UTILIZING LIFE CYCLE ROBUST OPTIMIZATION TO ASSESS THE ENVIRONMENTAL IMPACTS OF LIGHTWEIGHT MATERIALS FOR A CAR ENGINE

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الملخص

تبحث هذه الورقة استخدام المواد خفيفة الوزن وتناقش إمكانية الحد من التأثير البيئي عند صناعة السيارات. يطبق البحث منهجية تحسين تعتمد على دورة حياة المنتج (LCA) لتقييم الآثار البيئية لمحرك سيارة مصنوع من مادة الألومنيوم. في عملية التقييم أخذ بعين الاعتبار مرحلتي الاستخدام ونهاية دورة الحياة للمحرك. تطبق المنهجية المستخدمة تقنية نمذجة تحسين قوية بالتعامل مع نظرية عدم اليقين (الريبة) لقاعدة بيانات دورة حياة المنتج. الصيغة الرياضية المشتقة تحسب وتراعي القيود وعدم اليقين معا. يعمل نموذج تقييم دورة الحياة المطور كأداة لدعم القرار في مجال البيئة من خلال إجراء تحليل استهلاك الطاقة لدورة حياة المنتج وكذلك انبعاث غاز ثاني أكسيد الكربون. ينفذ نموذج تقييم دورة الحياة تحليلا شاملا لمحرك السيارة لتوجيه المصممين نحو اختيار المواد الآمنة بيئيا لمكونات سيارات معينة وهما كتلة المحرك ورأس الاسطوانة. اقترح البحث عدد اثنان سيناريو لتحسين المحرك، تحديدا مادتي سبائك المغنيسيوم والياف الكربون. وتم تقييم هاتين المادتين باستخدام المنهجية المقترحة لتطوير منتجات صديقة للبيئة (خضراء). أظهرت النتائج أن المواد خفيفة الوزن كسبائك المغنيسيوم وألياف الكربون بأنها مواد واعدة من حيث تقليل انبعاث غاز ثاني أكسيد الكربون وتوفير الطاقة مقارنة بالألومنيوم الذي يمثل مادة المحرك الأساسية. تزود المنهجية المقترحة رؤى ذات قيمة لعملية اختيار المواد وكذلك تبين تأثير خيارات المواد المختلفة على البيئة.

ABSTRACT

This paper explores the use of lightweight materials and discusses their potential for environmental impact reduction in the automotive industry. The research implements a life cycle assessment (LCA)-based optimization methodology to assess the environmental impacts of an aluminium-based automotive car engine. The assessment considered the usage and end of life cycle stages. The presented methodology applies robust optimization modelling technique to dealing with uncertainty in the life cycle inventory (LCI) database. The derived mathematical formulation simultaneously accounts for constraints and objective uncertainty. The developed LCA model serves as a design for environment (DFE) decision support tool by performing the analysis of the life cycle energy consumption and CO_2 emission. The LCA model applies a comprehensive car engine analysis to guide designers toward environmentally safe material selection for specific automotive components, namely the engine block and cylinder head. The research suggested two DFE improvement scenarios, specifically magnesium alloy and carbon fibres. The two materials are evaluated using the suggested methodology for developing green products. The results show that lightweight materials magnesium alloy and carbon fibres are promising materials in terms of reducing CO_2 emission and saving energy compared to aluminium the baseline engine. The proposed methodology provides valuable insights into the material selection process and displays the effect of different material choices on the environment.

KEYWORDS: Robust optimization; life cycle assessment; lightweight design; SolidWorks sustainability; uncertainty.

INTRODUCTION

In the automotive industry several strategies have been adopted to reduce fuel consumption and environmental impacts of automobiles in response to strict fuel economy and greenhouse gas (GHG) emissions regulations [1]. Lightweight automotive designs are regarded as one of the most important solutions for improving fuel economy and lowering harmful emissions, specifically during the dominant use stage of a vehicle [2]. Lowering automobiles' mass can be accomplished through two methods: innovative design, in which components are optimized for higher performance, and material substitution, in which conventional automotive materials like steel are replaced with lighter-weight alternatives. Lighter materials, such as magnesium alloy and carbon fibers, have demonstrated a great potential for weight savings in applications such as engine blocks, cylinder heads, structures, hoods, and so on. As a result, these materials are becoming more popular and are being used to replace steel in automotive applications [3-5]. This research employs the lightweight design strategy to improve the environmental performance of a car engine. In this article a systematic framework has been developed for improving products with less environmental impacts based on the integration of life cycle assessment (LCA) and robust optimization (RO) modeling technique. LCA has been proposed as a method for evaluating the inputs, outputs, and the environmental impacts of a car engine throughout its usage and end of life stages. This was achieved using SolidWorks software (CAD) to create a 3D engine model that permits simultaneously managing three key features of the product, shape, material, and production method, and obtaining the product's environmental impacts. LCA results are then used to assess some lightweight material alternatives using a robust optimization (RO) model to achieve environmental improvements. Additionally, robust optimization will give the designer the ability to address uncertainty in the product life cycle inventory (LCI) as well as uncertainty in the designer's judgments (weights). To illustrate the methodology's applicability, an application of the suggested methodology to a case study of an automotive car engine is provided.

Furthermore, the proposed framework is designed to achieve the following research aims: First, it establishes a systematic approach to evaluate the potential for lowering life cycle energy consumption and CO_2 emissions through the use of lightweight design strategy. The second is to incorporate data uncertainty into the optimization model to make sure that the optimal solution is robust to any changes. The third is to use the integrated LCA and robust optimization methodology to determine the best option for reducing engine environmental impacts.

