International Conference on Mechanical and Industrial Engineering
ICMIE2022
November 15-17, 2022 Tripoli-Libya

Integration of Environmental Quality Function Deployment into CAD Software for Impact Assessment

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Abstract

Due to the increase in the negative impact of products on the environment, and the rapid quantitative and technological development of products over the last decades, designers and manufacturers have become more concerned about environmental issues. This paper presents a novel methodology to fulfill eco-design requirements through the integration of environmental quality function deployment (EQFD) into computer-aided design (CAD) software at the early design stage. The main goal of this research is to reduce environmental impacts such as raw material consumption, energy consumption, air and water pollution, and material financial impact. The developed methodology consists of several steps, firstly, the EQFD translates the voice of the environment (VoE) into engineering metrics, then the metrics are correlated into product components through correlation matrices to identify the metrics and components that have a high effect on the environment. Secondly, the identified components are assessed from an environmental point of view. The environmental assessment is accomplished through a comparison of different alternative (scenarios) materials to capture the most environmentally friendly one. Life cycle assessment (LCA) method is used to fulfill this purpose through the use of CAD sustainability software (SolidWorks) to assess the environmental impacts of a product. The assessment process was accomplished by calculating the environmental impacts which are: carbon dioxide (CO2), energy consumption rate, air and water pollution rates, and the material financial impact. The refrigerator was selected as a case study for the demonstration of this research methodology. The results of the assessment show that Polypropylene (PP) is the most environmentally friendly material according to the compared ones

Keywords: Design for environment, life cycle assessment, environmental impact, computer-aided design, sustainability

I. INTRODUCTION

The consumption of natural resources and global warming problems are critical issues for manufacturers, developers and designers. In the USA, greenhouse gas emissions have grown by 4% in 2020, the industry sector comes in the third rank after energy supply and transportation [1]. Therefore, designers and manufacturers are required to decrease the environmental impacts caused by their products. To serve this purpose, environmental impacts such as energy consumption, gas emissions and raw material consumption must be taken into consideration at the early design stages, through the all life cycle stages. Eco-design aims to the achievement of these goals. Eco-design means a product with minimal or zeroes environmental impacts, less consumption of natural resources, minimization of production waste and reduction of emissions [2]. "Nearly 80% of the environmental impacts on products can be improved through the eco-design method" [3].

This paper focuses on the integration of environmental requirements into developed design. It is based on the identification and assessment factors that have the most design effects on the environment during the entire life cycle stages of design, from the materials extraction stage, usage stage, manufacturing processes, and transportation, to the end of life stage (disposal or recycling). The analysis carried out during the design stage allows for any required modifications to be made without economic consequences or time waste. Quality function deployment (QFD) is a suitable tool used to identify the most design factors that affect seriously the environment. It is one of quality tools that have been introduced to help designers and developers to translate customers' requirements into engineering metrics to satisfy their wishes [4]. QFD was introduced in Japan in the 1960s by Yogi Akao, and then it was used by Toyota Company as a strategy to discover customers' requirements at the early design stage. QFD became widely used and adopted by most American and European manufacturers in the early 1980s [5].

In the last decades, several analytical tools have been presented to assess the impacts of products' life cycle from cradle to grave [6]. Life cycle assessment (LCA) method provides designers with details and analyses about the environmental impacts at each product's life cycle stage. It is used to measure, assess and report details about raw materials, energy consumption, gas emissions and cost impacts [7]. Designers and developers need direct and quick information to be available and synchronized with the design process. Computer-aided design (CAD) system has become the most important tool in the traditional design process, it helps engineers to design a product that meets the geometrical, functional and structural customer's requirements [8], new versions of CAD systems are supported by integrating LCA tools within the traditional flow of product design activities. This integration is not only for easy and directly assessing the environmental impacts of a design, but also it comes up with reliable results and provides better alternatives. SolidWorks software has been used in this research and it is one of the CAD systems that is supported with LCA (GaBi software) to be a sustainable design tool used to perform an environmental assessment. The research contribution in this paper is to incorporate the EQFD outcomes into CAD software to simplify the environmental impact assessment. Yet, this approach has not been done in the research of eco-design.

