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# A weighted fuzzy approach for product sustainability assessment: a case study in automotive industry

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ABSTRACT

Moving toward sustainable manufacturing has turned to an important debate between managers of any manufacturing organizations in order to keep in touch with the enormous competitiveness of the market. One important step to achieve this goal is to control the impact of their manufactured products toward three dimensions of sustainability (environment, economic and social). During the years, methodologies have been developed in order to assess the sustainability level of manufactured products. However, none of them focused on weighing their selected elements and sub elements using mathematical approaches. Consequently, lack of these weighting can have negative effects on precision of the assessment results. In this paper, a weighted fuzzy assessment method for product sustainability assessment was developed. Fuzzy analytical hierarchy process was used to weight selected elements and sub elements. Then, fuzzy logic was utilized to assess the product sustainability level based on acquired weights. Integrating fuzzy evaluation with weighted elements and sub elements and as a result, inclusive involvement with expert knowledge has made the proposed method more precise than the other existing methods. A case study of an automotive component was conducted to illustrate the efficiency of the developed method. Consequently, the results show that how a simple replacement in the product material can lead a manufacturer toward producing more sustainable products and achieving the ultimate goal of sustainable manufacturing.



## 1. Introduction

Brundtland Commission (1987) defined sustainability as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Also, sustainability is defined or described in many other papers (Deif, 2011; Strange and Bayley, 2008; Ravetz, 2000; Common and Perrings, 1992; Lele, 1991; Dovers, 1990; Barbier, 1987). Sustainability seems to be attractive proposition because of its meeting points among environmental concerns, manufacturing and product design activities (Rusinko, 2007). Moreover, it is bonded with the triple bottom line balance on achieving economic success, environment cleanness, and social responsibility all together and is considered as the central concept of sustainability, or sustainable development (Fairley et al., 2011; Hacking and Guthrie, 2008). Othman et al. (2010) stated that "Design for sustainability" is a concept and also a design philosophy. By this, a variety of design methodologies have been developed for improving process design, product design, material design, etc., at different scales of time and length. Toward this issue, sustainable product design has gained considerable amount of attention among manufacturing companies' managers. For instance, recycling costs will reduce by designing a product that does not contain any toxic materials and is easily disassembled (Waage, 2007).

Generally, a product that has little possible impact on the environment can be classified as a sustainable product (Vinodh and Rathod, 2010; Hu and Bidanda, 2009; Ljungberg, 2007; Maxwell et al., 2006; Maxwell and van der Vorst, 2003; Rydberg, 1995). However, the term "sustainable product" can be subjective and include a wide variety of economic, social and environmental considerations (Khan et al., 2004). So, manufacturers should consider sustainable approaches in their policies. According to the National Council for Advanced Manufacturing (NACFAM, 2009) in the U.S., sustainable manufacturing includes the manufacturing of "sustainable" products and the sustainable manufacturing of all products. Consequently, first part of this definition includes manufacturing of renewable energy, energy efficiency, green building, and other green and social equity-related products and

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the second part focuses on the sustainable manufacturing of all products with consideration of full life cycle stages of product manufactured.

Vinodh and Joy (2011) pointed out that manufacturing organizations can survive in the competitive environment by integrating important drivers of sustainable manufacturing (environmental, economic, and social sustainability). Just recently, Gunasekaran and Spalanzani (2011) investigated that environmentally friendly manufacturing has become an interesting issue among companies around the world. Consequently, manufacturing a more sustainable product can help an organization to move toward sustainable manufacturing. In order to manufacture more sustainable products, the manufactured products first should be assessed. In this context, different methodologies for assessing the product sustainability considering one, two or an integration of all three dimensions of sustainability have been developed by various researchers. Goedkoop et al. (1996) introduced Eco-indicator 95 as a quantitative distance-target based on Life Cycle Assessment (LCA) methodology. By setting a target level for a particular environmental effect, the gap between the environmental impact and the target level will be measured. Not covering the economic aspect such as cost, resource depletion and technology can be considered as the weakness of this methodology. However, it is an applicable tool for evaluating any type of product and also understandable by any product designer who do not have a deep knowledge on the environmental issues. Five years later, Goedkoop and Spriensma (2001) developed Eco-indicator 99 based on damage-oriented method for LCA which is a modification of Eco-indicator 95. Human health, ecosystem and mineral resources are the main three damage categories. Eco-indicator 99 has the advantage of being a generalized tool to evaluate any product. However, Economic element of sustainability is not encompassed in this methodology. One of the important limitations of this method is with its boundary which is cradle to gate. So, use and end of life activities are not covered in this methodology. Jawahir et al. (2007) developed a new comprehensive evaluation methodology to assess the sustainability content of any given manufactured product. This new method considers all three components of sustainability (economy, environment and society), over its total life cycle (pre-manufacturing, manufacturing, use and post-use). This system will assist product developers and manufacturers in achieving their sustainability targets. This methodology needs a joint effort and commitment from legislators, product developers, manufacturers, researchers, etc. to standardize the scoring system and to subgroup the influencing factors that affect the product sustainability.

Integrated analysis of environmental and economic aspects of sustainability for expanding the domain of LCA is believed to be valuable by many researchers. The structure of the Analytical Hierarchy Process (AHP) model for the integrated assessment of environmental and economic performances of chemical products was developed by Qian et al. (2007). This method covers two dimensions of sustainability which are environmental and economic sustainability. In the AHP model, the top level of the hierarchy specifies the goal, and intermediate levels specify criteria and sub criteria, which reflect successive categorizations of environmental performance and economic performance. The lowest level corresponds to the inputs associated with chemical product alternatives. One advantage of this method is using AHP as its base algorithm of assessment. Fuzzy sustainability evaluation method which was developed by Hemdi et al. (2011) helps the designers and decision makers to assess products and processes toward sustainability approaches with the consideration on environmental, economic and social aspects. This method can focus on cradle to grave boundary (whole product life cycle) of analysis. One of the important advantages of this methodology is its capability to handle severe uncertainty and ability to evaluate qualitative and quantitative data simultaneously.