LITERATURE REVIEW

Life cycle assessment (LCA) is a systematic decision tool that enables practitioners to compare and optimize a product's environmental performance. According to Hellweg and Milà i Canals [6], the most important element of LCA is life cycle inventory (LCI) analysis, it is used to assess the inputs and outputs of a product system and relies on high-quality inventories to guarantee the accuracy of LCA results. At what time making decisions regarding product improvement, LCA can help designers determine which aspects of the product dominate its lifespan impacts [7].

In LCA research, variability and uncertainty are not consistently addressed. Product life cycle inventory (LCI) is subjected to a variety of uncertainties, and the calculated real value of LCI may differ significantly from the target LCI values, which are anticipated during the design phase. A robust design method was proposed to overcome the uncertainty issue in the decision-making stage [8]. Researchers used probability theory and the Monte Carlo method to address LCI uncertainty in their mathematical model. Ma [9] proposed a robust optimal usage modeling framework. A constant rate method was used to consider uncertainty by adopting probabilistic graphical models (PGMs) with simulation. In this research, LCI uncertainty is taken into account by assuming a symmetric interval with a mean value and a maximum deviation from the mean. This provides a single impact value (mean) as well as upper and lower estimations of the environmental impacts to improve the quality of the decision-making process.

Although the use of LCA has historically been focused on improving product environmental performance [10,11], several authors have recognized the LCA's unexplored potential as an optimization tool due to the need to incorporate life cycle considerations into process design and optimization procedures [12-14]. The theoretical justification of combining matrix-based LCA and robust optimization while accounting for constraint uncertainty is the main focus of Wang and Work's research [14]. Meanwhile, this research focuses on incorporating life cycle consideration into a robust optimization framework to help in selecting between various material options. The research takes into account both constraints and objective uncertainty. Additionally, it demonstrates how operations research-inspired analysis and life cycle assessments (LCAs) can be combined to create a powerful decision-making tool for car engines to be a more environmentally friendly product.

Several LCA studies have been conducted to assess the environmental impacts of the entire automotive material selection process as well as automotive part design processes. Duflou et al. [5] conducted a comprehensive life cycle analysis for a reference car design to investigate the effects of replacing conventional steel structures with lightweight composite alternatives. Dhingra and Das [4] compared the life-cycle environmental impacts of downsized versus lightweight automotive engines. The study focuses on lightening engine components, wherever feasible, by replacing the cast iron and steel with lighter weight metals such as aluminum and magnesium. The study concluded that the overall environmental competitiveness of the lightweight magnesium material option is superior compared to the baseline engine.

Car Engine: Baseline and Lightweight Alternatives

In this research, a baseline automotive car engine and lightweight alternatives are compared in terms of the engine's material to determine which makes the lowest environmental impacts during use and end of life stages. The engine has six cylinders with a lifespan of 200,000 miles (321868.8 km). The baseline engine material is aluminum. Table (1) lists the components included in the assessment, as well as their materials, quantities, and weights (kg). The engine block and cylinder head are the two heaviest components in the engine with the possibility of weight reduction. This research focuses on two lightweight engine scenarios. In scenario 1 the material is similar to the baseline engine, with the exception of the engine block and cylinder head, which are made of lighter-weight carbon fibers rather than aluminum. Likewise, the material in scenario 2 is identical to the baseline engine, with the exception of the engine block and cylinder head, which are made of magnesium alloy.

Table 1: List of engine components and materials.

Components	Quantity	Material	Weight (kg)
Engine block	1	Aluminum	26.54
Cylinder head	2	Aluminum	25.30
Front cover	1	AISI 316L stainless steel	4.97
Camshaft	2	Ductile iron	2.08
Camshaft retainer	8	Ductile iron	0.52
Camshaft bushing	8	Aluminum bronze	0.25
Camshaft belt wheel	2	Aluminum	0.56
Valve	24	201 annealed stainless steel	2.07
Valves cover	2	Ductile iron	14.86
Piston head	6	T5-6063 aluminum alloy	7.03
Piston pin	6	Plain carbon steel	1.22
Connecting rod	6	AISI 4340 Steel	5.45
Crankshaft	2	AISI 4340 Steel	24.05
Crankshaft bushing	2	Aluminum bronze	2.55
Crankshaft belt wheel	1	Aluminum	1.94
Exhaust manifold	2	Aluminum	5.33
Intake manifold	1	Aluminum	9.15
Rocker arm	12	AISI 1010 steel	3.16
Rocker arm spring	12	Stainless steel	0.33
Rocker arm hex nut	12	Stainless steel	0.27
Oil pan	1	Aluminum	2.51
Turbocharger	2	Cast stainless steel	2.19
Spark plug	6	Copper and other materials	0.19
Fuel filter	1	Paper, rubber, and steel	0.11
Air filter	2	Paper and rubber	0.66
Oil filter	1	Paper and steel alloys	0.55
Hose	1	Rubber	0.22
Total	-	-	144

The assumptions for magnesium alloy and carbon fiber as lightweight substitution materials for the engine are summarized in Table (2). The mass of the aluminum, carbon fibers and magnesium alloy engine components included for the assessment accounts for approximately 36%, 26%, and 25% of the total engine weight, respectively. The component weight is obtained from SolidWorks sustainability (Gabi), as explained in detail in the following sections. The estimated weight reductions shown in Table (2) are used in the calculations of car engine fuel economy.

Table 2: Material weight of baseline and lightweight engines.