II. LITERATURE REVIEW

In eco-design, many terms express environmentally friendly design such as ecological design, environmental design, design for environment, green design, sustainable design, and life cycle design [9]. The term eco-design is used in this paper. Eco-design has been defined by various researchers from different views. For example, Sakao [2], described the eco-design as a product assessed by reducing the environmental impacts throughout its life cycle stages by integrating environmental requirements into design activities. ISO 2002 [9], defines eco-design as activities that are integrated into a product to fulfill continual improvement for the environmental performance of the product throughout its all life cycle stages. Fiksel [10], commented, eco-design is a product that meets specified environmental performance criteria. In summary, eco-design means using materials, manufacturing products and recyclable materials with minimum impacts. Several methods and tools are presented and recommended, ISO/TR-14062 [2] presents about 30 various tools. The usage of these tools is based on different techniques and considerations according to the side that the researcher focused on, for instance, Alemam and Li [11] focus on design's functions through the identification of responsible functions that cause environmental impacts by correlating environmental impacts with product functions, then investigate possible solutions to improve the components that perform these functions.

Many proposed methodologies related to the eco-design topic represent an environmental extension of a traditional tool, it is a version of the quality function deployment (QFD). Environmental quality function deployment (EQFD) is used to capture the requirements of the environment to be transformed into design development. In the early design stage, product data is not available, therefore it is not easy to assess the environmental impacts on the complete life cycle of a product. Recently, the CAD system for eco-design has been identified in the literature. Most of the cases that support academic researchers have used SolidWorks which provides detailed assessments and safer alternatives of material, manufacturing processes, transportation and location for eco-design [12].

The extension of QFD has been expressed in many ways, for example, Sako [2] termed it during his research "Quality Function Deployment for Environment" (QFDE). Eco-QFD term is found in the research of Vinodh et al. [13]. In the research of Lee and Park [9], the expression was "Environmental Quality Function Deployment" (EQFD). The term "Integrated Green and Quality Function Deployment (IGQFD)" was presented by Cagno and Trucco [14]. While in the research of Fargnoli and Kimura [15], the extension for environmental requirements was expressed in "Green Quality Function Deployment" (G-QFD). For the integration of customer requirements as well as environmental requirements, Abele et al. [16] dealt with the integration of new and different requirements into the traditional QFD method using the expression "Life Cycle QFD" (LCQFD). This study focuses on environmental issues, thus, the EQFD expression is used in this research. Life cycle assessment (LCA) is a full view of environmental effects that covers most of the design activities by identifying and quantifying the consumption rate of energy, material usage and quantity of emissions that are released to the environment [17]. According to Romli et al. [18], the LCA method is considered the most important method to monitor the environmental impacts of designs currently available. There are different software versions of LCA that are available on the market in the form of computer programs such as SimaPro, Open LCA, Umberto and GaBi [19]. The assessment process is carried out through the measurement of four important environmental measures; air acidification, carbon footprint, total energy consumed; and water eutrophication. Measuring these impacts will help to obtain a better design for environment.

III. METHODOLOGY

The methodology of this paper is based on integrating the EQFD tool into CAD systems. The major goal of the integration is to improve products by decreasing harmful impacts such as gas emissions, energy consumption, and natural resources consumption. Figure 1 shows the procedure of the proposed eco-design methodology that is presented in this paper. Four steps of eco-design process are proposed as follows:

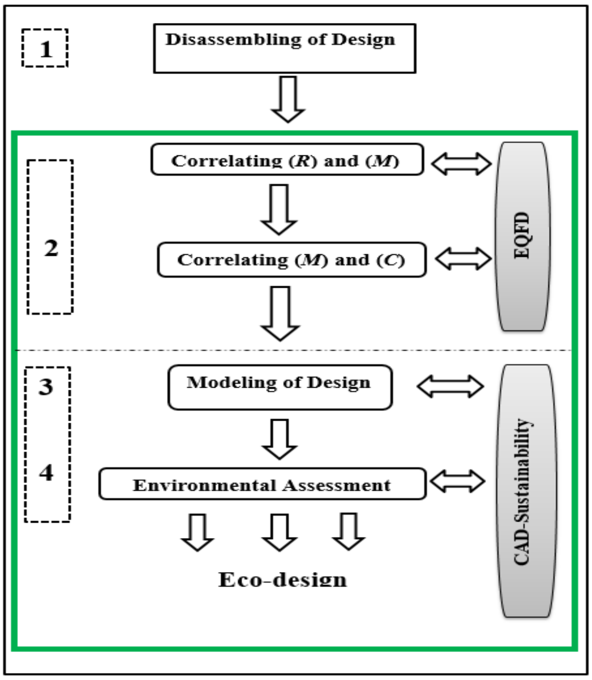

Fig. 1. Procedure of the proposed methodology

Step 1: Disassembling the selected product

The selected product will be disassembled to know the technical principles, product mechanism, structure and physical components to simplify the analysis and assessment of the selected product. Accordingly, the bill of material (BOM) list of the product's parts can be accomplished.

Step 2: Building the EQFD1 and EQFD2

After the environmental requirements (R) are recognized and converted to corresponding specific engineering metrics (M), as well as the components (C) of the selected product are identified, the EQFD can be established. As a result, engineers can identify where the improvement of eco-design can be done. The EQFD in this methodology consists of two phases EQFD1 and EQFD2.

Step 3: Modeling of design

Via SolidWorks system, each component of the selected product will be modeled according to the components 'dimensions. In this step, the components of the product have been shown on the disassembled case. At this step, data related to the environment can be selected from Gabi software to all required components.

Step 4: Assessing the material of the components environmentally

Via sustainable SolidWorks, the original material of the selected product will be assessed and compared to other candidates' materials, which are regularly used in manufacturing products.

IV. METHODICAL APPLICATION TO THE REFRIGERATOR

A. Introduction to the Case Example: Refrigerator

In this study, the existing product that is chosen as a case study to demonstrate the proposed methodology is a refrigerator. The reasons for choosing this product are: it is a common product for domestic use, and widely used globally. Almost it is available in every home, thus, this product is responsible for the great demand for residential electricity. Moreover, it makes relatively high energy consumption, so if there is an improvement, even in an insignificant amount, it will save large amounts of energy around the world. Furthermore, it consists of several components, which means any improvements that can be achieved, will reflect significant values that contribute to reducing the negative impacts on the environment.

B. Disassembling the Refrigerator

To establish the bill of material (BOM) list, the refrigerator is disassembled and torn out. The BOM contains the components of the refrigerator and their used materials, as shown in Table 1.

TABLE 1. BILL OF MATERIAL OF THE REFRIGERATOR

Item	Name of part	Material
1	External frame	Stainless steel AISI 304
2	Doors	Stainless steel AISI304
3	Inner frame	Plastic ABS
4	Pipes	Copper
5	Compressor	Steel
6	Condenser	Cast iron
7	Coils	Copper
8	Handles	Polycarbonate
9	Shelves	Metal coated in PVC
10	Egg trays	PVC
11	Insulators	Polyurethanes foam
12	Fan	Stainless steel AISI304
13	Base	Stainless steel AISI304
14	Gas	R 134a

C. Constructing the EQFD

The requirements of customers and environment $Rs = \{r_1, r_2 \ldots rn\}$ have been written in the customer language through varied resources and different ways such as visiting home appliance markets and workshops as well through manufacturer websites, scientific papers, and textbooks. Each customer requirement is given weight according to its level of importance. The levels are identified into five levels: very important (=5), important (=4), relative important (=3), less important (=2), and not important (=1). The identified requirements will be converted to engineering metrics $Ms = \{ m_1, m_2 \ldots mn\}$ then engineering metrics will be correlated to product components $C = \{ c_1, c_2, \ldots, cn\}$. Table 2 shows the list of the requirements, metrics and components.

