USING LIFE CYCLE ASSESSMENT AND ANALYTICAL HIERARCHY PROCESS TO EVALUATE THE DESIGN FOR ENVIRONMENTAL OPTIONS: A CASE STUDY ON A CAR ENGINE

Tasnem J. Showehdi and Abdulbaset M. Alemam
Department of Mechanical and Industrial Engineering,
Faculty of Engineering, University of Tripoli- Libya.
Email: a.alemam@uot.edu.ly

الملخص

بدأ المصنعون والمستهلكون إدراك الحاجة إلى الحد من الأثر البيئي والمصادر المستخدمة المؤثرة طول دورة حياة المنتج. يقدم هذا البحث طريقة دعم القرار لكل من مصنعي ومالكي محركات السيارات لتحديد خيار التصميم الأنسب للبيئة (DFE). في هذه الطريقة تم دمج أداة تقييم دورة الحياة (LCA) وعملية التسلسل الهرمي التحليلي (AHP) في مرحلة التقييم. على وجه الخصوص، تم تقييم دورة حياة المنتج خلال برنامج تصميم بالحاسب يحتوي على قائمة شاملة بالآثار البيئية للمنتج، مثل إنبعاث الغازات وإستهلاك الطاقة. ومنه تُستخدم نتائج تقييم دورة حياة المنتج لدعم صانعي القرار في تحديد الأهمية النسبية لمعايير التقييم عند إستخدام نموذج التسلسل الهرمي التحليلي. بعد ذلك، تم دمج أداة التسلسل الهرمي التحليلي وطريقة تعدد المعايير لتحديد الأولوية للخيارات (DFE Options) من خلال مصفوفات المقارنة المزدوجة، بالنظر إلى مرحلتين من مراحل دورة الحياة على الصعيدين المحلي المتمثل في التقييم بين بدائل التصميم والمعايير البيئية والتقييم الآخر متمثلا في التقييم بين بدائل التصميم وعناصر دورة حياة المنتج. مراحل دورة الحياة التي تم تقييمها في هذا البحث هما مرحلتي الإستخدام ونهاية العمر. في هذا البحث تم إستخدام محرك سيارة (نوع فورد ذات ستة إسطوانات) لإثبات إمكانية تطبيق منهجية البحث المقترحة. أظهرت نتائج هذا البحث أن أهم العوامل التي تؤثر على الأداء البيئي للمحرك هما إنبعاثات غاز ثاني أكسيد الكربون وإستهلاك الطاقة. بالإضافة إلى ذلك، ومن الواضح أن مرحلة الإستخدام تساهم أكثر في التأثيرات البيئية مقارنة بمرحلة نهاية العمر. في حين يعتبر عامل الإستخدام منخفض التأثير عاملا واعدا بيئيا لمرحلتي دورة الحياة المقيمة.

ABSTRACT

Manufacturers and consumers have recently begun to recognize the need for environmental impact reduction and responsible resource use throughout the product life cycle. This research presents a decision support method for both manufacturers and owners of automobile engines to identify the most appropriate design for environment (DFE) option. The method combines life cycle assessment (LCA) and analytical hierarchy process (AHP) in the assessment process. In particular, LCA is conducted through SolidWorks sustainability (GaBi) software. Thus, a comprehensive inventory of the product's environmental impacts, such as gas emissions and energy consumption, is identified. Then, the LCA results are used to support decision makers in determining the relative importance of the evaluation criteria in the AHP model. The AHP incorporates a multi-criteria assessment to prioritize the DFE options through pairwise comparison matrices considering two life cycle stages at the local and global levels. The life cycle stages which are evaluated in this research are usage and end of life stages. An existing car engine (Ford F-150 with six-cylinders) is used for this work to illustrate the method's applicability. The results of this research show that CO_2 emissions and energy consumption are the most significant factors affecting the engine's environmental performance. In addition, it is clear that the usage stage contributes the most to the environmental impacts compared to the end of life stage. Whereas low impact use is evaluated as the most environmentally promising alternative for both life cycle stages.

KEYWORDS: Analytic Hierarchy Process; Life Cycle Assessment; Design for Environment; SolidWorks Sustainability; Car Engine.

INTRODUCTION

Throughout history, internal combustion (IC) engines have been and continue to be the most widely used technology in the automotive sector [1]. The rapid development of the automobile engine industry has led to serious resource and environmental problems, forcing competitive pressure on manufacturers to achieve higher performance with lower emissions [2]. As a result, engineers are always seeking ways to improve the design and manufacturing of automobile engines [1,3].

Successful design for environment (DFE) requires understanding the life cycle impact of design decisions [4]. Automobile usage and disposal stages have a variety of environmental impacts. For example, fuel consumption creates air, water, and gas emissions. Besides, consumed parts such as filters, spark plugs, and so on are discarded and replaced regularly. Once the engine reaches the end of its lifespan, it must be discarded. Some materials used for the engine, such as steel and aluminum, can be reused or remanufactured. However, none of these processes can be achieved without generating environmental impacts.

It is clear that the majority of environmental studies have been focused on the car itself or diesel engines, and only a few studies have considered the assessment of gasoline engines. At the same time, 99.8% [5] of global transportation is powered by IC engines. As a result, evaluating car engines is essential for reducing transportation's local and global environmental impacts.

This article develops a systematic approach for DFE improvement using life cycle assessment (LCA) and analytical hierarchy process (AHP) methods. Specifically, the method is developed for pickup truck engines, to assist in identifying the engine’s environmental hotspots at both the usage and end of life stages. As well as it helps in prioritizing between various DFE options. The decision making process is based on multiple and conflicting evaluation criteria that could contribute significantly to the relative importance of each DFE option.

Furthermore, the research utilizes a method that focuses on fulfilling the following research aims: i) Conduct LCA as a method to discover components or processes of a car's engine causing high environmental impacts. ii) Develop an evaluation model that allows for the use of both quantitative and qualitative evaluations with a high degree of flexibility in cases where accurate information may not be available through the use of AHP. iii) Use the integrated LCA-AHP methodology to rank the four introduced DFE options for the suggested life cycle stages considered individually (local level) and simultaneously (global level).

The rest of this paper is organized as follows: the next section presents a literature review. Subsequently, the following section provides car engine modeling. Then, section provides life cycle assessment (LCA) and the specifications of the car engine. After that, section describes the proposed AHP hierarchy model along with the formation of the pairwise comparison matrices, computation of criteria and options weights, consistency measurement, and finally, ranking of DFE options. Results discussion and conclusions are presented in the last two sections.

LITERATURE REVIEW

Due to the importance of the product's environmental life cycle evaluation in the development process, a considerable number of research articles have been published in the last two decades. Choi et al. [6] proposed a systematical methodology for incorporating environmental and business aspects into the product development process. LCA is used for the prioritization of the product's environmental impacts through the entire life cycle. Taha et al. [7] focused only on the manufacturing phase, utilizing a CAD model of a product with several design scenarios to analyze the energy consumption of the machining process using an environmental impact calculator approach. In the same context, Remery et al. [8] employed two multi criteria decision making (MCDM) approaches, AHP and TOPSIS, to select appropriate end of life (EOL) destinations for discarded products. Ma [9] considered only the use phase of a product's life cycle. The author proposes a framework to model the usage phase for LCA with consideration of the uncertainty and optimal usage. Another study evaluated the environmental impacts of different photo fuels in terms of both fuel production and vehicle use [10]. Meanwhile, this research considers both the usage and end of life stages of a product's life cycle assessment.