Some of these methodologies are focused on just one or two dimension(s) of sustainability. Moreover, some others focused on all three dimensions but there is a same gap in all of these methods which is lack of weighting for their selected elements and sub elements. Besides that, no research has been attempted from the viewpoint of focusing on continuous improvement of products toward achieving more sustainable products which can contribute to sustainable manufacturing. In order to fill the gaps existed in the aforementioned research works, a new product sustainability assessment methodology integrated with fuzzy logic and Fuzzy Analytical Hierarchy Process (FAHP) was developed. FAHP was used to weight selected elements and sub elements in order to have more precise assessment. Then, fuzzy logic was utilized to assess the product sustainability level based on acquired weights. Weighted Fuzzy Assessment Method (WFAM) can help decision makers to decide better. Moreover, more precise assessment can be achieved by utilizing the proposed method. In addition, an extension of improvement phase was added to this methodology to make it more dynamic. Because the proposed new method has a dynamic behavior due to its improvement phase, it will help decision makers inside any manufacturing company to easily decide on what to do next in order to make the product manufactured more sustainable and move toward sustainable manufacturing.

The rest of this paper is arranged as follows. Preliminary knowledge to be used in the subsequent sections is given in Section 2. In Section 3, the WFAM is introduced. This section is followed by Section 4 in which our case study and results are detailed. Finally, conclusion and discussion are provided in Section 5.

## 2. Preliminaries and basic notations

### 2.1. FAHP

Chang (1996) proposed the extent analysis method which is used as the most common method in the solution of FAHP applications. In the method, fuzzy number is used to quantify the “extent”. For the extent analysis of each object, a fuzzy synthetic degree value can be obtained based on the fuzzy values. $X = \{x_1, x_2, \ldots, x_n\}$ can present elements of the alternatives as an object set. Besides that, the elements of the criteria as a goal set are represented by $U = \{u_1, u_2, \ldots, u_m\}$. According to the method of Chang’s (1996) extent analysis, each object is taken and extent analysis for each goal, $g_i$, is performed respectively. Consequently, $m$ extent analysis values for each object can be obtained with the Equation (1) as follows:

$$M^1_{g_1}, M^2_{g_2}, \ldots \ldots, M^m_{g_i} \ldots, \quad i = 1, 2, 3, \ldots \ldots \ldots, n \tag{1}$$

where $M^j_{g_i}$ is triangular fuzzy number that can be displayed by $(a, b, c)$. Where all the$M^j_{g_i}, j = 1, 2, 3, \ldots, m$ are triangular fuzzy numbers. Now the steps of Chang’s extent analysis are described as follows (Kahraman et al., 2004):

- Step 1: The value of fuzzy synthetic extent is defined as:

$$S_i = \sum_{j=1}^{m} M^j_{g_i} \otimes \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{g_i} \right]^{-1} \tag{2}$$

If $M^j_{g_i} = (a_{ij}, b_{ij}, c_{ij})$, then $\sum_{j=1}^{m} M^j_{g_i}$ with the fuzzy addition operation of $m$ extent analysis values for a particular matrix is defined as:

$$\sum_{j=1}^{m} M_{g_i}^{j} = (a_{i1}, b_{i1}, c_{i1}) \oplus (a_{i2}, b_{i2}, c_{i2}) \oplus \ldots \oplus (a_{im}, b_{im}, c_{im}) = \left( \sum_{j=1}^{m} a_{ij}, \sum_{j=1}^{m} b_{ij}, \sum_{j=1}^{m} c_{ij} \right) = (a_i', b_i', c_i') \tag{3}$$

Also, for calculating $[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j}]^{-1}$, fuzzy addition operation is to be performed:

$$\sum \sum M_{g_i}^{j} = \sum_{i=1}^{n} \left( \sum_{j=1}^{m} a_{ij}, \sum_{j=1}^{m} b_{ij}, \sum_{j=1}^{m} c_{ij} \right) = \left( \sum_{i=1}^{n} a_i', \sum_{i=1}^{n} b_i', \sum_{i=1}^{n} c_i' \right)$$
$$\left( \sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j} \right)^{-1} = \left( \frac{1}{\sum_{i=1}^{n} c_i'}, \frac{1}{\sum_{i=1}^{n} b_i'}, \frac{1}{\sum_{i=1}^{n} a_i'} \right) \tag{4}$$

So:

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left( \sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j} \right)^{-1} = (a_i', b_i', c_i') \otimes \left( \frac{1}{\sum_{i=1}^{n} c_i'}, \frac{1}{\sum_{i=1}^{n} b_i'}, \frac{1}{\sum_{i=1}^{n} a_i'} \right) = \left( \frac{a_i'}{\sum_{i=1}^{n} c_i'}, \frac{b_i'}{\sum_{i=1}^{n} b_i'}, \frac{c_i'}{\sum_{i=1}^{n} a_i'} \right) = (a_i, b_i, c_i) \tag{5}$$

- Step 2: Possibility degree calculation: If $S_i = (a_i, b_i, c_i)$ $S_k = (a_k, b_k, c_k)$, then possibility degree of $S_i \geq S_k$ that indicated by $V(S_i \geq S_k)$ is defined as:

$$V(S_i \geq S_k) = \sup_{y \geq x} \left( \min \{ \mu_{S_i}(x), \mu_{S_k}(y) \} \right) \tag{6}$$

And can be equivalently expressed as follows:

$$V(S_i \geq S_k) = hgt(S_i \cap S_k) = \mu_{S_i}(d) \tag{7}$$

$$V(S_i \geq S_k) = \mu_{S_i}(d) = \begin{cases} 1 \Rightarrow \text{if } (a_i \geq a_k) \\ 0 \Rightarrow \text{if } (a_k \geq c_i) \\ \dfrac{a_k - c_i}{(b_i - c_i) - (b_k - a_k)} \Rightarrow \text{otherwise} \end{cases} \tag{8}$$

where $d$ is the ordinate of the highest intersection point between $\mu_{S_i}$, $\mu_{S_k}$. Fig. 1 shows $V(S_i \geq S_k)$:

- Step 3: the degree of possibility for a convex fuzzy number to be greater than $k$ convex fuzzy numbers $S_i$; $i = 1, 2, \ldots, k$ can be defined by:

$$V(S \geq S_1, S_2, \ldots, S_k) = V((S \geq S_1), (S \geq S_2), \ldots (S \geq S_k)) = \min(V(S \geq S_1), V(S \geq S_2), \ldots, V(S \geq S_k)) = \min V(S \geq S_i) \quad i = 1, 2, \ldots, k \tag{9}$$

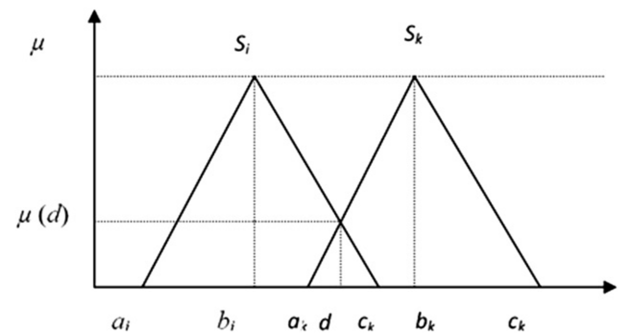


**Fig. 1.** Possibility degrees between to TFN.

If it is assumed that for $(k = 1, 2, \ldots, n \; k \neq i)$, $d'(A_i) = \min V(S_i \geq S_k)$ then, weight vector is given by:

$$W' = (d'(A), d'(A_2), \ldots, d'(A_n))^T \tag{10}$$

where $A_i$ (i = 1, 2,…, $n$) are $n$ elements.