Components	Quantity	Aluminum (kg)	Carbon fibers (kg)	Magnesium alloy (kg)
Engine block	1	26.54	16.69	15.94
Cylinder head	2	12.65	7.96	7.60
Total engine weight	-	144	125	123

Car Engine Fuel Economy Computation

The potential of lightweight materials to reduce fuel consumption and, thus, the life cycle of energy consumption and CO_2 emissions are determined by weight reduction and a few other factors. Consequently, in this section fuel economy computation for a car engine is represented. Fuel economy in cities and highways are typically separated to represent the fuel economy characteristics of an automobile car engine. The city fuel economy of the aluminum engine is 20 mpg (8.5 km/l), and the highway engine's fuel economy is 24 mpg (10.2 km/l). According to Telenko and Seepersad [15], the total (combined) fuel economy determined using equation (1), takes into account the proportion of city-to-highway driving based on residential density.

$$FE_T(baseline) = \left(R_{hwy} * FE_{hwy} + (1 - R_{hwy}\right) * FE_{City}) \quad (1)$$

Where FE_{city} is city fuel economy, FE_{hwy} is highway fuel economy, and R_{hwy} is the proportion of driving on the highway based on residential density, which ranges in values from 0.42 to 0.7. Using equation (1) and the lower and upper limits of the R_{hwy}.

Materials offering high weight savings, such as carbon fibers and magnesium alloy, can improve the environmental performance of a car engine. Any reduction in weight reduces the energy required to accelerate the vehicle, lowers rolling friction, and lowers resistance to airflow, all of which are reducing an automobile's fuel consumption. The improved fuel economy is proportional to the amount of mass saved and is calculated using the baseline engine's fuel economy [16]. The fuel economy for the lightweight engines over their lifetimes (km/l) can be calculated using equation (2).

$$\mathrm{FE_T(lightweight)} = \left(\mathrm{R_{hwy}} * \mathrm{FE_{hwy}} + (1 - \mathrm{R_{hwy}}\right) * \mathrm{FE_{City}})(1 + \mathrm{R_{FRR*}}\frac{\mathrm{m_{reduced}}}{\mathrm{m_{curb}}}) \quad (2)$$

Where m_{curb} is total engine weight (kg), which has been obtained from SolidWorks software, $m_{reduced}$ is engine weight savings (kg) due to the application of a lightweight engine scenarios, and R_{FRR} is fuel savings as a percentage of weight reduction. Ghassemieh [17] stated that fuel efficiency is improved by 7% for every 10% reduction in weight. Using equation (2) and the lower and upper limits of the R_{FRR}, the corresponding optimistic and pessimistic estimations of the baseline and lightweight engines' fuel economy are summarized in Table (3).

Table 3: Car engine fuel consumption estimations.

	Aluminum	Carbon fibers	Magnesium alloy
FE range (km/l)	[9.2 km/l-9.7 km/l]	[9.26 km/l-9.78 km/l]	[9.27 km/l-9.79 km/l]
Lifetime	200,000 miles (321,868.8 km)	200,000 miles (321,868.8 km)	200,000 miles (321,868.8 km)
Lifetime gallons	8,766	8,694	8,685

Quantifying Environmental Impacts Weight

The analytic hierarchy process (AHP) method is used to obtain the priority importance (weighting) of environmental criteria by making a series of pairwise comparisons.

The criteria considered for the environmental performance assessment of a car engine are compared pairwise to assign their weights. The details of how the results of AHP are obtained are explained in the published paper by Showehdi and Alemam [18].

The overall weights of the environmental impacts are presented in Table (4). They are obtained by multiplying the relative weight of each life cycle stage by the weight of the corresponding environmental impact. The overall weight is achieved by multiplying the life cycle stage with the fewest environmental impacts by reducing factor (*RF*), which is defined in equation (3). The environmental impacts are consequently normalized, and the sum of their all weights would be unity.

Overall weight = life cycle stage weight * environmental impact weight * RF (3)

For illustration, the overall weight of the environmental impact of energy consumption at end of life stage is 0.167 * 0.080* 0.86 = 0.011. Adding the weight of energy consumption at usage stage, 0.011 + 0.223= 0.234. Similarly, gas emissions' (CO_2) overall weight is equal to 0.307 + 0.008 = 0.315.

Table 4: Environmental impacts' overall weight.

	Life cycle weight	Environmental impacts	Impact weight	RF	Overall weight
Usage	0.833	Energy consumption	0.268	-	0.223
		Consumables	0.061		0.051
		Gas emissions (CO_2)	0.369		0.307
		Cost	0.038		0.032
		Solid waste	0.099		0.082
		Life span	0.039		0.032
		Durability	0.126		0.105
End of life	0.167	Energy consumption	0.080	0.86	0.011
		Gas emissions (CO_2)	0.058		0.008
		Cost	0.033		0.005
		Solid waste	0.272		0.039
		Disassembly	0.405		0.058
		Reuse	0.152		0.022

To obtain more precise results, the weights could be considered as uncertain weights. Salari and Bhuiyan [19] proposed to improve the accuracy of their optimization model. This was achieved by estimating the upper and lower limits of the weights of environmental impacts to increase the accuracy of the proposed model. Table (5) shows the uncertainty ranges of the CO_2 emissions weight which are appointed at 10% of the mean, while the uncertainty ranges on energy consumption are appointed at 8% of the mean. Incorporating these findings into the mathematical optimization model will result in the optimal tradeoff between the specified materials.

Table 5: Weight of CO_2 emissions and energy consumption.

Environmental impacts	Mean value	Range
Gas emissions (CO_2)	0.315	[0.284 - 0.347]
Energy consumption	0.234	[0.215 - 0.253]

Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is used to evaluate the total gas emissions and energy consumption for the baseline engine and lightweight engine materials. Throughout this stage, engine parts are assessed individually by using SolidWorks associated with GaBi sustainability software to perform a life cycle assessment. The assessment includes usage and end of life stages. Figure (1) shows an example of how the results of the environmental impacts can be obtained after using the software. It shows a 3D model of an engine block with the required inputs and outputs. The inputs contain four categories: type of material, anticipated lifetime, manufacturing method, and duration of use.