The analytical hierarchy process (AHP) developed by Saaty [11] can be used individually or in collaboration with other design tools. For the selection of the best polymer to manufacture solar flat plate collectors, Venkataramaiah et al. [12] employed AHP without using or integrating any other design tools. A framework that integrates AHP and a technique for order preference through similarity to ideal solution (TOPSIS) to assist designers in identifying customer requirements and design characteristics is adopted by Lin et al. [13]. A model for evaluating the environmental impacts of design alternatives during product development is proposed. The model integrates rough-cut LCA with an MCDM approach, which combines AHP, fuzzy set theory (FST), and evidential reasoning (ER) [14]. Ramanujan et al. [15] developed a framework for applying design for environment (DFE) using LCA and AHP to improve the environmental performance of a product while considering business related aspects. The scope of the assessment includes the entire product's life cycle. In addition, Madu et al. [16] applied a hierarchic framework by combining AHP-QFD approach to aid the design of environmentally conscious products. AHP is used to develop priority for customer requirements, and quality functional deployment (QFD) is used to match design requirements to customer requirements.

Additionally, the analytical hierarchy process (AHP) has been used by decision makers in product development activities such as customer need identification, developing product design specifications, and design concept selection. Kumar et al. [17] presented AHP to assist users in making car purchasing decisions based on the selection of engines for three purposes, namely: personal, race, and commercial usage, which made consumer decision making easier. The usage of the AHP in design specification determination has been described. AHP was used to determine the optimum combination of operating parameters for a diesel engine while considering qualitative and quantitative attributes [18]. Moreover, a framework for concurrent decision making is developed during the conceptual design stage, with tasks divided into design concept selection and material selection [19].

The above literature review identifies potential gaps in the related research to guide future research directions. It illustrates that, to date, a few MCDM approaches have been implemented for assessing the life cycle of a car engine and considering both the usage and end of life stages. Therefore, this research is intended to develop a method that helps engineers prioritize the DFE alternatives for a car engine assessment.

Car Engine Modeling

The assessed car engine in this study is Duratec 33, with six-cylinders, V-configuration and a total displacement of 3.3 L. Duratec 33 has been a part of the Ford Motor Cyclone engine family since 2018, and it is used to power Ford F-150 pickup trucks. SolidWorks software (CAD) is used to create a 3D engine model. The engine is required to be used in the assessment process from the environmental point of view, along with obtaining information about parts' weight through geometric measures and the type of the used material. Figure (1) shows the main components of the engine.

The operation of the automotive car engine is not free of negative impact. The transport of goods and people contributes around 25% of global CO_2 emissions [5]. Carbon dioxide (CO_2) emissions and the depletion of nonrenewable energy resources are directly related to car engine fuel consumption. Thus, it has been viewed as a significant disadvantage due to its negative impact on the environment and human health. Besides that, a large number of discarded engines at the end of their useful lives will result in metal resource depletion and significant resource waste environmental issues, posing a significant challenge to automotive component manufacturers. As a result, the environmental impacts at both life cycle stages should be modeled to identify the most significant environmental impacts, reveal possible improvement opportunities, and suggest more environmentally friendly life cycle stage options.

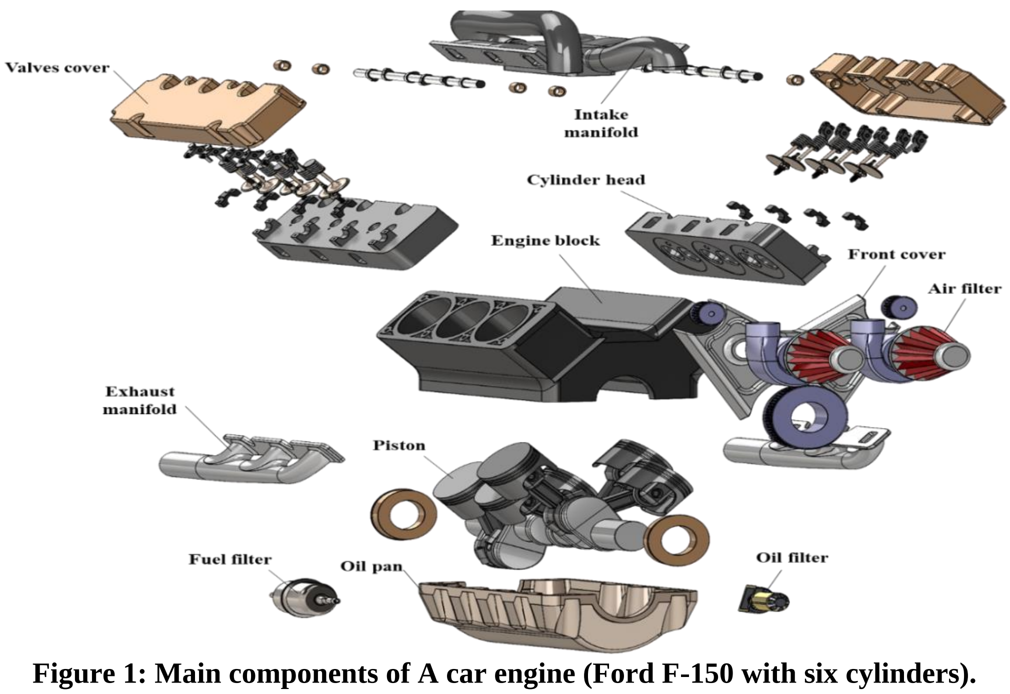

Figure 1: Main components of A car engine (Ford F-150 with six cylinders).

When assessing the environmental impacts of a product's life cycle, use phase modeling is extremely important, especially for energy consuming products within the use stage, such as car engines, to have a better insight into how the engine affects the environment. Most of the environmental impacts occur during driving and are greatly associated with fuel consumption, which is the main contributor to air pollution due to exhaust gas emissions such as carbon dioxide (CO_2). During the operation of a car engine, heat is generated as a result of the combustion, and nearly one-third of it will end up as waste heat dumped into engine parts and air, which adds to global warming. An engine consumes a significant number of spark plugs and filters for fuel, oil, and air, which are discarded as solid waste. Car engines consume fuel, oil, and coolant, which are necessary to keep the engine running until they are discarded as liquid waste. Additional harm caused by car engines is related to the fact that engines consume oxygen in the surrounding environment, lowering its percentage content. This makes an impact on human health and the environment.

The end of life stage of automobiles constitutes a minor portion of the life cycle impacts for most environmental impacts [20]. However, it is important to note that the environmental impacts of a car engine use stage are distributed over a sufficiently long time compared to the shorter time during the end of life stage. End of life stage modeling is necessary for environmental impact assessment, especially in the areas suffering from saturated landfills and solid waste issues. A car engine remains in the use stage until it approaches the end of its useful life, where it is disassembled. Its parts can be reused, remanufactured, or recycled. Engine disassembly requires use of labor and machinery, which consumes a lot of energy. Inspection of disassembled and cleaned parts comes next to determine whether they can be recycled or reused. Otherwise, they are disposed of in landfills as solid waste. Figure (2) depicts the inputs and outputs of a car engine use and end of life phases model.