- Step 4: via normalization, the normalized weight vectors are defined as:

$$W = (d(A), d(A_2), \ldots, d(A_n))^T \tag{11}$$

where $W$ is a non-fuzzy number. This gives the priority weights of one alternative over another.

## 3. Weighted fuzzy assessment method (WFAM)

The proposed method followed during this project is shown in Fig. 2. The research analogy behind this project is that how the case organization can move toward sustainable manufacturing by manufacturing more sustainable products. With this methodology, a road map for organizations that want to improve their manufactured product design to move toward having more sustainable products and ultimately implementing of sustainable manufacturing is provided. Dynamic structure is an outstanding part of this methodology which is because of having an FAHP weighting mechanism based on expert decision makers' ideas within and outside the organization, a fuzzy evaluation mechanism and an expert advice mechanism for making an improvement in the current design in order to achieve more sustainable products. These concepts are clarified properly by explaining each step and also performing the case study. The proposed method has seven steps as follows:

- Step 1: selecting a product to be assessed
- Step 2: selecting appropriate sub elements and influencing factors
- Step 3: weighting the selected sub elements and influencing factors
- Step 4: data collection
- Step 5: fuzzy evaluation
- Step 6: calculating the current design sustainability index
- Step 7: calculating the improved design sustainability index

A detailed explanation of each step is presented in the followings:

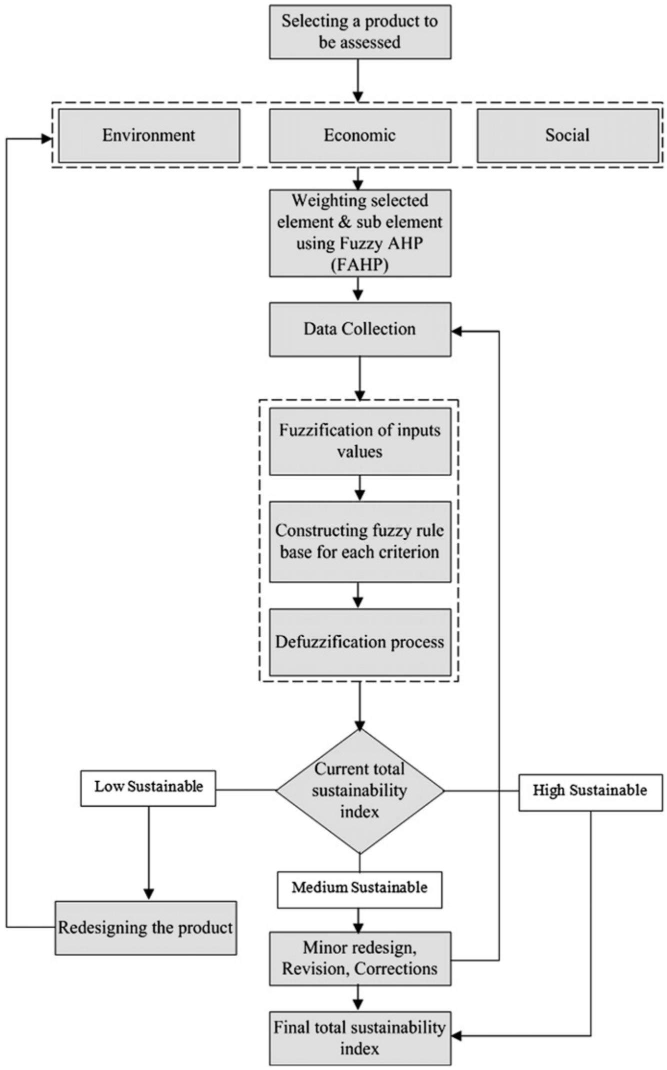


**Fig. 2.** WFAM.

- Step 1 is involved with selecting a product from a typical organization. For a product to be selected for the assessment, all the required data should be available. Consequently, if an organization does not have the product specification documents, a system analysis activity must be done in the selected organization in order to obtain all needed data.
- Step 2 is about selecting all elements and sub elements and their influencing factors. Selecting these sub elements and their influencing factors are based on previous research activities which can be validated by decision makers' expert opinions.
- Step 3 encompasses weighting the selected elements and sub elements. In this step, the weights of all selected sustainability elements and sub elements will be calculated using FAHP. These weighting will be used in step 5 in order to calculate the scores of each element and sub element. Using these weights will make the assessment more precise and real because calculations of these weights are involved with the decision makers' expert ideas inside and outside the organization. Consequently, total sustainability index which will be obtained in step 6 is real and can be used as a good basis for making further decisions. These decisions could be some minor or major redesigning and etc. which are discussed in step 6.
- Step 4 is about collecting the required data. These data can be obtained from the product specification documents that are prepared by a system analysis activity. Moreover, there is no need to involve all related data for the assessment. Involving the data into the assessment is based on the selected elements and sub elements.
- Step 5 covers the fuzzy evaluation part. In this step, fuzzy logic is involved in assessing the input data. All crisp data that are gathered in step 4 are transformed into grades of membership for linguistic terms of fuzzy sets. These grades of membership are set based on the knowledge of a system manager inside the organization based on the importance and criticality of each influencing factors or input variables. After determining the grades of membership, the target range or reference value is to be set for each input variable. This value indicates the minimum and maximum values of the input variable. The selection of reference value is usually based on the national and local policy or may be set by the organization or manufacturer to meet their objectives. Constructing the input variables' membership function is based on these reference values. Then, the linguistic value of zero to one (0–1) is selected as a reference value for constructing the output membership function. The minimum value is zero which is interpreted as a low sustainability while maximum value of one is defined as a high sustainability. After constructing the membership functions for input and output variables, fuzzy rule base system will be constructed based on the decision makers' knowledge inside the organization. These decision makers can be a group of the company owner, chief executive officer, general manager, system manager. Number of rules for each sub element to be constructed depends on the number of input variables and the grades of membership function for input variables which can be determined using Equation (12) (Cornelissen et al., 2001):

$$R = n^{v} \tag{12}$$

where $n$ represents number of grades of membership function for input variables and $v$ is the number of input variable for each sub element and $R$ stands for the number of rules to be constructed. Fuzzy inference system comes after constructing the rules. In this part, result of each rule is generated as fuzzified inputs and goes through the inference system. The output of fuzzy inference system is the input for defuzzification process. But, due to large number of inputs and rules, rules evaluation and defuzzification the inputs will be difficult for the mechanisms. Therefore, MATLAB, $C^{++}$ and Visual Basic or other programming languages can be utilized in this step in order to perform the fuzzy evaluation. Ultimately, scores of all sub elements will be calculated.

