferable.

For water use, the score is 0.34, corresponding to Class B. Although the benefit is slightly less pronounced than for GWP100 and energy resources, the redesigned solution still provides a clear environmental improvement. In this case, the operational savings associated with reduced mass are sufficient to compensate for the higher water intensity of additive manufacturing, unlike what was observed in Case Study 1.

This case study demonstrates that when the operational burden associated with transported mass is sufficiently high, lightweight redesign can consistently produce environmental advantages across multiple impact categories, even when production burdens increase.

4.3. Comparative discussion

The comparison between the two case studies highlights the practical value of the proposed indicator and score methodology in capturing how the environmental convenience of component substitution depends not only on the redesign itself, but also on the transport context and on the selected environmental category.

In both case studies, the redesigned AM components reduce GWP100, confirming that lightweighting generally provides climate-related benefits when operational emissions are considered. However, the magnitude of this benefit differs substantially. In the automotive case, the benefit is moderate (Class B), while in the aeronautical case it is very high (Class A). This difference is directly linked to the relative importance of mass during operation. Since aircraft and helicopters are considerably more sensitive to weight than road vehicles, mass reduction generates much larger cumulative life-cycle benefits. For non-renewable energy resource consumption, the contrast is even more informative. In Case Study 1, the substitution is nearly neutral (Class C), showing that manufacturing energy burdens can offset operational gains in lower-intensity applications. In Case Study 2, by contrast, operational savings dominate so strongly that the substitution becomes highly advantageous (Class A). Water use provides the clearest example of category dependence. The automotive redesign performs poorly (Class E), demonstrating that a lightweight strategy may be environmentally unfavorable if evaluated from a freshwater resource perspective. Conversely, the same design philosophy applied to the aeronautical component achieves a positive result (Class B) because of the much larger operational savings.

4.4. Break-even analysis

A further decision-oriented interpretation of the proposed score can be obtained by identifying the operating life at which the environmental advantage of a component substitution changes sign. In lightweight redesign applications, the redesigned component may exhibit a higher production and EoL burden than the baseline configuration, while providing lower use-phase impacts because of its reduced mass. Consequently, the environmental convenience of the substitution may depend on the actual operating life of the vehicle.

For a given environmental impact category, the environmental indicators of the baseline and redesigned components can be expressed as functions of the operating life L:

$$E_{base}(L) = C_{base} + u_{base} \cdot L \tag{8}$$

$$E_{red}(L) = C_{red} + u_{red} \cdot L \tag{9}$$

where C_{base} and C_{red} represent the production and EoL contributions of the baseline and redesigned components, respectively, while u_{base} and u_{rev} represent their corresponding use-phase impacts per unit of operating life. Depending on the application, L can be expressed in travelled distance, operating hours, or another appropriate lifetime parameter.

The environmental break-even point L^* is defined as the operating life at which the two alternatives have the same total environmental impact, corresponding to a score equal to one:

$$E_{base}\quad(L^*) = E_{red}\quad(L^*) \tag{10}$$

from which:

$$L^* = \frac{C_{red} - C_{base}}{u_{base} - u_{red}} \tag{11}$$

when a positive solution exists.

When the redesigned component has a higher initial production and EoL burden but a lower use-phase impact, L* represents the operating life required for the cumulative use-phase savings to compensate for the additional initial environmental burden associated with the redesign. Below this value, the redesigned solution remains environmentally disadvantageous, whereas above L* it becomes environmentally preferable. Conversely, when the redesigned component already exhibits lower production and EoL impacts together with a lower use-phase impact, no positive break-even point exists because the redesigned solution is environmentally preferable from the beginning of the use phase.

Fig. 8 illustrates this concept for GWP100 in Case Study 1.

The baseline component has a production and EoL impact of 4.03 kg CO_2-eq, compared with 8.26 kg CO_2-eq for the redesigned component. However, because of its lower mass, the redesigned component exhibits a lower cumulative use-phase impact. Considering the assumed vehicle lifetime of 200,000 km, the use-phase contributions are 18.76 kg CO_2-eq for the baseline component and 6.44 kg CO_2-eq for the redesigned one. The corresponding use-phase impacts per kilometre are therefore 9.38×10^{-5} and 3.22×10^{-5} kg CO_2-eq/km, respectively. By applying the break-even formulation, the two environmental indicators become equal at approximately 68,700 km. Below this distance, the higher initial environmental burden of the redesigned component has not yet been compensated by the use-phase savings, whereas above approximately 68,700 km the redesigned component becomes environmentally preferable in terms of GWP100. At the assumed vehicle lifetime of