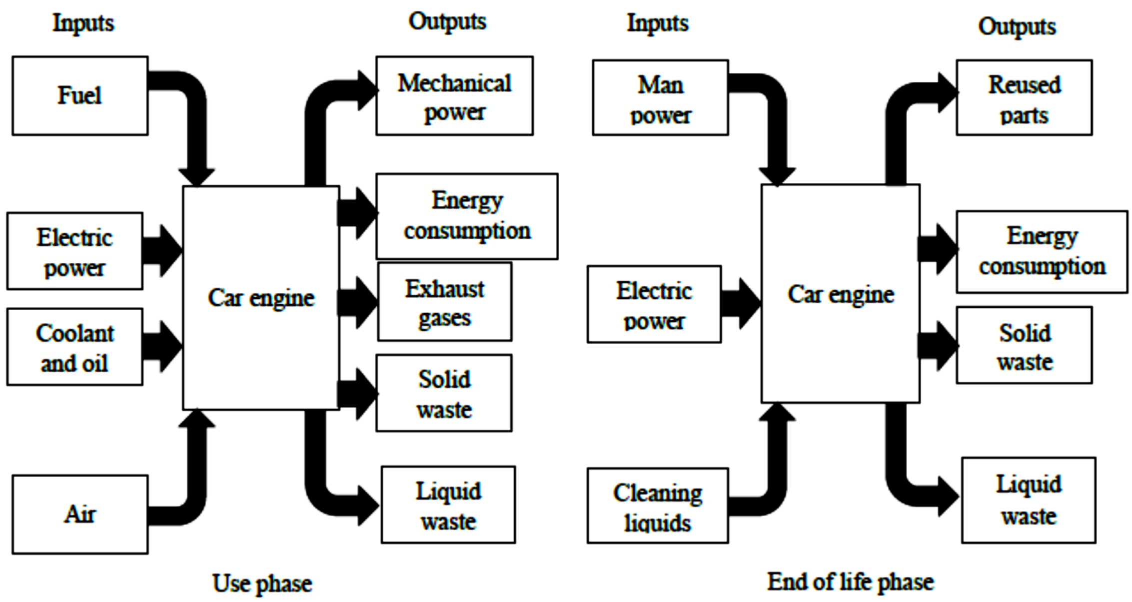

Figure 2: Inputs and outputs of car engine usage and end of life stages.

Life Cycle Assessment (LCA)

Life cycle assessment is conducted through the use of Solid Works associated with GaBi sustainability software, a widely used, commercially available software program that calculates the environmental impacts based on the life cycle assessment method. In particular, the four environmental impacts provided by SolidWorks sustainability (GaBi) are carbon footprint or global warming potential (CO_2), total energy consumed (MJ), air acidification (SO_2), and water eutrophication (PO_4). In the LCA, the engine is expected to last roughly ten years or 200,000 miles (321,869 kilometers). Table (1) contains the engine specifications [21].

Table 1: Ford F-150 engine specifications.

Fuel economy	21 miles per gallon (mpg)/ 9 km/l
Fuel tank capacity	23 gallons
Oil capacity	5.7 liters
Coolant capacity	12 liters

User inputs in GaBi sustainability are classified into four categories: materials type, expected lifetime, manufacturing process, and use duration. When a sustainability analysis is performed, the results are displayed in the form of a sustainability report. The sustainability analysis must be done for each part of the product separately, and then the results are gathered and summarized to form a life cycle inventory (LCI) database, which involves material and energy analysis, as well as gas emissions and solid waste. Thus, it enables an objective assessment of the specified life cycle stages and attempts to discover the life cycle stage with the greatest environmental impacts during the engine's lifespan. Table (2) shows the LCI results for usage and end of life stages.

Most data is obtained using SolidWorks software, except data for the usage stage's consumable fluids (fuel, coolant, and oil). The refilled consumable fluids and the replaced parts are estimated using engine specifications over the engine's lifespan. For instance, coolant refilling time is 200,000 miles/ 30,000 miles = 6.6 $\simeq$ 7 times over the engine's lifespan. Meanwhile, the expected spark plug lifespan is 18 months, implying that spark-plug replacement times over 10 years will be 120 months/18 months = 6.6 $\simeq$ 7 times.

Engine parts have their weight determined by SolidWorks, whereas the weight of consumables is determined by a few simple calculations. For example, considering that the engine coolant capacity is 12 liters, the amount of coolant consumed over the engine lifespan is 7*12 = 84 liters. To convert a liter measurement to a kilogram, the volume is multiplied by the density of the ethylene glycol based coolant recommended by Ford Motor company. The weight of engine coolant consumed over ten years is 84 liters*1.090 kg/liter = 91.56 kg.

For usage stage consumables, only fuel emissions and energy consumption are calculated. The reason is that the effect of oil and coolant is relatively small in comparison to fuel, hence they were neglected and left (blank) in Table (2). The car engine fuel economy is 21 mpg (miles per gallon), and thus the fuel gallons consumed over ten years is equal to 200,000/ 21 = 9524 gallons. Every gallon of gasoline consumed emits approximately 8.887 kg of CO_2 [22]. Therefore, over ten years it emits 8.887*9524 = 84639.79 kg of CO_2. Afterward, the following equation is used to calculate SO_2 emissions from fuel consumption [23]:

$$SO_2 = 2 * S * F \tag{1}$$

Where SO_2 is sulfur dioxide emissions (tons), 2 represents pounds of sulfur dioxide per pound of sulfur, S is fuel sulfur content, which is in Libyan petroleum estimated at 0.3% [24], and F is the quantity of fuel consumed (tons). The equivalent of 9524 gallons of fuel is 300 tons. The amount of SO_2 emitted by the engine over ten years is 2*0.003*300 = 1.8 tons of SO_2, which is equal to 1800 kg of SO_2.

Based on the expected lifespan of the car engine and its fuel economy, the total amount of fuel consumed over the engine's lifespan is 321,868.8 km / 9 km/l = 35,763.2 liters. According to [25], 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 * 35,763.2 liters = 1,144,422 MJ. The life cycle assessment results will be used later to support the multi-criteria decision tool (AHP).

Table 2: Results of environmental impacts of automotive 6V engine components for usage and end of life stages.