- Step 6 is about the calculation of total current sustainability index which is the aggregate value of the three sustainability elements' weighted scores using Equation (14). Equation (13) calculates the score of each sustainability element.

$$I_j = \sum_i w_{ij} I_{ij} \tag{13}$$

where,

$I_j$ = score of $j$th sustainability element,
$w_{ij}$ = weight of $i$th sub sustainability element of $j$th sustainability element,
$I_{ij}$ = score of $i$th sub sustainability element of $j$th sustainability element,

$i = 1,\ldots, n$ index of sub sustainability elements,
$j = 1,\ldots, m$ index of sustainability elements.

$$I_{\text{sustainability}} = \sum_j w_j I_j \tag{14}$$

where,

$I_j$ = score of $j$th sustainability element,
$w_j$ = weight of $j$th sustainability element,
$I_{\text{sustainability}}$ = total sustainability index.

According to the obtained index, $I_{\text{sustainability}}$, a decision is to be made according to the predefined thresholds. The step relieves the burden of manufacturing managers by decreasing the workload and the stress due to thinking about improving their products toward having more sustainable products. In this step, according to the results of current sustainability index calculations, some decisions and advice about that system such as executing a comprehensive restructuring study or revision, correction and renewal study are presented to manufacturer or system managers. The decisions and advice will be similar to expert views to a very high degree.

- Step 7 covers applying the decisions which are made in the previous step into the selected product, reassessing the product in the perspective of sustainability and obtaining new total sustainability index. According to proposed methodology, this loop will be continued until the threshold of total sustainability index which is set in step 6 is achieved.

## 4. Case study and results

In this section, details about the case company, product, data collection, sustainability assessment and improvement of current design are presented.

- *Step 1: About the case company*

This case study was conducted in an Iranian automotive components manufacturing company (hereafter referred to as GGS). GGS Company manufactures fuel filters, fuel pumps for injection, carbureting engines, pressure regulators and etc. Fuel filter was selected as the appropriate product to be assessed. This decision was taken based on the consultation with the manager and executives of GGS. The reasons for the selection of fuel filter were based on high production rate, high customers' demand and availability of useful portion of required data related to this product. So, the manager and executives were unanimous about selecting fuel filter as the case product. The boundary of analysis for this case study is selected as "Cradle to Gate" which covers two stages of product life cycle from raw material extraction until the end of manufacturing stage that, consequently, makes this case study a partial assessment. This decision was made due to lack of some appropriate data related to "use and end of life" stages of the product life cycle.

- *Step 2: Criteria selection*

In WFAM, selecting the sub elements and influencing factors is done based on various studies, reviewing the literature (Roca and Searcy, 2012; Herva et al., 2011; Tokos et al., 2011; Singh et al., 2009; Okkonen, 2008; Petrie et al., 2007; Block et al., 2007; Jain, 2005; Labuschagne et al., 2005; Khan et al., 2004; Krajnc and Glavic, 2003; Andersson et al., 1998; Ragas et al., 1995) and discussion with the decision makers of GGS. In this case study, owner of the company, chief executive officer, general manager and a system manager were selected as the expert decision makers. Experts' opinions are used for validating the selected sub elements and influencing factors. Table 1 shows all elements, sub elements and influencing factors that were selected.

As it was mentioned before, the boundary of analysis selected for this research activity is cradle to gate and the total sustainability index for this research has been calculated regarding this boundary. It is worth to note that due to lack of enough information for the two excluded stages (use and end of life), cradle to grave boundary which includes all four stages of product life cycle (raw material extraction, manufacturing, use and end of life stages) was not applied in this research paper to prevent misleading results.

- *Step 3: Weighting selected elements and sub elements using FAHP*

In this step, the elements and sub elements of product sustainability have been weighted using FAHP. As tabulated in Table 1, the hierarchy structure including three levels has been

**Table 1**
Selected elements, sub elements and influencing factors.

| Total sustainability (level zero) | Sustainability element (level one) | Sustainability sub element (level two) | Influencing factor |
|---|---|---|---|
| Total sustainability | Environment | Pollution | - Plastic waste (PW) |
| | | | - Steel waste (StW) |
| | | | - Paper waste (PaW) |
| | | | - Chemical waste of plastic (ChW) |
| | | Greenhouse effect | - Carbon dioxide emission to air ($CO_2$) |
| | | | - Methane emission to air ($CH_4$) |
| | | | - Nitrogen dioxide emission to air ($NO_2$) |
| | Economic | Cost | - Operating (OC) |
| | | | - Packaging (PaC) |
| | | | - Raw material (RMC) |
| | | | - Transportation to inventory (TIC) |
| | | Resource | - Non-renewable materials (NRM) |
| | | | - Renewable materials (RM) |
| | | Technology | - Technology status (TS) |
| | | | - Technology verification (TV) |
| | | Process | - Numbers of processes involved (NP) |
| | | | - Phase of chemical (PC) |
| | Social | Social performance | - Mercury (Hg) |
| | | | - Sulfur dioxide ($SO_2$) |
| | | | - Particles ($PM_{10}$) |
| | | | - Safety risk (SR) |

made. Level zero presents the main goal which is the product sustainability index; level one indicates the elements for assessing the product sustainability and level two shows the sub elements for assessing the product sustainability. In this research, according to decision makers' opinion and to facilitate the process of fuzzy logic assessment, no weights have been allocated to the influencing factors. So, influencing factors were not included in FAHP process. In this step, using the fuzzy scale shown in Table 2, four experts as a group were asked to make pairwise comparison of the relative importance of elements and sub elements. Firstly, the expert compared the main elements with respect to the total sustainability index. Then, the experts compared the sub elements with respect to the main elements. The results are shown in Table 3. After that, based on Chang's FAHP steps, elements and sub elements have been weighted. Owing to the limited space, the final results of the elements and sub elements weights were shown in Table 4.