Once a sustainability analysis is accomplished, the results are displayed in a sustainability report. Carbon footprint or global warming potential (CO_2) and total energy consumed are two of the main environmental impacts provided by the SolidWorks Sustainability (GaBi) report (MJ). The values marked in the red circles are those that constitute the life cycle inventory (LCI) database. The results are then compiled into a life cycle inventory (LCI) database, which includes information of materials, energy consumed, and gas emissions at various life cycle stages. High quality inventories ensure the accuracy of LCA results, which is especially important when deciding between various design variations. The engine consumes fuel and several parts during operation, such as spark plugs, filters for (fuel, oil, and air), and hoses, all of which are included in the usage stage assessment.

For the purpose of quantifying the uncertainty in usage stage inventory data, the upper and lower limits estimated fuel economy of the assessed engines are used to determine the range of fuel consumption-related impacts, which are CO_2 emissions and consumed energy. Meanwhile, uncertainty associated with the GaBi database is introduced by a ratio and proportionality procedure employing values determined from fuel consumption-related impacts. The life cycle assessment (LCA) calculations for the baseline engine and the two evaluated lightweight engines, made of carbon fibres and magnesium alloy are illustrated in the following subsections.

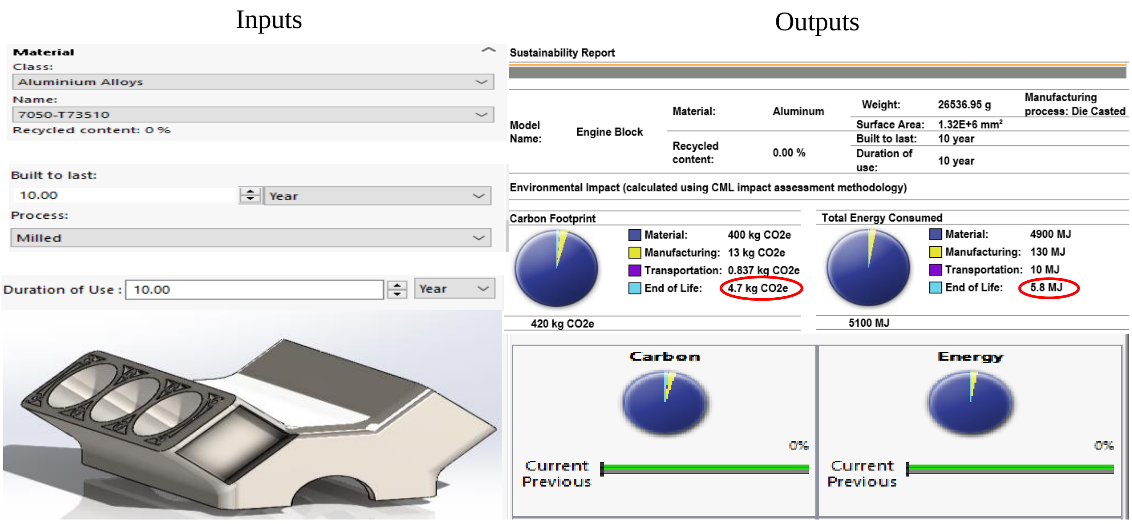

Figure 1: Engine block assessment results using GaBi sustainability software.

The CO_2 emissions are mainly made of fuel consumption. The amount of fuel consumed over the baseline (aluminum) engine lifespan using the upper limit is 321,868.8 km / 9.7 km/l = 33,182 liters. This is equivalent to 8,766 gallons of fuel. To convert CO_2 emissions into mass-based emissions, assuming every gallon of gasoline consumed emits approximately 8.887 kg of CO_2 [20], then the aluminum emits 8.887 * 8,766 = 77,903 kg of CO_2. Besides the CO_2 emissions, the study considers the impact of energy consumption due to the usage stage fuel consumption. As stated by Dayma et al. [21], the energy content of gasoline is assumed to be 32 MJ/l. Given the amount of fuel consumed over the baseline engine lifespan, this implies that its energy consumption is equal to 32 MJ/l * 33,182 liters = 1,061,824 MJ.

The fuel economy and energy consumption of a car engine are affected by a variety of factors, including driver behavior and residential density. When modeling data uncertainty, it is critical to consider the lower limit of the estimated engine fuel economy. The lower limit estimates result in less fuel economy, which increases engine fuel consumption and has a greater negative environmental impact. The pessimistic estimations of a baseline engine fuel economy over its lifespan is 321,868.8 km / 9.2 km/l = 34,986 liters. This is equivalent to 9,242 gallons of fuel and results in 8.887 * 9,242 = 82,134 kg of CO_2. The baseline engine consumes about 32 MJ/l * 34,986 liters = 1,119,552 MJ of energy. The following sub-sections describe the proposed scenarios in this research:

Scenario 1. Carbon Fibers

Carbon fibers are one of the most common composite materials used in the automotive industry as a promising alternative to steel and non-ferrous structures [5].

Based on the information in Table (3), the pessimistic and optimistic estimations of CO_2 emissions and consumed energy associated with the proposed carbon fiber engine can be determined. Given a fuel economy of 9.78 km/l, the amount of fuel consumed over the engine's lifespan is 321,868.8 km / 9.78 km/l = 32,911 liters. This is equivalent to 8,694 gallons of fuel. Thereby, the carbon fiber engine emits 8.887 * 8,694 = 77,265 kg of CO_2. Energy consumption can be calculated using fuel economy data for the carbon fiber engine, which consumes about 32 MJ/l * 32,911 liters = 1,053,149 MJ of energy.