	Components	Quantity	Material	Weight (kg)	Duration of use (month)	Carbon footprint (kg CO_2e)	Total energy consumed (MJ)	Air acidification (kg SO_2e)	Water eutrophication (kg PO_4e)
Usage stage	Fuel	21 mpg	Gasoline	27000	120	84639.79	1,144,422	1,800	0
	Coolant	7	Ethylene glycol	91.56	120				
	Oil	40	5W-20 SAE GF6	202	120				
	Spark plug	42	Copper and other materials	1.34	18	3.05	7.08	0	0.0028
	Fuel filter	5	Paper, rubber, and steel	0.5727	24	2.27	24.96	0.01	0.0016
	Air filter	40	Paper and rubber	13.23	6	355.44	261.52	0.18	0.4453
	Oil filter	40	Paper and steel alloys	21.85	3	695.68	7,599.68	3.56	0.4897
	Hose	2	Rubber	0.4314	60	0.14	0.10	0	0.0002
	Total	-	-	27331	-	85696.37	1152315.34	1803.75	0.9396
End of life	Engine block	1	Aluminum	26.54	120	4.70	5.80	0.0047	0.00091
	Cylinder head	2	Aluminum	25.30	120	4.40	5.60	0.0046	0.00086
	Front cover	1	AISI 316L stainless steel	4.97	120	3.90	44	0.0210	0.00270
	Camshaft	2	Ductile iron	2.08	120	1.14	0.84	0.0006	0.00140
	Camshaft retainer	8	Ductile iron	0.52	120	0.29	0.21	0.0001	0.00040
	Camshaft bushing	8	Aluminum bronze	0.25	120	0.04	0.05	0.0000	0
	Camshaft belt wheel	2	Aluminum	0.56	120	0.10	0.12	0.0001	0
	Valve	24	201 annealed stainless steel	2.07	120	1.63	18.14	0.0086	0.00113
	Valves cover	2	Ductile iron	14.86	120	8.20	6	0.0042	0.01020
	Piston head	6	T5-6063 aluminum alloy	7.03	120	1.24	1.54	0.0013	0.00020
	Piston pin	6	Plain carbon steel	1.22	120	0.97	10.80	0.0050	0.00070
	Connecting rod	6	AISI 4340 Steel	5.45	120	4.31	48	0.0228	0.00300
	Crankshaft	2	AISI 4340 Steel	24.05	120	19	220	0.1000	0.01320
	Crankshaft bushing	2	Aluminum bronze	2.55	120	0.45	0.56	0.0005	0.00010
	Crankshaft belt wheel	1	Aluminum	1.94	120	0.34	0.43	0.0004	0.00010
	Exhaust manifold	2	Aluminum	5.33	120	0.94	1.17	0.00096	0.00018
	Intake manifold	1	Aluminum	9.15	120	1.60	2.00	0.00160	0.00031
	Rocker arm	12	AISI 1010 steel	3.16	120	2.50	27.38	0.01314	0.00168
	Rocker arm spring	12	Stainless steel	0.33	120	0.25	2.86	0.00132	0.00018
	Rocker arm hex nut	12	Stainless steel	0.27	120	0.22	2.35	0.00112	0.00014
	Oil pan	1	Aluminum	2.51	120	0.44	0.55	0.00045	0.000086
	Turbo charger	2	Cast stainless steel	2.19	120	1.74	19.20	0.00920	0.0012
	Total	-	-	142.33	-	58.40	417.60	0.20169	0.03868

FRAMEWORK OF THE AHP v

This section describes the main steps required in the formulation of the AHP framework, which comprises hierarchy construction, pairwise comparisons, deriving relative weights, consistency measurement, and synthesizing results.

Construction Of The AHP Hierarchy

A typical AHP model consists of four levels. It begins with level 1 as a goal, the main criteria are placed at level 2, the sub-criteria are put at level 3, and the DFE options are placed at level 4 of the hierarchy. Overall, the criteria, sub-criteria, and DFE options are used to realize the overall goal. Figure (3) illustrates the AHP hierarchy model for a car engine.

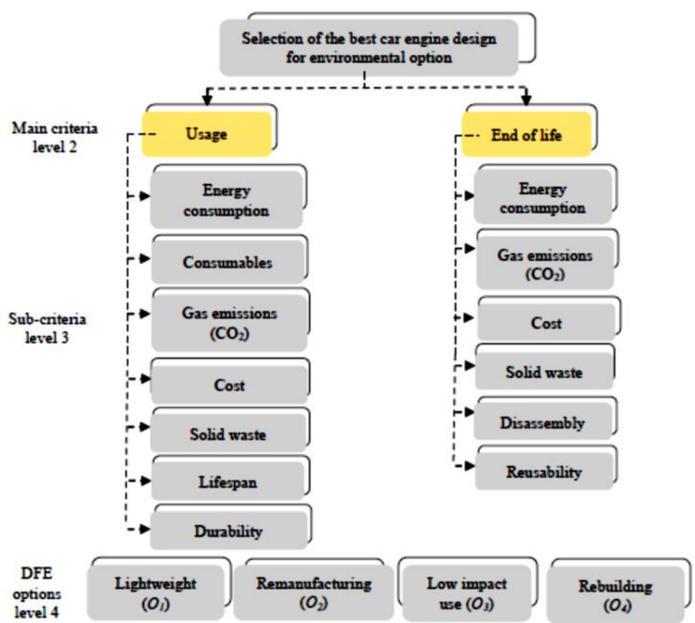

Figure 3: Car engine hierarchy block diagram.

Formation of the Pairwise Comparison Matrices

The AHP assessment begins with the construction of a pairwise comparison matrix (*A)*. The matrix (*A)* is an $n \times n$ real matrix, where (*n)* denotes the number of evaluation criteria considered in the analysis.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{2}$$

The pairwise comparison is based on the linguistic (1–9) scale according to Saaty [11], which is defined as (1) equal importance, (3) moderate importance, (5) strong importance, (7) very strong, and (9) extreme importance. Where 2,4,6 and 8 are intermediate values of importance. If the criteria in the column are preferred to the criteria in the row, then the inverse of the rating is given.

In this model, a series of pairwise comparison matrices must be developed, one of which is for the main criteria level with respect to the goal, as shown in Table (3). The sub-criteria level comes next, which is subdivided into usage stage and includes: energy consumption, consumables, gas emissions (CO_2), cost, solid waste, lifespan, and durability. And end of life stage includes energy consumption, gas emissions (CO_2), cost, solid waste, disassembly, and reusability. Table (4) presents the sub-criteria level matrices at both life cycle stages. The last level is the DFE options level, where options are compared in terms of all environmental impacts at the sub-criteria level, as presented in the following sections.

Table 3: Pairwise comparison matrix of the main criteria level.

Main criteria	Usage	End of life
Usage	1	5
End of life	0.20	1

The greatest environmental impacts are generated during the operational stage of the engine life cycle, followed by the production of materials (cast iron, aluminum, etc.), electricity, and diesel. As a result, when it comes to minimizing environmental impacts, the usage stage takes strong priority over the end of life stage, as illustrated in the pairwise comparison (Table 3).

While assigning the pairwise comparisons between the sub-criteria at the usage stage, it is recognized that the major cause of a car engine's gas emissions is fuel consumption, as shown in Table (4). Engine gas emissions depend on fuel parameters such as: fuel type, and fuel additives, in addition, to lubricants. Therefore, gas emissions (CO_2) and energy consumption are given a higher priority over the rest of the sub-criteria at this stage.

Another example of the assessment process at the end of life stage is disassembly, which is given a higher priority over the rest of the sub-criteria at this stage because it is an essential criterion in product recovery as it allows for the selective separation of parts and materials to be disposed of, repaired or reused.

Table 4: Pairwise comparison matrix for the sub-criteria level.

Usage	Energy consumption	Consumables	Gas emissions	Cost	Solid waste	Life span	Durability
Energy consumption	1.00	5.00	0.50	7.00	3.00	9.00	3.00
Consumables	0.20	1.00	0.17	2.00	0.50	3.00	0.33
Gas emissions	2.00	6.00	1.00	8.00	5.00	9.00	3.00
Cost	0.14	0.50	0.13	1.00	0.33	2.00	0.20
Solid waste	0.33	2.00	0.20	3.00	1.00	5.00	0.50
Life span	0.11	0.33	0.11	0.50	0.20	1.00	1.00
Durability	0.33	3.00	0.33	5.00	2.00	1.00	1.00

End of life	Energy consumption	Gas emissions	Cost	Solid waste	Disassembly	Reusability
Energy consumption	1.00	2.00	3.00	0.20	0.20	0.33
Gas emissions	0.50	1.00	2.00	0.20	0.14	0.50
Cost	0.33	0.50	1.00	0.14	0.11	0.20
Solid waste	5.00	5.00	7.00	1.00	0.50	2.00
Disassembly	5.00	7.00	9.00	2.00	1.00	3.00
Reusability	3.00	2.00	5.00	0.50	0.33	1.00

Computation of Criteria Weight Vector

The comparison matrix (A) must be normalized (matrix A_n) before the calculation of the criteria weight vector or the vector of priorities (W). This was accomplished by dividing each column by the sum of the corresponding column's entries. As a result, a normalized matrix is obtained in which the sum of the elements of each column vector equals 1.

$$(a_{ij})_n = a_{ij} / \sum_{k=1}^{n} a_{kj} \tag{3}$$

The criteria weight vector (W), which is an (n) dimensional column vector, is then computed by adding the entries in each row of the normalized matrix (A_n) and dividing the sum by the number of entries in the row, as shown below:

$$W_i = {\sum_{k=1}^{n} a_{ik}} / {n} \tag{4}$$

The significance of the criteria is represented by the criteria weight vector (W). The calculated values allow for the organization of the evaluation criteria based on their contribution to the overall environmental impacts. Table (4) illustrates the AHP comparison results. Equations (3) and (4) have been applied to all pairwise comparison matrices to compute the corresponding normalized matrix (A_n) and the criteria weight vector (W) for each matrix. Table (5) shows the normalized matrix of the results from Table (4).