- *Step 4: Data collection*

### 4.1. Environment element data

#### 4.1.1. Pollution sub element data

For pollution sub element, four influencing factors were selected. In Table 5, these four influencing factors with their amount and functional unit are shown. The method that these data were gathered is according to Equation (15):

$$D = \frac{W}{N} \tag{15}$$

where,

$D$ = amount of waste in gram per product,
$W$ = total amount of production waste in grams for a typical month,
$N$ = number of fuel filter manufactured in that typical month.

For the chemical waste of producing plastic which is related to raw material extraction, data were retrieved from Plastics Europe Data set version 2.0 for Nylon 66 GF 30 compound (PA 66 GF 30) (Plastic Europe, 1996). The amount of chemical waste for producing 1 kg of plastic is provided in this database. For making these data acceptable for this study, the amount of chemical waste for 59 g of plastic which is used in this product was calculated.

#### 4.1.2. Greenhouse effect

In the case of greenhouse effect sub element, $CO_2$, $CH_4$ and $NO_2$ emission to air were identified to be the most influencing factors. In Table 5, data that were collected from Plastic Europe database version 2.0 (Plastics Europe, 1996) are related to produce 1 kg of Nylon 66 GF 30 compound (PA 66 GF 30) which is used in this product. These data were calculated later to be accepted as an appropriate information for producing this fuel filter.

**Table 2**
The linguistic variables and their corresponding fuzzy numbers.

| Linguistic scale | Triangular fuzzy scale |
|---|---|
| Just equal | (1,1,1) |
| Equally important | (2/3,1,3/2) |
| Weakly important | (1,3/2,2) |
| Strongly more important | (3/2,2,5/2) |
| Very strong more important | (2,5/2,3) |
| Absolutely more important | (5/2,3,7/2) |

**Table 3**
Fuzzy pairwise comparisons.

| | | | | |
|---|---|---|---|---|
| *Fuzzy pairwise comparison matrix for main elements* | | | | |
| | Environment | Economic | Social | |
| Environment | (1,1,1) | (2/3,1,3/2) | (1,3/2,2) | |
| Economic | (2/3,1,3/2) | (1,1,1) | (2/3,1,3/2) | |
| Social | (1/2,2/3,1) | (2/3,1,3/2) | (1,1,1) | |
| *Fuzzy pairwise comparison matrix for environment sustainability sub elements* | | | | |
| | Greenhouse effect | Pollution | | |
| Greenhouse effect | (1,1,1) | (2/3,1,3/2) | | |
| Pollution | (2/3,1,3/2) | (1,1,1) | | |
| *Fuzzy pairwise comparison matrix for economic sustainability sub elements* | | | | |
| | Resource | Cost | Process | Technology |
| Resource | (1,1,1) | (2/3,1,3/2) | (1,3/2,2) | (3/2,2,5/2) |
| Cost | (2/3,1,3/2) | (1,1,1) | (2/3,1,3/2) | (1,3/2,2) |
| Process | (1/2,2/3,1) | (2/3,1,3/2) | (1,1,1) | (1,3/2,2) |
| Technology | (2/5,1/2,2/3) | (1/2,2/3,1) | (1/2,2/3,1) | (1,1,1) |

### 4.2. Economic element data

#### 4.2.1. Cost sub element data

Cost sub element contains four influencing factors which are operating cost, packaging cost, raw material cost and transportation to inventory cost. First influencing factor in cost sub element that is considered in this study is operating cost which can be calculated based on Equation (16):

$$OC = WS + ED + DD \tag{16}$$

where,

OC = operating cost,
WS = worker salary,
ED = equipment depreciation,
DD = die depreciation.

Functional unit of these influencing factors is Iranian Rial (IRR) per producing each product (IRR/product). These data were collected from the cost analysis document which was carried out for this type of fuel filter inside the GGS in 2010. Second considered influencing factor is packaging cost per each fuel filter. This cost type is basically calculated based on the price of each packaging box for each fuel filter.

The third influencing factor is transportation to inventory cost. All transportations were done by 30 tones trucks. This influencing factor covers all the cost that was incurred by the company during transporting of raw materials from the raw material extraction site and suppliers' warehouse to its own inventory for manufacturing the fuel filter. Transportation cost was calculated based on Equation (17):

$$TC = \frac{(FC^{*}d_k) + (OC^{*}q)}{N} \tag{17}$$

TC = transportation cost,
FC = fuel cost of 30 ton truck per 1 km travel in a typical month,

**Table 4**
Final results of the elements and sub elements weights.

| Elements | Weight | Sub elements | Weight |
|---|---|---|---|
| Environment | 0.38 | Greenhouse effect | 0.50 |
| | | Pollution | 0.50 |
| | | Cost | 0.28 |
| Economic | 0.33 | Resource | 0.34 |
| | | Technology | 0.13 |
| | | Process | 0.25 |
| Social | 0.27 | Social performance | 1 |

**Table 5**
Input data.

| Sustainability element | Influencing factor | Unit | Input | Sustainability element | Influencing factor | Unit | Input |
|---|---|---|---|---|---|---|---|
| Environment element | *Input data for pollution* | | | Economic element | *Input data for cost* | | |
| | PW | g/product | 2.95 | | OC | IRR/ product | 6509 |
| | StW | g/product | 1.05 | | PaC | IRR/product | 266 |
| | PaW | g/product | 0.7 | | RMC | IRR/product | 9784 |
| | ChW | g/product | 0.66 | | TIC | IRR/product | 342 |
| | *Input data for greenhouse effect* | | | | *Input data for resource* | | |
| | $CO_2$ | g/product | 357.41 | | NRM | g/product | 80 |
| | $CH_4$ | g/product | 2.4 | | RM | g/product | 14 |
| | $NO_2$ | g/product | 0.65 | | *Input data for technology* | | |
| Social element | *Input data for social performance* | | | | TS | Dimensionless | New |
| | Hg | g/product | 4.1e-7 | | TV | Dimensionless | Tested |
| | $SO_2$ | g/product | 0.97 | | *Input data for process* | | |
| | $PM_{10}$ | g/product | 0.20 | | NP | Number/product | 23 |
| | SR | injury/year | 24 | | PC | Dimensionless | Solid |

$d_k$ = distance between supplier $k$ to factory warehouse,
OC = raw material ordering cost,
$q$ = number of orders in that typical month,
$N$ = number of fuel filters manufactured in that typical month,
$k = 1,\ldots, K$ index of suppliers.