If the carbon fiber engine has a fuel economy of 9.26 km/l, the total amount of fuel consumed over its lifespan is 321,868.8 km / 9.26 km/l = 34,759 liters or 9,182 gallons of fuel, producing 8.887 * 9,182 = 81,604 kg of CO_2 and consuming approximately 32 MJ/l * 34,759 liters = 1,112,290 MJ of energy.

Scenario 2. Magnesium Alloy

The notion of replacing aluminum components by magnesium alloy in the lightweight engine was taken from the research of Dhingra and Das [4], and Beste et al. [22]. Using Table (3) range of fuel economy for the magnesium engine, the amount of fuel consumed after replacing aluminum components with magnesium through the engine's lifespan is determined to be 321,868.8 km/9.79 km/l = 32,877 liters. This is equivalent to 8,685 gallons of fuel. Thereby, the magnesium engine emits 8.887 * 8,685 = 77,186 kg of CO_2. Energy consumption can be calculated using fuel economy data for the magnesium engine, which consumes approximately 32 MJ/l * 32,877 liters = 1,052,074 MJ of energy.

Finally, when the magnesium engine fuel economy is 9.27 km/l, the total amount of fuel consumed over the lifespan is determined by 321,868.8 km / 9.27 km/l = 34,722 liters or 9,172 gallons of fuel, resulting in 8.887 * 9,172 = 81,516 kg of CO_2. Additionally, it consumes approximately 1,111,090 MJ of energy, which is 32 MJ/l multiplied by 34,722 liters.

All CO_2 emissions and energy results are incorporated into the LCIs of the competing design scenarios. Table (6) provides the overall environmental impacts estimated for the usage and end of life stages of the assessed materials. The impacts of the usage stage consist of fuel and consumed engine parts (spark plugs, filters, and hoses), while the end of life stage addresses the remaining engine parts, as presented in Table (1). In terms of CO_2 emissions and energy consumption, the baseline engine uncertainty range and the lightweight engine scenarios' uncertainty range are both estimated to be 3% of the mean for both lifecycle stages. This percentage was calculated using the estimated range of fuel consumption's associated CO_2 emissions and energy consumption, which have been shown in Table (6). The environmental impacts quantified in this section represent an input into the optimization model, which is formulated in the next section.

Table 6: Usage and end of lifecycle stages data (LCI database and uncertainty range).

Material	Environmental impact	Usage		End of life	
		Mean value	Range	Mean value	Range
Aluminum alloy	Gas emissions (kg of CO_2)	81,075	[78,932- 83,218]	58	[56 - 60]
	Energy consumption (MJ)	1,098,581	[1,069,508 - 1,127,654]	418	[407 - 429]
Carbon fibers	Gas emissions (kg of CO_2)	80,491	[78,293 - 82,689]	67	[65 - 69]
	Energy consumption (MJ)	1,090,613	[1,060,827 - 1,120,399]	419.29	[406.58 - 429.42]
Magnesium alloy	Gas emissions (kg of CO_2)	80,408	[78,214 - 82,601]	67	[65, 69]
	Energy consumption (MJ)	1,089,475	[1,059,752 - 1,119,199]	418.79	[407.57 - 430.43]

Environmental Impacts Constraints

Environmental regulations must be satisfied to fulfill the requirements of environmental law across countries. This constraint is represented by the regulation of CO_2 emissions and energy consumption. The proposed model sets an admissible CO_2 emission for cars of 80 g of CO_2 per kilometer [23]. The vehicles will need to emit no more than 0.08 kg of CO_2 per kilometer * 321,868.8 km= 25,750 kg of CO_2 on average over the entire engine operation period. The average energy consumption of the baseline engine, which is 1,098,581 MJ, serves as the target for the restriction on energy consumption and cannot be exceeded by design options. Table (7) summarizes the environmental constraints on a car engine.

Table 7: Demand on car engine CO_2 emission and energy consumption.

Environmental impacts	**Demand**
Gas emissions (kg of CO_2)	25,750
Energy consumption (MJ)	1,098,581

Formulation of Robust Optimization Model in the Context of LCA

In this research study, the life cycle stages under consideration are represented as a matrix (*P*), which is divided into two vectors, each of them represents a unit process (*pj*) based on Heijungs and Suh's [24] framework for the fundamental LCA equations. The vector elements quantify the environmental flows (outputs) of each unit process. As mentioned in the scope of the assessment, the usage and end of life stages are the unit processes in the matrix-based LCA modeling. In terms of both usage and end of life stages, the vector elements quantify the environmental impacts, CO_2 emissions, and energy consumption. In this work, life cycle balance equations are integrated into a linear programming framework to minimize the environmental impacts of car engines. The equations below express the basic LCI linear programming model that describes the overall environmental impacts balance for the life cycle stages of a car engine:

$$\text{Minimize}_{s,g} = \mathrm{c}^T g$$

$$\text{Subject to: } \mathrm{P}s \leq f \qquad (4)$$

$$s \leq 0$$

Where matrix (*P*) represents the car engine considered life cycle stages, vector (*g*) represents the environmental impacts, vector (*f*) represents the boundary condition of the system, also known as the final demand vector or output vector, the scaling vector (*s*) need to be determined to minimize the environmental impacts while satisfying demand, and vector (c^T) is a vector of weighting coefficients and reflects the relative importance of the considered environmental impacts derived from AHP. The values of these vectors and matrices are obtained from the previous sections' calculations. This integration of life cycle assessment (LCA) with optimization alerts the designer to the influence that each change in component material makes an improvement on the environmental impact of the car engine. This model is used as the basic computational framework for robust optimization modeling in the equations (5-10).