As shown in Table (5), the most important evaluation criteria in the context of reducing environmental impacts at usage stage are the criteria with the highest weight (W), such as gas emissions (CO_2) and energy consumption. Durability comes next. It is recognized that low engine durability will result in increasing problems such as engine reluctance and harsh transmission shifts over time. This indicates that the engine will barely survive its intended life cycle, which is one of the worst environmental impacts besides gas emissions (CO_2) and energy consumption from an environmental point of view. In addition, it is anticipated that engines consume a significant number of spare parts during the use stage, such as engine oil filters, fuel filters, and spark plugs. These have a lifespan of (5,000–10,000 km), (50,000–60,000 km), and (25,000–50,000 km) respectively [26], all of which are discarded as solid waste and have a considerable environmental impact. Whereas lifespan and cost contribute less.

Table 5: Normalized matrix and criteria weight for the sub-criteria level.

Usage	Energy consumption	Consumables	Gas emissions	Cost	Solid waste	Life span	Durability	Weight
Energy consumption	0.243	0.280	0.205	0.264	0.249	0.300	0.332	0.268
Consumables	0.049	0.056	0.068	0.075	0.042	0.100	0.037	0.061
Gas emissions	0.485	0.336	0.410	0.302	0.416	0.300	0.332	0.369
Cost	0.035	0.028	0.051	0.038	0.028	0.067	0.022	0.038
Solid waste	0.081	0.112	0.082	0.113	0.083	0.167	0.055	0.099
Life span	0.027	0.019	0.046	0.019	0.017	0.033	0.111	0.039
Durability	0.081	0.168	0.137	0.189	0.166	0.033	0.111	0.126

End of life	Energy consumption	Gas emissions	Cost	Solid waste	Disassembly	Reusability	Weight
Energy consumption	0.067	0.114	0.111	0.049	0.087	0.047	0.080
Gas emissions	0.034	0.057	0.074	0.049	0.062	0.071	0.058
Cost	0.022	0.029	0.037	0.035	0.049	0.028	0.033
Solid waste	0.337	0.286	0.259	0.247	0.219	0.284	0.272
Disassembly	0.337	0.400	0.333	0.495	0.437	0.427	0.405
Reusability	0.202	0.114	0.185	0.124	0.146	0.142	0.152

In the same manner, disassembly, solid waste, reusability, and gas emissions (CO_2) are considered the most important evaluation criteria with the highest weight (*W*) in the context of reducing environmental impacts at the end of life stage. Solid waste represents the number of materials and parts to be discarded at the end of life, and it is essential to consider when developing a more environmentally friendly car engine. Reuse as a method can be applied to reduce the amount of scraped materials at the end of life stage. Gas emissions (CO_2) and energy consumption are next as one of end of life impacts that can harm the environment. Whereas cost, once again, is the one with the least impact.

Consistency Measurement

The next step is to check the consistency of the comparisons using the criteria weight vector that was calculated in the previous step. Equation (5) represents how to compute the eigenvector (λ_i).

$$\lambda_i = {\sum_{i=1}^{n}(AW)_i}/{W_i} \tag{5}$$

Then the average of these computed values (λ_i) is calculated for each pairwise comparison matrix to obtain the maximum eigenvector (λ_{max}) according to equation (6):

$$\lambda_{\max} = {\sum_{i=1}^{n}\lambda_i}/{n} \tag{6}$$

Afterward, AHP evaluates the inconsistency of the comparisons by calculating the consistency index (*CI*), which is defined as:

$$CI = {\lambda_{\max} - n}/{n-1} \tag{7}$$

Where λ_{max} is the maximum eigenvalue corresponding to the pairwise comparison matrix, and n is the number of elements being compared in the matrix. Finally, the consistency ratio CR is defined by:

$$CR = {CI}/{RI} \quad (8)$$

RI is a constant known as the random consistency index that depends on matrix size. The values of RI [11] for small matrices ($n \leq 10$) are shown in Table (6). The value of CR should be less than 0.1 to be acceptable for the assessment. Otherwise, the pairwise comparisons should be reviewed again.

Table 6: Values of the random consistency index (*RI*).

Matrix size	2	3	4	5	6	7	8	9	10
Random consistency index	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

All the steps mentioned in this section are applied to all of the matrices developed in the analysis to calculate the consistency index (*CI)* and the consistency ratio (*CR)*. Table (7) is obtained by applying equations (5), (6), (7), and (8) from the previous section to the pairwise comparison matrix of the sub-criteria level. As the value of the consistency ratio, (*CR*) is less than 10%, the comparisons are considered acceptable at both the usage and end of life stages. Once the pairwise comparison matrix is consistent, the criteria weight vector (*W*) allows for the organization of the evaluation criteria based on their contribution to the overall environmental impacts.

Table 7: Criteria weight for the sub-criteria level at usage and end of life stages.

Usage	Energy consumption	Consumables	Gas emissions	Cost	Solid waste	Life span	Durability	Weight
Energy consumption	0.243	0.280	0.205	0.264	0.249	0.300	0.332	0.268
Consumables	0.049	0.056	0.068	0.075	0.042	0.100	0.037	0.061
Gas emissions	0.485	0.336	0.410	0.302	0.416	0.300	0.332	0.369
Cost	0.035	0.028	0.051	0.038	0.028	0.067	0.022	0.038
Solid waste	0.081	0.112	0.082	0.113	0.083	0.167	0.055	0.099
Life span	0.027	0.019	0.046	0.019	0.017	0.033	0.111	0.039
Durability	0.33	3.00	0.33	5.00	2.00	1.00	1.00	0.126
λ_{max}	=	7.586				CR	=	7%

End of life	Energy consumption	Gas emissions	Cost	Solid waste	Disassembly	Reusability	Weight
Energy consumption	0.067	0.114	0.111	0.049	0.087	0.047	0.080
Gas emissions	0.034	0.057	0.074	0.049	0.062	0.071	0.058
Cost	0.022	0.029	0.037	0.035	0.049	0.028	0.033
Solid waste	0.337	0.286	0.259	0.247	0.219	0.284	0.272
Disassembly	0.337	0.400	0.333	0.495	0.437	0.427	0.405
Reusability	0.202	0.114	0.185	0.124	0.146	0.142	0.152
λ_{max}	=	6.15			CR	=	2%

As shown in Table (8), the usage stage pairwise comparisons between the DFE options and the sub-criteria result in an acceptable consistency ratio (less than 10%). The low impact use option is prioritized because it is anticipated to significantly reduce environmental impacts during its usage stage. Some of the low impact engine use procedures include following the manufacturer's maintenance schedule and instructions, such as using the recommended engine oil, avoiding engine idling as it pollutes the air, wastes fuel, and causes excess engine wear. In addition, reducing the weight loaded on the car is important as it puts more pressure on the engine and consumes more fuel, which leads to higher gas emissions.