The last influencing factor in this sub element is raw material cost of fuel filter. As mentioned in step 1, the boundary of analysis of this project is cradle to gate. For cost sub element, operating and packaging costs are considered to be categorized in manufacturing life cycle stage. Besides that, transportation to inventory and raw material costs are included in raw material extraction stage. In Table 5, cost amount of each four influencing factors are tabulated.

*4.2.2. Resource sub element data*

Resource sub element contains two influencing factors which are non-renewable and renewable material. Paper is categorized as renewable material. On the other hand, plastic, rubber and steel are categorized in non-renewable material which means that these materials cannot be easily reprocessed and reused inside the manufacturing plant which may cause further costs to the company. The justification of why it was decided to consider resource sub element in the economic element is because these two influencing factors were interpreted based on the cost that the company will be incurred by using them. For instance, using renewable or non-renewable materials in design of the product might affect the operating cost that the manufacturing company should pay. Besides that, remanufacturing of renewable materials may cost less comparing with non-renewable materials. For example, steel will charge the company a further cost in order to be remanufactured and reused in the process of manufacturing; accordingly, the raw material cost will be affected. In Table 5, related data for this sub element is presented.

*4.2.3. Technology sub element data*

Technology sub element contains two influencing factors which are: technology status and technology verification. Technology status is a qualitative data which can be expressed by words and opinions. In this research project, the technology status is for expressing the type of manufacturing technology which is being used in producing the fuel filter. Moreover, it is categorized qualitatively as new, fairly new and old. As a justification for technology sub element being included in economic element category, it is worth to mention that, for instance, although technology status is expressed qualitatively, having a new, fairly new and old manufacturing technology would cause different kinds of costs. In our case, the company paid huge amount of money in order to improve its production technology such as implementing lean manufacturing techniques, using semi automated machines, increasing employees' knowledge related to these technologies. Table 6 provides a ranking order of technologies for being used as input for fuzzy process.

Second parameter that was selected for this project is technology verification which is based on the numbers of times they have been tested. In Table 6, a ranking order of technologies verification is provided. Based on several visits from the factory, reviewing the history records of the company and also several meetings with decision makers, the data for technology sub element was decided which is presented in Table 5.

*4.2.4. Process sub element data*

Process sub element contains two influencing factors to be measured which are numbers of processes involved and phase of chemical. Actually, it is categorized in economic element based on the justification that is provided in Section 4.2.3. For instance, based on assessing every product, the phase of chemical influencing factor can be different that accordingly the type of production technology may differ. Consequently, the incurred cost involved with that can be different.

For the first influencing factor, numbers of processes that are involved in manufacturing each fuel filter are 23 processes that are listed down in Table 7. The second influencing factor is phase of chemical which is basically the phase of chemical that manufacturing of fuel filter is involved with. It can vary from gas, liquid-gas, liquid, liquid–solid and solid. For being applicable in fuzzy assessment, there should also be a ranking order for this

**Table 6**
Ranking orders.

| Category | Ranking |
|---|---|
| *Ranking order of technology status* | |
| Old | 1 |
| Fairly new | 2 |
| New | 3 |
| *Ranking order of verification of technology* | |
| Not tested | 1 |
| Not well tested | 2 |
| Tested | 3 |
| *Ranking orders of process phases* | |
| Gas | 1 |
| Liquid–gas | 2 |
| Liquid | 3 |
| Solid–liquid | 4 |
| Solid | 5 |

**Table 7**
Manufacturing processes.

| ID | Part name | Numbers of processes involved | Type of processes involved |
|---|---|---|---|
| 1 | Bonnet | 2 | Injection, deburring |
| 2 | Main body | 2 | Injection, deburring |
| 3 | Upper washer | 4 | Spread cut, forming, bending, final cut |
| 4 | Lower washer | 5 | Spread cut, forming, bending, punch, final cut |
| 5 | Filter paper | 6 | Cutting, sinuous roll forming, decoction, separating decocted papers, circling the papers, clenching |
| 6 | Secondary bonnet | 2 | Injection, deburring |
| 7 | Pincer | 2 | Pressing, bending |
| 8 | Stuffing box | Item bought | Item bought |

parameter which is considered to be as follows in Table 6. Solid phase is considered to be the best phase for this type of manufacturing based on the opinion of the decision maker. Almost all stages of manufacturing the fuel filter from manufacturing bonnet to clip are solid. So, phase of chemical for this product could be selected as solid.

### 4.3. Social element data

#### 4.3.1. Social performance

Four influencing factors are considered in this sub element. First of all, it was considered that which factors could be more important in this sub element. The most important factor that must be taken care of is worker health during extracting the raw materials and also manufacturing a product. According to Malaysia environmental record in 2006, Hg, $SO_2$ and $PM_{10}$ were identified as some important factors that can affect workers health during the raw material extraction stage. Also, safety risk is taken into account for the manufacturing stage which measures the number of injuries occurring for the workers during the manufacturing processes. It can be perceived that the fewer numbers of injuries mean that the company owners are paying more attention to their employees by providing them more safe work environment. Table 5 presents the obtained data for social performance sub element.

- *Step 5: Fuzzy evaluation*

In this step, firstly, the crisp input and output variables have been transformed into grades of membership for linguistic terms of fuzzy sets, as shown in Tables 8–11. Then, a fuzzy rule base has been constituted using the fuzzificated variables. Membership grades of the crisp input and output variables have been defined based on the consultant with decision makers and also according to reviewing the literature. Finally, low, medium and high were selected for input variables. Besides, it was decided to define low, low to medium, medium, medium to high and high as output variable membership grades.

Moreover, MATLAB fuzzy logic package was utilized in step 5. In this step, the parameters of membership functions were edited and some rules were created using MATLAB. Equation (12) was used to calculate the number of rules to be constructed for each sub element. Some realistic rules of the rule base have been defined according to the four decision makers' knowledge. Besides, in order to have precise and definite assessment, the whole knowledge was translated in rules. Table 12 shows some rules from the rule base.

- *Step 6: Current sustainability index*

### 4.4. Environment, economic and social sustainability scores

Overall score for each sub element of environment, economic and social sustainability was calculated and then the environment, economic and social sustainability scores were obtained using Equation (13). Table 13 demonstrates the obtained scores for selected sub elements for each sustainability element.

### 4.5. Total sustainability index

After that all three sub sustainability scores were obtained, the total sustainability index for fuel filter was calculated by using Equation (14) which are also narrowed down in Table 13.