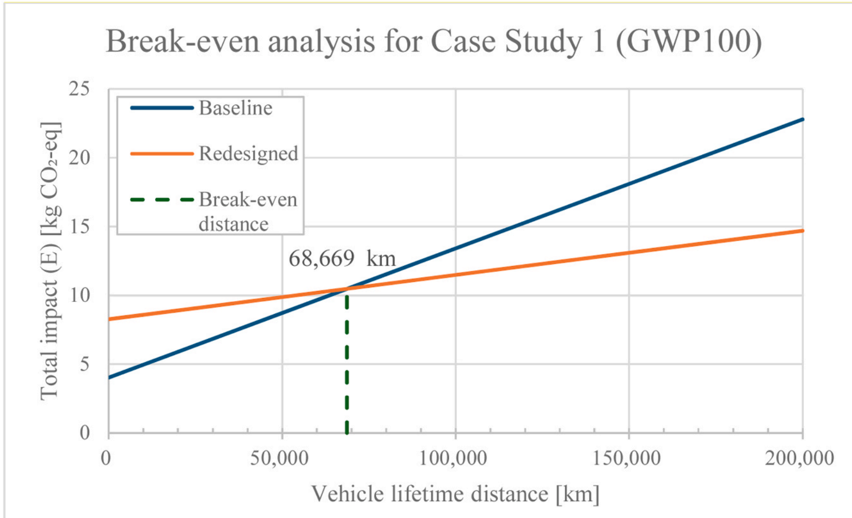

Fig. 8. Break-even analysis for GWP100 in Case Study 1.

200,000 km, the substitution is therefore well beyond the break-even condition, consistently with the GWP100 score of 0.64 obtained for Case Study 1.

The same analysis can be performed independently for each environmental impact category and for different operating contexts. The resulting break-even values for the investigated case studies are summarized in Table 9.

These results further show that the environmental convenience of component substitution depends not only on the characteristics of the redesigned component, but also on the environmental category considered and on the expected operating life. In Case Study 2, no positive break-even is obtained for GWP100 because the redesigned component already exhibits a lower impact than the baseline configuration before the use phase and maintains a lower use-phase impact throughout operation. Conversely, for water use in Case Study 1, a positive break-even is mathematically obtained at approximately 2.77×10^6 km, which is far beyond a realistic vehicle lifetime and is therefore considered not practically achievable.

5. Conclusions

This work introduced a novel environmental indicator and an associated dimensionless score specifically conceived to support the evaluation of vehicle component substitution strategies, particularly in the context of lightweight redesign. By integrating production, use-phase, and EoL contributions into a single comparative framework, the methodology captures the balance between the additional environmental burdens potentially associated with advanced materials or manufacturing technologies and the operational benefits generated by mass reduction over the vehicle lifetime. In this way, the proposed approach provides a direct and transparent comparison between a baseline component and a redesigned alternative with equivalent functional and mechanical performance. The proposed score proved effective in condensing this complexity into an interpretable metric. A score equal to 1 represents environmental neutrality, while values below or above 1 indicate environmental benefit or penalty, respectively. The introduction of environmental classes further enhances usability by translating numerical outcomes into an intuitive design-support tool suitable for early-stage engineering decisions. Although the selected class thresholds are inherently conventional, they provide a practical and symmetric framework for rapid interpretation while preserving methodological flexibility.

Table 9
Environmental break-even operating life for the investigated impact categories and case studies.

Environmental impact category	Case Study 1	Case Study 2
GWP100	68,669 km	No positive break-even
Non-renewable energy resource	108,204 km	35.7 h
Water use	Break-even beyond realistic vehicle lifetime	1345 h

The results obtained from the two case studies demonstrate that the environmental convenience of lightweight substitution cannot be assessed solely on the basis of production impacts or mass reduction alone. Rather, the overall outcome depends on the interaction between manufacturing burdens, operational conditions, service life, and the specific environmental category considered. In both applications, lightweight redesign reduced GHG emissions, but the magnitude of the benefit differed substantially according to the transport context. Moreover, the analysis of additional categories, such as water use and non-renewable energy resource consumption, showed that improvements in one environmental dimension do not necessarily correspond to improvements in others. This confirms the importance of adopting a multi-category perspective when evaluating sustainable design strategies. These findings indicate that indicator and score constitute a pragmatic complement to full LCA and broader sustainability frameworks by offering a faster, component-oriented, and design-oriented assessment tool. While conceived for vehicle component substitution, the methodological structure is sufficiently general to be extended to other engineering systems in which alternative component configurations, materials, or manufacturing routes must be compared. In non-transport engineering systems, the same score framework can be retained by adapting the use-phase contribution to the relevant operating mechanism. As an illustrative example, for static industrial machinery, if component substitution does not affect operational energy demand, the use-phase term can be neglected and the comparison reduces to production and EoL contributions. Conversely, if the redesigned component affects machine efficiency, power demand, operating time, or service life, the use-phase contribution can be formulated accordingly while keeping the dimensionless score unchanged. The break-even analysis further complements the dimensionless score by providing an additional decision-oriented parameter indicating, when applicable, the minimum operating life required for the redesigned solution to become environmentally advantageous. With appropriate adaptation of system boundaries and inventory data, the proposed framework can therefore support environmentally informed decision-making across a broad range of industrial applications.

CRediT authorship contribution statement

Fabio Salmeri: Writing – original draft, Visualization, Software, Investigation, Formal analysis. **Emmanuele Barberi:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Mauro Giacalone:** Writing – original draft, Software. **Alessandro Ceruti:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Sara Mantovani:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Gianpaolo Savio:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Filippo Cucinotta:** Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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