Besides the low impact use, the lightweight design is given a moderate priority since reducing the engine's weight through the use of lightweight materials will reduce fuel consumption and carbon emissions during the use stage of a vehicle. Therefore, lightweight design option is effective in reducing the environmental impacts of a car engine. However, lightweight materials yield higher component costs and decrease engine durability. The other DFE options, which are remanufacturing and rebuilding, have considerably less priority than those mentioned at this stage.

Table 8: Results of the pairwise comparison matrices at usage stage.

Energy consumption	Lightweight	Remanufacturing	Low impact use	Rebuilding	Weight
Lightweight	1.00	3.00	0.33	5.00	0.24
Remanufacturing	0.33	1.00	0.14	3.00	0.10
Low impact use	3.00	7.00	1.00	9.00	0.60
Rebuilding	0.20	0.33	0.11	1.00	0.05
λ_{max}	=	4.09	CR	=	3%
Consumables					
Lightweight	1.00	1.00	0.11	1.00	0.08
Remanufacturing	1.00	1.00	0.11	1.00	0.08
Low impact use	9.00	9.00	1.00	9.00	0.75
Rebuilding	1.00	1.00	0.11	1.00	0.08
λ_{max}	=	4.00	CR	=	0%
Gas emissions (CO_2)					
Lightweight	1.00	9.00	3.00	9.00	0.58
Remanufacturing	0.11	1.00	0.11	3.00	0.08
Low impact use	0.33	7.00	1.00	7.00	0.30
Rebuilding	0.11	0.33	0.14	1.00	0.04
λ_{max}	=	4.22	CR	=	8%
Cost					
Lightweight	1.00	7.00	0.33	9.00	0.33
Remanufacturing	0.14	1.00	0.14	3.00	0.08
Low impact use	3.00	7.00	1.00	9.00	0.55
Rebuilding	0.11	0.33	0.11	1.00	0.04
λ_{max}	=	4.25	CR	=	9%
Solid waste					
Lightweight	1.00	0.20	0.11	0.33	0.05
Remanufacturing	5.00	1.00	0.20	3.00	0.21
Low impact use	9.00	5.00	1.00	7.00	0.64
Rebuilding	3.00	0.33	0.14	1.00	0.10
λ_{max}	=	4.17	CR	=	6%
Life span					
Lightweight	1.00	0.20	0.14	0.33	0.06
Remanufacturing	5.00	1.00	0.33	3.00	0.26
Low impact use	7.00	3.00	1.00	5.00	0.56
Rebuilding	3.00	0.33	0.20	1.00	0.12
λ_{max}	=	4.12	CR	=	9%
Durability					
Lightweight	1.00	0.20	0.11	0.20	0.05
Remanufacturing	5.00	1.00	0.33	3.00	0.25
Low impact use	9.00	3.00	1.00	5.00	0.57
Rebuilding	5.00	0.33	0.20	1.00	0.14
λ_{max}	=	4.19	CR	=	7%

Likewise, the results of the consistency ratio at the end of life stage in Table (9) indicate that the pairwise comparisons of the DFE options are consistent. At this stage, rebuilding and remanufacturing are given top priority in the assessment. It is recognized that a remanufactured engine requires more extensive machining and consumes more energy than a rebuilt engine, since remanufacturing returns the engine to factory condition and specifications. Consequently, remanufacturing is very exhaustive. It can be more expensive and time consuming. Meanwhile, rebuilding requires only the replacement of the necessary engine parts and parts that do not meet the required specifications. Accordingly, a rebuilt engine has a much shorter lifespan and less durability than a remanufactured engine. The other options fall significantly short of meeting the evaluation criteria at this stage.

Table 9: Results of the pairwise comparison matrices at end of life stage.

Energy consumption	Lightweight	Remanufacturing	Low impact use	Rebuilding	Weight
Lightweight	1.00	0.33	3.00	0.20	0.122
Remanufacturing	3.00	1.00	5.00	0.33	0.263
Low impact use	0.33	0.20	1.00	0.14	0.057
Rebuilding	5.00	3.00	7.00	1.00	0.558
λ_{max}	=	4.12	CR	=	4%
Gas emissions (CO_2)					
Lightweight	1.00	0.20	3.00	0.14	0.09
Remanufacturing	5.00	1.00	7.00	0.33	0.29
Low impact use	0.33	0.14	1.00	0.11	0.04
Rebuilding	7.00	3.00	9.00	1.00	0.57
λ_{max}	=	4.17	CR	=	6%
Cost					
Lightweight	1.00	0.11	1.00	0.11	0.05
Remanufacturing	9.00	1.00	9.00	0.33	0.34
Low impact use	1.00	0.11	1.00	0.11	0.05
Rebuilding	9.00	3.00	9.00	1.00	0.56
λ_{max}	=	4.15	CR	=	6%
Solid waste					
Lightweight	1.00	0.20	3.00	0.14	0.09
Remanufacturing	5.00	1.00	7.00	0.33	0.29
Low impact use	0.33	0.14	1.00	0.11	0.04
Rebuilding	7.00	3.00	9.00	1.00	0.57
λ_{max}	=	4.17	CR	=	6%
Disassembly					
Lightweight	1.00	0.11	3.00	0.11	0.07
Remanufacturing	9.00	1.00	9.00	1.00	0.44
Low impact use	0.33	0.11	1.00	0.11	0.04
Rebuilding	9.00	1.00	9.00	1.00	0.44
λ_{max}	=	4.16	CR	=	6%
Reuse					
Lightweight	1.00	0.11	1.00	0.11	0.05
Remanufacturing	9.00	1.00	9.00	0.33	0.34
Low impact use	1.00	0.11	1.00	0.11	0.05
Rebuilding	9.00	3.00	9.00	1.00	0.56
λ_{max}	=	4.15	CR	=	6%

RATING FOR COMPETITIVE DESIGN OPTIONS

Once the consistency check is done and the weight vector (W) is computed for all the matrices, the next step is to compute a local weight vector (L) for the DFE options by:

$$L = C * x \tag{9}$$

The matrix of the DFE options weights is an $n \times m$ matrix (C). The elements of the matrix represent the weight of each DFE option regarding the considered life cycle stage criteria. (x) is defined as the criteria weight vector (W) of the considered life cycle stage (either usage or end of life stages). For recall, the proposed DFE options in this study are lightweight, remanufacturing, low impact use, and rebuilding. Starting with usage stage using equation (9) and the matrix multiplication rule:

$$L = \begin{bmatrix} 0.24 & 0.08 & 0.58 & 0.33 & 0.05 & 0.06 & 0.05 \\ 0.10 & 0.08 & 0.08 & 0.08 & 0.21 & 0.26 & 0.25 \\ 0.60 & 0.75 & 0.30 & 0.55 & 0.64 & 0.56 & 0.57 \\ 0.05 & 0.08 & 0.04 & 0.04 & 0.10 & 0.12 & 0.14 \end{bmatrix} * \begin{bmatrix} 0.268 \\ 0.061 \\ 0.369 \\ 0.038 \\ 0.099 \\ 0.039 \\ 0.126 \end{bmatrix} = \begin{bmatrix} 0.34 \\ 0.11 \\ 0.48 \\ 0.07 \end{bmatrix}$$

$$L_{i=1} = (0.24 * 0.268) + (0.08 * 0.061) + (0.58 * 0.369) + (0.33 * 0.038) + (0.05 * 0.099) + (0.06 * 0.039) + (0.05 * 0.126) = 0.34$$

The rest of the results are computed in the same manner and presented in Table (10). It also shows the results of the local weight vector (L) calculations for the end of life stage.