The values of the process (life cycle stages) matrix (*P*) and the vector of weighting coefficients (*C*) are both subject to estimation uncertainty. The robust formulation of the linear programming model proposed in the preceding section based on Wang and Work [14], accounts only for constraint uncertainty in estimating the values of the process matrix (*P*). In this paper, the model is further extended to account for objective uncertainty when estimating the values of the vector of weighting coefficients (*C*). This is accomplished using a reformulation technique applied in Gorissen et al.'s research work to develop the robust counterpart of the basic optimization model [25]. This was achieved using the additional reformulation variable as described below:

$$\text{Minimize}_{s,g,t} = t$$

$$\text{Subject to: } C^T g - t \leq 0 \qquad \forall C \in \mathcal{C} \tag{5}$$

$$Ps \leq f \qquad \forall P \in \mathcal{P}$$

$$s \geq 0$$

The uncertainty set of matrix (P) is represented by ($\mathcal{P}$) and the vector of weighting coefficients is represented by ($\mathcal{C}$). They are expressed as symmetric intervals, as shown in Tables (5 and 6), respectively, where each of these sets' elements can have an interval with a mean value and a maximum deviation from the mean. For simplicity, the reformulated model is presented in the robust optimization's standard form:

$$\text{Minimize}_x = C^T x$$

$$\text{Subject to: } Min_K \{Kx\} \leq l \qquad \forall K \in \mathcal{K} \tag{6}$$

$$x \geq 0$$

$$K = \begin{bmatrix} C & -I & 0 \\ 0 & 0 & P \end{bmatrix}, x = \begin{bmatrix} g \\ t \\ s \end{bmatrix}, l = \begin{bmatrix} 0 \\ f \end{bmatrix}, c = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

Where x represents the decision variables vector that consists of the environmental impacts vector (g), additional reformulation variable (t), and the scaling vector (s). The model's uncertainty set is represented as ($\mathcal{K}$).

The robust optimization model is enhanced by the inclusion of the budget of uncertainty (Γ), suggested by Bertsimas and Sim [26], which provides greater control over the number of uncertain variables in the model. The budget of uncertainty (Γ) is identified as the maximum number of variables in constraint (i) that can have the potential for fluctuation or change from their mean values (uncertain variables). Adding the budget of uncertainty, the uncertainty set ($\mathcal{K}$) is then defined as:

$$\mathcal{K} = \left\{ (K_{ij}) \middle| K_{ij} = \bar{k}_{ij} + \hat{k}_{ij} z_{ij}, \forall i, j, z \in Z \right\}$$

Where Z *is* defined to describe the deviation of K_{ij} from its mean value $\hat{k}_{ij}$.

$$Z = \left\{ z \middle| |z_{ij}| \leq 1, \forall i, j, \textstyle\sum_{j=1}^{n} |z_{ij}| \leq \Gamma_i, \forall i \right\}$$

Thus, equation (6) is redefined as follows:

$$\bar{k}_i x + Min_k \left\{ \textstyle\sum_{j=1}^{n} \hat{k}_{ij} x_j z_{ij} \middle| z_i \in Z_i \right\} \leq l \qquad \forall K \in \mathcal{K} \tag{7}$$

Model Solution

At this point, the robust optimization model becomes a linear programming problem with an internal linear programming problem inside it. Strong duality is generally used to solve these problems by replacing the inner minimization problem with its dual maximization problem. The inner linear programming problem has the form of:

$$\text{Minimize}_z = \sum_{j=1}^{n} \hat{k}_{ij} x_j z_{ij}$$

Subject to: $\sum_{j=1}^{n} z_{ij} \leq \Gamma_i$ (8)

$0 \leq z_{ij} \leq 1$

The dual of the inner linear programming problem is given by:

$\text{Maximize}_z = (-\text{Minimize}_z) = -\left(\sum_{j=1}^{n} q_{ij} + \Gamma_i v_i\right)$

Subject to: $v_{i+} q_{ij} \geq \hat{k}_{ij} x_j$ (9)

$v_i \geq 0$

$q_{ij} \geq 0$

The proposed robust optimization model for assessing magnesium alloy and carbon fibers as alternatives to aluminum is summarized below. The optimization is based on the environmental impacts of a car engine for the period of its life cycle stages under uncertainty.

$\text{Minimize}_x = C^T x$

Subject to: $\bar{k}_i x - \Gamma_i v_i - \sum_{j=1}^{n} q_{ij} \leq l \quad \forall i$ (10)

$v_{i+} q_{ij} \geq \hat{k}_{ij} x_j \quad \forall i, j$

$x, v_i, q_{ij} \geq 0 \quad \forall i, j$

This formulation has the advantage of modeling alternatives within a single dataset as opposed to modeling them separately in the optimization problem. The model discussed in this section is then used to determine the most effective material for reducing an automobile engine's overall environmental impacts.