Finally, three ranges were defined in order to apply the changes in the current design. In this study, the sustainability is indexed between 0 and 1. If the index is between the ranges of 0–0.33, it will be considered as low sustainable, if it is between the ranges of 0.34–0.66, it will be considered as medium sustainable and if it is between the ranges of 0.67–1, it will be considered as high sustainable. For each of these ranges some expert advices would be appropriate which can be gathered based on discussions with product design managers inside the company. For instance, having a low sustainable product design would require executing a comprehensive redesigning study for the design and manufacturing of the product which would cause major replacements in materials, major manufacturing process renewal, major production planning changes and fundamental changes in element and sub element selections which can lead to new data gathering and system analysis activities. According to the results of this step, the weakness of

**Table 8**
Environment element variables and their membership functions.

| Linguistics value | Numerical range | Linguistics value | Numerical range | Linguistics value | Numerical range |
|---|---|---|---|---|---|
| Linguistics variable: PW | | Linguistics variable: StW | | Linguistics variable: PaW | |
| Low | [−2.95 0 2.95] | Low | [−1.05 0 1.05] | Low | [−0.7 0 0.7] |
| Medium | [0 2.95 5.9] | Medium | [0 1.05 2.1] | Medium | [0 0.7 1.4] |
| High | [2.95 5.9 8.85] | High | [1.05 2.1 3.15] | High | [0.7 1.4 2.1] |
| Linguistics variable: ChW | | Linguistics variable: $CO_2$ | | Linguistics variable: $CH_4$ | |
| Low | [−0.5 0 0.5] | Low | [−250 0 250] | Low | [−2.5 0 2.5] |
| Medium | [0 0.5 1] | Medium | [0 250 500] | Medium | [0 2.5 5] |
| High | [0.5 1 1.5] | High | [250 500 750] | High | [2.5 5 7.5] |
| Linguistics variable: $NO_2$ | | | | | |
| Low | [−0.5 0 0.5] | | | | |
| Medium | [0 0.5 1] | | | | |
| High | [0.5 1 1.5] | | | | |

**Table 9**
Economic element variables and their membership functions.

| Linguistics value | Numerical range | Linguistics value | Numerical range | Linguistics value | Numerical range |
|---|---|---|---|---|---|
| Linguistics variable: OC | | Linguistics variable: PaC | | Linguistics variable: RMC | |
| Low | [−6737.5 0 6737.5] | Low | [−274.8 0 274.75] | Low | [−10062.5 0 10062.5] |
| Medium | [0 6737.5 13480] | Medium | [0 274.8 549.5] | Medium | [0 10060 20125] |
| High | [6738 13480 20210] | High | [274.8 549.5 824.25] | High | [10060 20130 30187.5] |
| Linguistics variable: TIC | | Linguistics variable: NRM | | Linguistics variable: RM | |
| Low | [−355.25 0 355.25] | Low | [−47 0 47] | Low | [−47 0 47] |
| Medium | [0 355.3 710.5] | Medium | [0 47 94] | Medium | [0 47 94] |
| High | [355.3 710.5 1065.75] | High | [47 94 141] | High | [47 94 141] |
| Linguistics value | Numerical range | Linguistics value | Numerical range | Linguistics value | Numerical range |
| Linguistics variable: TS | | Linguistics variable: TV | | Linguistics variable: NP | |
| Low | [0 1 2] | Low | [0 1 2] | Low | [7.5 15 22.5] |
| Medium | [1 2 3] | Medium | [1 2 3] | Medium | [15 22.5 30] |
| High | [2 3 4] | High | [2 3 4] | High | [22.5 30 37.5] |
| Linguistics variable: PC | | | | | |
| Low | [−1 1 3] | | | | |
| Medium | [1 3 5] | | | | |
| High | [3 5 7] | | | | |

**Table 10**
Social element variables and their membership functions.

| Linguistics value | Numerical range | Linguistics value | Numerical range | Linguistics value | Numerical range |
|---|---|---|---|---|---|
| Linguistics variable: Hg | | Linguistics variable: $SO_2$ | | Linguistics variable: $PM_{10}$ | |
| Low | [−5e-007 0 5e-007] | Low | [−0.75 0 0.75] | Low | [−0.5 0 0.5] |
| Medium | [0 5e-007 1e-006] | Medium | [0 0.75 1.5] | Medium | [0 0.5 1] |
| High | [5e-007 1e-006 1.5e-006] | High | [0.75 1.5 2.25] | High | [0.5 1 1.5] |
| Linguistics variable: SR | | | | | |
| Low | [−20 0 20] | | | | |
| Medium | [0 20 40] | | | | |
| High | [20 40 60] | | | | |

**Table 11**
Total sustainability variables and their membership functions.

| Linguistics value | Numerical range | Linguistics value | Numerical range | Linguistics value | Numerical range |
|---|---|---|---|---|---|
| Linguistics variable: Environment | | Linguistics variable: Economic | | Linguistics variable: Social | |
| Low | [−0.25 0 0.25] | Low | [−0.25 0 0.25] | Low | [−0.25 0 0.25] |
| Low to Medium | [0 0.25 0.5] | Low to Medium | [0 0.25 0.5] | Low to Medium | [0 0.25 0.5] |
| Medium | [0.25 0.5 0.75] | Medium | [0.25 0.5 0.75] | Medium | [0.25 0.5 0.75] |
| Medium to High | [0.5 0.75 1] | Medium to High | [0.5 0.75 1] | Medium to High | [0.5 0.75 1] |
| High | [0.75 1 1.25] | High | [0.75 1 1.25] | High | [0.75 1 1.25] |

the current product design will be explained and discussed with the managers as an expert system.

In current step, the current sustainability of the product has been determined as “Medium sustainable”. Consequently, the system can have a much better sustainability level and the decision makers can conduct some redesigns, corrections, renewal studies, material replacements and etc. to improve the sustainability level. These kinds of activities are to be applied in an identified product design weak point. In this research work, in order to identify a weak point, scores of seven sub sustainability elements before multiplying the obtained weights in step 3 were considered as a basis for selecting the weak point. These results are also tabulated in Table 13 under “unweighted sub element score” column. Thereupon, it can be identified that resource score

**Table 12**
Some rule examples from the rule base.

| Rule no. | Rules |
|---|---|
| Rule 1 | If (Hg is high) and ($SO_2$ is high) and ($PM_{10}$ is high) and (SR is high) then (Social performance Score is low) |
| Rule 2 | If ($CO_2$ is low) and ($CH_4$ is low) and ($NO_2$ is low) then (Greenhouse Score effect is high) |
| Rule 3 | If (OC is low) and (PaC is low) and (TIC is low) and (RMC is medium) then (Cost Score is Medium to high) |
| Rule 4 | If (PW is high) and (StW is high) and (PaW is high) and (ChW is high) then (Pollution Score is low) |
| Rule 5 | If (NP is low) and (PC is low) then (Process Score is high) |
| Rule 6 | If (NRM is high) and (RM is high) then (Resource Score is medium) |
| Rule 7 | If (TS is high) and (TV is high) then (Technology Score is high) |