Table 10: Usage and end of life stages local weight vector.

Usage	Energy consumption	Consumables	CO_2	Cost	Solid waste	Life span	Durability	Local weight
Lightweight	0.24	0.08	0.58	0.33	0.05	0.06	0.05	0.34
Remanufacturing	0.10	0.08	0.08	0.08	0.21	0.26	0.25	0.11
Low impact use	0.60	0.75	0.30	0.55	0.64	0.56	0.57	0.48
Rebuilding	0.05	0.08	0.04	0.04	0.10	0.12	0.14	0.07
End of life	**Energy consumption**	**CO_2**	**Cost**	**Solid waste**	**Disassembly**	**Reusability**		**Local weight**
Lightweight	0.12	0.09	0.05	0.09	0.07	0.05		0.08
Remanufacturing	0.26	0.29	0.34	0.29	0.44	0.34		0.36
Low impact use	0.06	0.04	0.05	0.04	0.04	0.05		0.04
Rebuilding	0.56	0.57	0.56	0.57	0.44	0.56		0.52

Similarly, equation (9) is used to calculate the global weight vector (Lg) given the weight vector (W) and the local weight vector (L) of both life cycle stages:

$$Lg = \begin{bmatrix} 0.34 & 0.08 \\ 0.11 & 0.36 \\ 0.48 & 0.04 \\ 0.07 & 0.52 \end{bmatrix} * \begin{bmatrix} 0.833 \\ 0.167 \end{bmatrix} = \begin{bmatrix} 0.300 \\ 0.154 \\ 0.404 \\ 0.142 \end{bmatrix}$$

$$Lg_{i=1} = (0.34 * 0.833) + (0.08 * 0.167) = 0.300$$

The local and global weight results of the DFE options for the considered life cycle stages are shown in Figure (4). As shown the higher relative importance of the usage stage over the end of life stage greatly affected the ranking of rebuilding (O_4), because its weight on the local level of the usage stage is low.

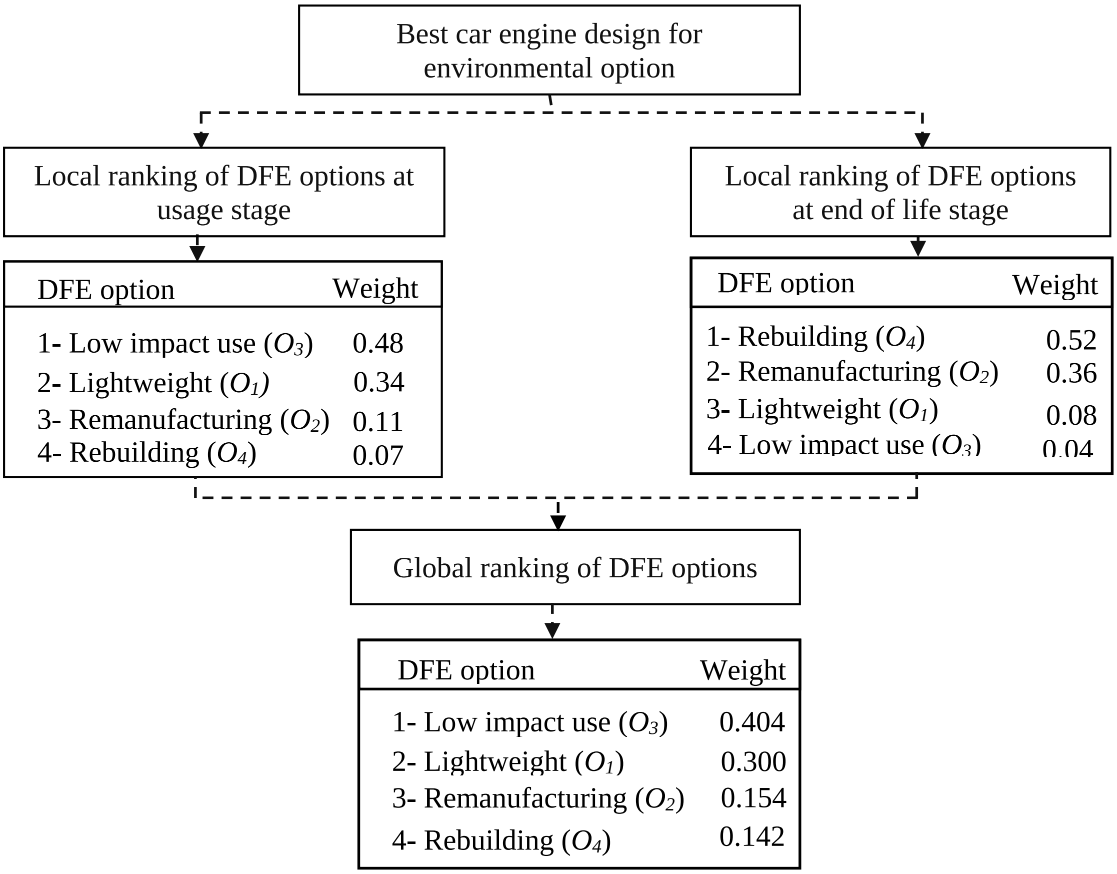

Figure 4: Overall evaluation diagram.

DISCUSSION

This research aims to assess the effectiveness of lightweight (O_1), remanufacturing (O_2), low-impact use (O_3), and rebuilding (O_4) as design for environmental options for a car engine. This study focused on two stages of the car's engine, usage and end of life. The findings of the assessment revealed the following significant details:

During the usage and end of life stages, a car engine mainly produces air emissions (CO_2 and SO_2), water emissions (PO_4), and solid waste. These are generated by consumed parts replacement, energy consumption (primarily from gasoline combustion during usage stage), and material disposal at the end of the life stage. The majority of gas emissions occur during the usage stage, with a total of 27,331 kg of consumed material, 1152315.34 MJ of consumed energy, 85,696.37 kg of CO_2, 1,803.75 kg of SO_2, and 0.9396 kg of PO_4 being released as shown in Table (2), which is certainly reasonable for ten years. According to these findings, the usage stage has a higher priority than the end of life stage. Conversely, at the end of life stage, the amount of consumed energy has the greatest impact among the other considered factors, with a total of 417.60 MJ gas emissions (CO_2), material and energy consumption are the most significant contributors to the overall environmental impacts of engines. Following that, SO_2 and PO_4 emissions can be overlooked due to their relatively low impact.

On the AHP evaluation model at the usage stage (local level), low impact use (O_3) is regarded as the top ranking option as it performs best in all of the evaluation criteria, except for the gas emissions (CO_2). Next is lightweight (O_1), which does well only on the CO_2 gas emissions. Then, as shown in Table (8), neither remanufacturing (O_2) nor rebuilding (O_4) offers the best performance for any of the usage stage criteria. Meanwhile, at the end of life stage, both remanufacturing (*O_2*) and rebuilding (*O_4*) perform best in disassembly criteria, but rebuilding (*O_4*) takes over the top ranking as it performs best in all of the evaluation criteria. In contrast, lightweight (*O_1*) and low impact use (*O_3*) options do not perform best at any of the end of life stage criteria, as illustrated in Table (9).