Model Implementation

Once the input data is obtained, the MATLAB R2016a software is used to solve the formulated mathematical model. A comparison between the assessed new materials and the baseline engine is established using the proposed robust optimization model. For the comparison between the baseline engine and carbon fiber engine, the lifecycle stages matrix (*P*), vector of weighting coefficients (*c*), final demand vector (*f*), and the uncertainty set ($\mathcal{K}$) are constructed as follows:

$$P = \begin{bmatrix} 81{,}075 & 58 & 80{,}491 & 67 \\ 1{,}098{,}581 & 418 & 1{,}090{,}613 & 419.29 \end{bmatrix}, C = \begin{bmatrix} 0.315 \\ 0.234 \\ 0.315 \\ 0.234 \end{bmatrix}, f = \begin{bmatrix} 25{,}750 \\ 1{,}098{,}581 \\ 25{,}750 \\ 1{,}098{,}581 \end{bmatrix}$$

$$\bar{k} = \begin{bmatrix} 0.032 & 0.019 & 0.032 & 0.019 & -1 & 0 \\ 0 & 0 & 2{,}143 & 2 & 2{,}198 & 2 \\ 0 & 0 & 29{,}073 & 11 & 29{,}786 & 10 \end{bmatrix}$$

The baseline engine and the magnesium engine are also compared using the data below. The results of the comparison have been shown in the following section.

$$P = \begin{bmatrix} 81{,}075 & 58 & 80{,}408 & 67 \\ 1{,}098{,}581 & 418 & 1{,}089{,}475 & 418.79 \end{bmatrix}, C = \begin{bmatrix} 0.315 \\ 0.234 \\ 0.315 \\ 0.234 \end{bmatrix}, f = \begin{bmatrix} 25{,}750 \\ 1{,}098{,}581 \\ 25{,}750 \\ 1{,}098{,}581 \end{bmatrix}$$

$$\bar{k} = \begin{bmatrix} 0.032 & 0.019 & 0.032 & 0.019 & -1 & 0 \\ 0 & 0 & 2{,}143 & 2 & 2{,}194 & 2 \\ 0 & 0 & 29{,}073 & 11 & 29{,}723 & 12 \end{bmatrix}$$

RESULTS AND DISCUSSION

In this section, the comparison between the baseline engine and the lightweight engine materials in terms of CO_2 emissions and energy consumption is presented. The results show how the environmental impacts of a car engine (the optimal solution) are affected by varying degrees of uncertainty (Γ) in both the optimization model's constraints and objective function. The objective function results, which comprise the total CO_2 emissions and energy consumption are compared between the baseline engine and the lightweight engine materials, as depicted in Figures (2 and 3), respectively.

When the budget of uncertainty (Γ) is 0, the solution is computed using the average predicted values of CO_2 emissions. Figure (2) shows that carbon fibers have lower CO_2 emissions than aluminum (the baseline engine material) over most of the budget of uncertainty (Γ) values. After being compared to aluminum, the CO_2 emissions emitted by carbon fibers are slightly higher than those from magnesium. However, the highest significant CO_2 emissions reduction for carbon fibers occurs at budgets of uncertainty of 0% and 44%, with approximately 9kg of CO_2 and 13kg of CO_2 respectively. When the estimated CO_2 emission in matrix P is subject to a worst-case deviation of 44% of data uncertainty, magnesium will achieve the highest possible CO_2 emissions reduction of approximately 23kg of CO_2 equivalents compared to aluminum. At what time magnesium is compared to carbon fibers and data uncertainty takes a worst-case deviation of more than 40%, there is a significant difference between aluminum and the two materials, with magnesium having the lowest impact.

Part of the uncertainty arises from fuel economy estimates resulting from material substitution since materials with lower densities require less energy per kilometer. Concurrently, the corresponding CO_2 emissions per gallon of fuel are reduced depending on the engine's fuel economy. While uncertainty (Γ) is fully considered, magnesium makes less impact, emitting 0.54kg of CO_2 equivalents, followed by the baseline, aluminum, with an environmental impact of 1.76 kg of CO_2 equivalents, and carbon fiber, with an environmental impact of 4.67kg of CO_2 equivalents.

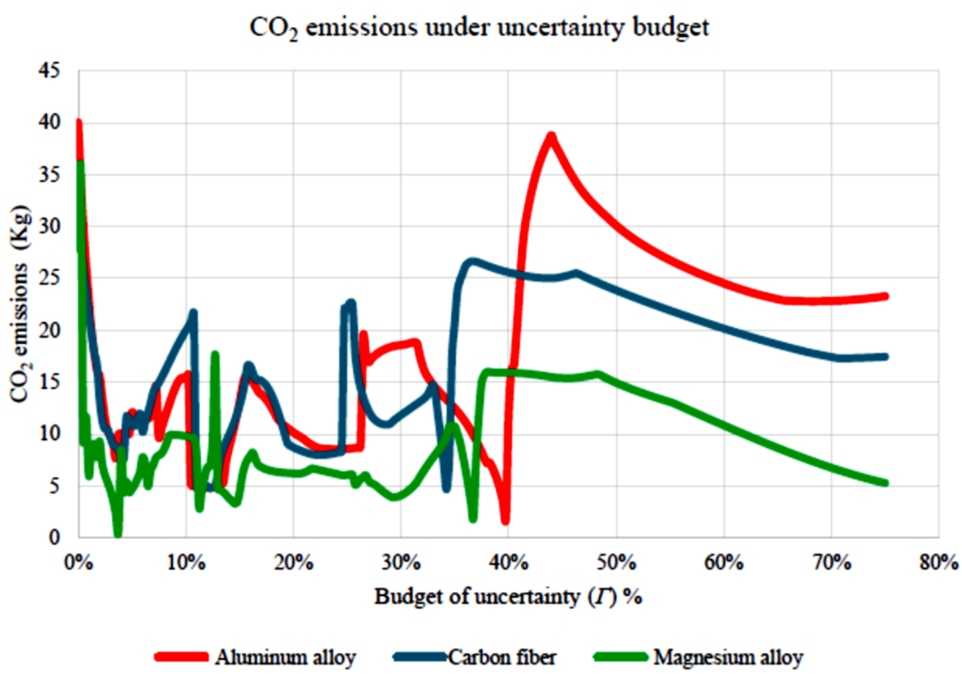

Figure 2: Life cycle CO_2 emissions of baseline engine Vs. lightweight engine materials.