**Table 13**
Overall scores of current design.

| Influencing factor | Sub element | Unweighted sub element score | Weighted | Element sustainability | Weighted element score |
|---|---|---|---|---|---|
| *Overall score for environment sustainability element* | | | | | |
| PW | Pollution | 0.41 | 0.20 | 0.44 | 0.17 |
| StW | | | | | |
| PaW | | | | | |
| ChW | | | | | |
| $CO_2$ | Greenhouse effect | 0.47 | 0.24 | | |
| $CH_4$ | | | | | |
| $NO_2$ | | | | | |
| *Overall score for economic sustainability element* | | | | | |
| OC | Cost | 0.51 | 0.14 | 0.54 | 0.18 |
| PaC | | | | | |
| RMC | | | | | |
| TIC | | | | | |
| NRM | Resource | 0.30 | 0.1 | | |
| RM | | | | | |
| TS | Technology | 0.92 | 0.12 | | |
| TV | | | | | |
| NP | Process | 0.73 | 0.18 | | |
| PC | | | | | |
| *Overall score for social sustainability element* | | | | | |
| Hg | Social performance | 0.55 | 0.55 | 0.55 | 0.16 |
| $SO_2$ | | | | | |
| $PM_{10}$ | | | | | |
| SR | | | | | |
| **Total sustainability index**: | | | | | **0.51** |

is the lowest among other sub elements. This decision can be considered as a suggestion to the product designers or may be neglected by them due to high costs of implementation. Further research is to be done to replace a non-renewable material with a renewable one or at least replacing a non-renewable material with a non-renewable material with more advantages than the previous one in terms of manufacturing costs, lighter weight, less numbers of manufacturing processes and etc.

In this study, GGS Company was planning to replace the steel upper and lower washers with their plastic ones. The most important reason was that these washers basically do nothing just helping to hold the main body so there is no need to use steel material for manufacturing them. Besides that, there is less manufacturing cost incurred by the company in term of cost, process and raw material used. Furthermore, this decision seems to be helpful in order to reduce the total weight of the product which could be an important achievement. In the next section, another sustainability assessment will be carried out to show how a change can increase or decrease the total sustainability index for a product.

- *Step 7: Improved sustainability index*

The two upper and lower washers can be replaced by their plastic versions. New data regarding a possible change of material are obtained. Due to the changes, four sub elements got involved which are cost, social performance, pollution and greenhouse effect. New changes were considered in the new assessment and

**Table 14**
Overall scores after replacement.

| Influencing factor | Sub element | Weighted sub element score | Element score | Weighted element score |
|---|---|---|---|---|
| *Overall score for environment sustainability element* | | | | |
| PW | Pollution | 0.30 | 0.52 | 0.20 |
| StW | | | | |
| PaW | | | | |
| ChW | | | | |
| $CO_2$ | Greenhouse effect | 0.22 | | |
| $CH_4$ | | | | |
| $NO_2$ | | | | |
| *Overall score for economic sustainability element* | | | | |
| OC | Cost | 0.17 | 0.59 | 0.20 |
| PaC | | | | |
| RMC | | | | |
| TIC | | | | |
| NRM | Resource | 0.10 | | |
| RM | | | | |
| TS | Technology | 0.12 | | |
| TV | | | | |
| NP | Process | 0.20 | | |
| PC | | | | |
| *Overall score for social sustainability element* | | | | |
| Hg | Social performance | 0.52 | 0.52 | 0.15 |
| $SO_2$ | | | | |
| $PM_{10}$ | | | | |
| SR | | | | |
| **Total sustainability index**: | | | | **0.55** |

the new weighted scores and improved total sustainability index were calculated and shown in Table 14.

## 5. Conclusion and discussions

Excessive use of natural resources and the production of products containing too many hazardous materials can affect our environment, society and economy. Moreover, an unsustainable design of a product can lead to excessive waste and use of toxic material. This will result in an increase in production and operational costs. In this respect, manufacturing sustainable products becomes a crucial issue for most manufacturing and production managers in order to move toward sustainable manufacturing. First step to achieve this goal is to assess the sustainability level of any manufactured product inside the company with a great precision. In this paper, WFAM was proposed together with a case study to illustrate the effectiveness of the proposed method. An important advantage of the proposed method is integrating the human perception in all steps of the methodology which makes it more precise. Using FAHP for weighing the selected elements and sub elements, utilizing fuzzy assessment procedure for scoring and applying expert advice for each sustainable range made the proposed method more accurate.

According to acquired scores, changing the raw materials had a positive impact on environmental and economic sustainability elements but this trend was reversed for the social sustainability element. Economic sustainability has changed because replacing steel with plastic decreased raw material cost, weight of non-renewable materials. Also, instead of nine processes that were involved with manufacturing the steel version of upper and lower washer, after replacement, this number has decreased to four processes which are two injections and two deburrings. In the case of environment sustainability, there is a quite interesting point. Although the change has a positive effect on the pollution score and increased it to 0.30 compared to previously 0.20 which can be considered as an outstanding improvement, the greenhouse effect score was decreased because all greenhouse effect influencing factors were involved with the plastic material in the raw material extraction life cycle stage. This means that although changing the resource is good in some points but there are some other points that can be affected in a negative manner. Finally, two total sustainability indices are compared with each other. It can be concluded that after a replacement in the materials, the total sustainability index had a slight increase from 0.51 to 0.55 and this trend can be continued by some other improvements in the product design, material selection and manufacturing processes design stages.

In order to highlight the accuracy of the proposed WFAM, a comparison was made without considering the weights. Total sustainability index without considering the weights was obtained which is 0.53 comparing with the results obtained by current proposed approach, it can be perceived that although 0.53 is inside the medium sustainable range the same as weighted result, there might be some occasions that not considering the weights or experts opinions would end up to some misleading decisions. Consequently, WFAM gives the managers and decision makers more precise insights about what is really going on regarding the sustainability issues.

In this research activity, a validated methodology was proposed in order to be used as a road map for manufacturers to move toward manufacturing more sustainable products. Consequently, it was illustrated that how a simple product sustainability improvement can contribute toward achieving sustainable manufacturing. For future work, a hybrid methodology could be proposed in order to assess the sustainability level of both manufacturing process and manufactured product with covering the supply chain stages of the whole system.

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