Low impact use gained the highest weight, approximately 40% compared to the other DFE options based on the results in Figure (4), which includes the local and global options rankings and their associated weights. Therefore, more attention should be focused on low impact use as an option since it primarily depends on user driving behavior, which includes using a more efficient automobile (higher fuel economy), reducing idle time, reducing weight loaded on the engine, and only using air conditioning when necessary. Improving the engine maintenance based on the engine's annual mileage. Finally, it is necessary to use the appropriate type of coolant and quantity of lubricant oil. Lightweight (*O_1*) is next, with about 30%. Remanufacturing (*O_2*) and rebuilding (*O_4*) were relatively close to each other with weights of approximately 15%, and 14%. The discussion of these results points to the fact that car engine users and manufacturers need to focus on environmental management practices. The findings encourage users to adopt low impact use option, and designers to focus on lightweight option to reduce the engine's environmental impacts.

CONCLUSIONS

This study proposes a structured LCA-AHP methodology that supports decision makers' priorities in design for environmental (DFE) options at usage and end of life stages of a car engine. LCA is used to arrange a considerable amount of product information through the use of life cycle inventory (LCI) data. The LCI includes a comprehensive list of engine parts and materials, and their associated environmental impacts, such as energy consumption, gas emissions, etc. All of these are obtained using SolidWorks sustainability software. LCA results are integrated with analytical hierarchy process (AHP) to develop a comprehensive assessment of each criterion, sub-criterion, and DFE options through pairwise comparisons. The AHP weighting and ranking procedure helped in identifying impacts that have a great influence on engine environmental aspects, such as CO_2 emissions and energy consumption. Moreover, based on the obtained results, low impact use appears to be the most promising option, because over the course of an engine's lifespan, user behavior has an essential role to play in reducing environmental impacts. However, other DFE options can reduce engine environmental impacts, either by using lightweight as a design option early in the design process or through the use of remanufacturing and rebuilding options at the end of life stage. To adequately reflect the entire potential environmental impacts of car engines, the assessment of the manufacturing stage can be included in future work, since this stage is more controllable in terms of changing engine design and improving the manufacturing process to reduce the environmental impacts of car engines.

REFERENCES

[1] Payri, F. Luján, J.M. Guardiola, C. and Pla, B. (2015). A challenging future for the IC engine:new technologies and the control role. Oil & Gas Science and Technology–Revue. IFP Energies Nouvelles 70(1): 15-30.

[2] Jiang, Q. Liu, Z. Li, T. Zhang, H. and Iqbal, A. (2014). Life cycle assessment of a diesel engine based on an integrated hybrid inventory analysis model. Procedia CIRP 15: 496-501.

[3] Vijayashree and Ganesan, V. (2018). Application of CFD for analysis and design of IC engines. In Advances in Internal Combustion Engine Research. Springer, Singapore, pp. 251-306.

[4] Michalek, J.J. Hendrickson, C.T. and Cagan, J. (2011). Using economic input-output life cycle assessment to guide sustainable design. In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 54792: 951-958.

[5] Leach, F. Kalghatgi, G. Stone, R. and Miles, P. (2020). The scope for improving the efficiency and environmental impact of internal combustion engines. Transportation Engineering 1: 100005.

[6] Choi, J.K. Nies, L.F. and Ramani, K. (2008). A framework for the integration of environmental and business aspects toward sustainable product development. Journal of Engineering Design 19(5): 431-446.

[7] Taha, Z. Gonzales, J. Sakundarini, N. Ghazila, R.A.R. and Rashid, S.A. (2011). Optimization of product design to reduce environmental impact of machining. Industrial Engineering and Management Systems 10(2): 128-133.

[8] Remery, M. Mascle, C. and Agard, B. (2012). A new method for evaluating the best product end-of-life strategy during the early design phase. Journal of Engineering Design 23(6): 419-441.

[9] Ma, J. (2019). Robust optimal usage modeling of product systems for environmental sustainability. Journal of Computational Design and Engineering 6(3): 429-435.

[10] Ketzer, F. Rösch, C. and Bouter, A. (2016). LCA design of photofuel processes. Report, European Union, EU, June.

[11] Saaty, T.L. (1980). The analytic hierarchy process. Mcgraw Hill, New York.

[12] Venkataramaiah, P. Rohith, B. and MohanaReddy, P. (2012). Material selection for Solar flat plate collectors using AHP. International Journal of Engineering Research and Applications 2(2): 1181-1185.

[13] Lin, M.C. Wang, C.C. Chen, M.S. and Chang, C.A. (2008). Using AHP and TOPSIS approaches in customer-driven product design process. Computers in Industry 59(1): 17-31.

[14] Ng, C.Y. and Chuah, K.B. (2015). Evaluation of design alternatives' environmental impact by integrating fuzzy analytic hierarchy process and evidential reasoning approach. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering 1(1): 011008-1.

[15] Ramanujan, D. Bernstein, W.Z. Choi, J.K. Koho, M. Zhao, F. and Ramani, K. (2014). Prioritizing design for environment strategies using a stochastic analytic hierarchy process. Journal of Mechanical Design 136(7): 071002.

[16] Madu, C.N. Kuei, C. and Madu, I. E. (2002). A hierarchic metric approach for integration of green issues in manufacturing: a paper recycling application. Journal of Environmental Management 64(3): 261-272.

[17] Kumar, V.N. Raja, R.P. Sanjeevi, K.S. Anbuudayasankar, S.P. and Srihari, S. (2019). Multi-criteria engine selection for unique purpose using AHP. In IOP Conference Series: Materials Science and Engineering 577 (1): 012118.

[18] Geetha, N.K. and Bridjesh, P. (2018). AHP approach to select optimum operating parameters on engine. International Journal of Pure and Applied Mathematics 119 (12): 2291-301.

[19] Hambali, A. Sapuan, S.M. Rahim, A.S. Ismail, N. and Nukman, Y. (2011). Concurrent decisions on design concept and material using analytical hierarchy process at the conceptual design stage. Concurrent Engineering 19(2): 111-121.

[20] Gaudillat, P.F. Antonopoulos, I.S. Dri, M. Traverso, M. and Canfora, P. (2017). Best environmental management practice for the car manufacturing sector. JRC Science for Policy Report EUR 28937 EN, European Union.

[21] Ford Motor Company. (2021). Ford F-150 technical specifications. Date Retrieved (10 March 2022) from (www.media.ford.com).

[22] U.S. EPA (United States Environmental Protection Agency). (2021). Greenhouse gas emissions from a typical passenger vehicle. Date Retrieved (16 March 2022) from (www.epa.gov).

[23] Oregon DEQ (Department of Environmental Quality). (2009). Actual sulfur dioxide emissions from fuel burning using material balance. Date Retrieved (20 March 2022) from (www.oregon.gov).

[24] U.S. EIA (United States Energy Information Administration). (2011). Libya is a major energy exporter, especially to Europe. Date Retrieved (20 March 2022) from (www.eia.gov).

[25] Dayma, G. Togbé, C. and Dagaut, P. (2011). Experimental and detailed kinetic modeling study of Isoamyl alcohol (Isopentanol) oxidation in a jet-stirred reactor at elevated pressure. Energy& fuels 25(11): 4986-4998.

[26] What is the lifespan of a number of automotive parts. (2018). Date Retrieved (20 March 2022) from (www.almuraba.net).