In comparison with aluminum, carbon fiber achieves a maximum energy savings of approximately 42,749 MJ. Energy savings from carbon fiber are considerably higher than those from magnesium, indicating that carbon fibers perform better in terms of the impact of energy consumption. This advantage is most likely due to the lower estimated energy consumption of carbon fiber at the end of its lifetime. Aluminum has a slightly lower energy consumption than magnesium at the end of its lifetime. Magnesium offers an approximate 5,606 MJ energy savings potential over aluminum. This significant energy savings is due to the noticeably lower fuel consumption at the usage stage. Once data uncertainty exceeds 40%, there is a significant difference between aluminum and magnesium, with magnesium having the least impact. To sum up, carbon fibers outperform aluminum, achieving an optimal energy consumption of 61,548.49 MJ versus 65,570.96 MJ for aluminum. Magnesium outperforms both materials, with an optimal energy consumption of 55,480.05 MJ.

The assessment's findings imply that engine light-weighting through the use of materials like carbon fiber and magnesium requires less energy and emits fewer gas emissions. It is brought on by significant improvements in fuel economy as well as lower manufacturing material requirements. In conclusion, magnesium is the most sustainable lightweight design because it resulted in the largest overall net decrease of the CO_2 emissions values (23kg of CO_2 equivalents) and lower energy consumption compared to aluminum (baseline material) over the car engine lifetime of 321,868.8 km. Furthermore, carbon fiber is another sustainable lightweight design that exhibits the lowest energy consumption over the lifetime of a car engine, as shown in Figure (3).

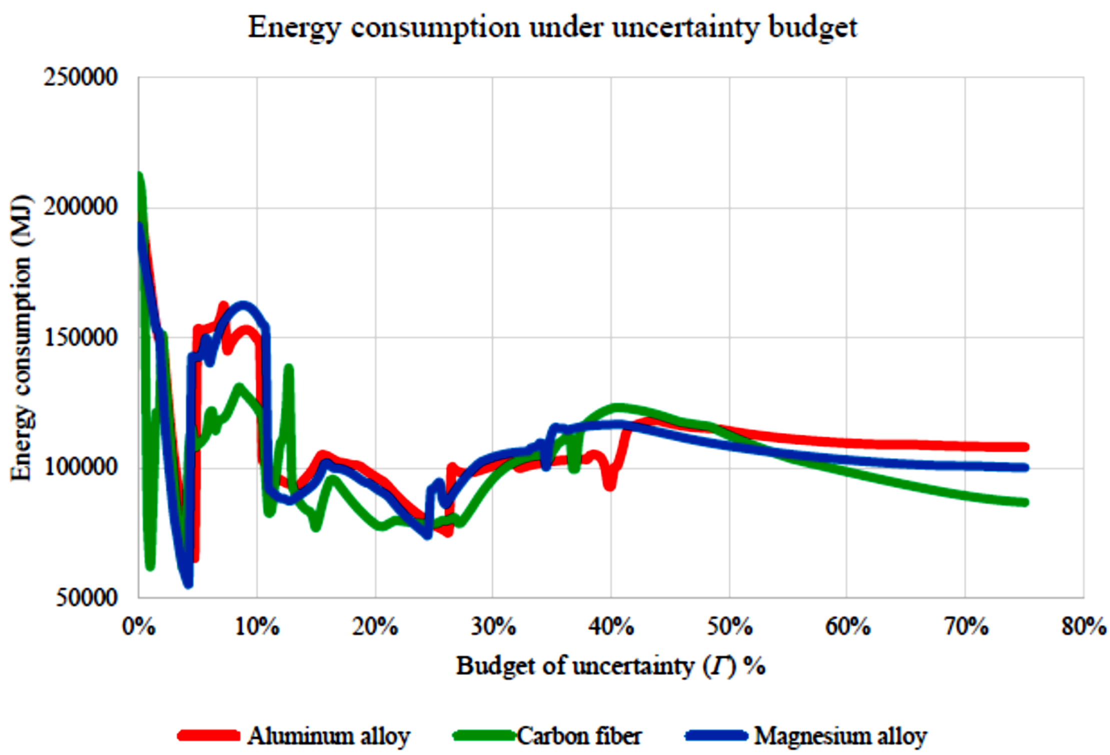

Figure 3: Lifecycle energy consumption of baseline engine vs. lightweight engine materials.

CONCLUSION

This study proposed a robust optimization model based on the life cycle assessment (LCA) under uncertainty. The proposed framework aims to determine an optimal engine design to minimize the environmental impacts of the usage and end of life stages. An automotive aluminum engine and two lightweight engine materials, specifically magnesium alloy and carbon fiber were used in the case study to demonstrate the feasibility of the proposed framework. Fuel consumption for the suggested lightweight engine scenarios was quantified for fractional weight savings per fractional fuel savings. The analytic hierarchy process (AHP) is used to assign the relative importance to the objective function variables, which makes the model appropriate for assessing different design options. The study focuses on the uncertainty of CO_2 emissions and energy consumption, because these are regarded as the most important driving criteria according to the AHP assessment matrix results. The assessment's findings imply that engine light-weighting through the use of materials like carbon fiber and magnesium alloy, require less energy and emit less gas emissions. It is brought on by significant improvements in fuel economy as well as lower manufacturing material requirements. Magnesium is found to be the most sustainable lightweight material because it results in the largest overall net decrease in CO_2 emissions and lower energy consumption compared to aluminum. Moreover, carbon fiber is another sustainable lightweight design that exhibits the lowest energy consumption over the lifetime of a car engine. The current research can be extended to include an economic perspective, considering material costs besides the assessment to make the model more realistic. In addition, it is better to take the manufacturing stage in the assessment to be guided for making less environmental impacts.

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