TABLE 2. LIST OF REQUIREMENTS, METRICS AND COMPONENTS

Requirements	Metrics	Components
r_1:Less energy	m_1:Energy (J)	c_1:Compressor
r_2:Harmless	m_2:Cooling (c)	c_2:Shelves
r_3:Freezing a long time	m_3:Gas flow type	c_3:Doors
r_4:Freezing quickly	m_4:Cost (DL)	c_4:Freezing control
r_5:Less cost	m_5:Dimensions (mm)	c_5:Light lamps
r_6:Long life	m_6:Weight (kg)	c_6:Frame
r_7:Multi volume	m_7:Shelves number	c_7:Insulators
r_8:Easy to smash	m_8:Lifespan (year)	c_8:Pipes
r_9:High durability	m_9:Noise (dip)	c_9:Fan
r_{10}:Easy to clean	m_{10}:Materials type	c_{10}:Base
r_{11}:No vibration	m_{11}:CO2 (kg)	
r_{12}:Easy to transport		
r_{13}:Less material usage		
r_{14}:Easy to recycle		
r_{15}:No ice		
r_{16}:Easy disassemble		
r_{17}:Easy assemble		
r_{18}.Easy disposal		
r_{19}:Multi-color		

1. Building EQFD1

The identified requirements will be converted to engineering metrics $Ms = \{ m_1, m_2 \ldots mn\}$, the EQFD1 is built to correlate the qualitative requirements with quantitative measurable metrics in the *RM* matrix, as shown in Figure 2. Then calculate the relative weight of each metric to show the metrics that have the greatest relation to the environment. The correlation metrics have four levels of correlation strengths: strong (=9), medium (=3), and weak (=1), no relation (blank). Through the *RM* matrix, the relative weight of each metric (*Wmi*) is calculated using equations (1), (2), and (3). The row score of each metric (*Smi*) is calculated by summing up all the multiplied importance weights of requirements by correlation strengths between requirements and metrics.

$$Smi \sum_{j=1}^{n} (Ij.Cij) \quad (1)$$

Then, the relative weight of each metric (*Wmi*) is calculated as follows:

$$Wmi \; = (Smi/\sum_{i=1}^{n} Sm) \times 100 \quad (2)$$

$$\sum_{i}^{n} Wm = 100 \quad (3)$$

EQFD 1	Metrics (M)											
Requirements (R)	**Customer Importance**	m_1	m_2	m_3	m_4	m_5	m_6	m_7	m_8	m_9	m_{10}	m_{11}
r_1	5	9	9	3	9	9	3	3	9	1	9	9
r_2	5	9	3	9	9	3	1	1	9	1	9	9
r_3	5	9	9	9	3	3	1	1	3	1	9	3
r_4	5	9	9	9	3	3	1	3	3	3	3	9
r_5	4	9	3	3	9	9	3	3	9	3	9	1
r_6	4	9	3	3	3	3	9	3	9	9	9	3
r_7	4	3			9	9	3	3		1	1	9
r_8	3	9			1	3	3	3			9	9
r_9	4		3	3	9				9	9	9	
r_{10}	3		3		3	9	3	3	9		3	
r_{11}	4	9	3	1	1	1	1	3	3	9	3	
r_{12}	3	9				9	9	3	3		3	9
r_{13}	3				3	9	3	9			9	9
r_{14}	3	9			1	1	1	3	1		9	9
r_{15}	4	1	3	9	3	1			9			
r_{16}	3	3			3	3	1	3			3	1
r_{17}	3	9			3	3	3	3			9	3
r_{18}	2					3	1	3	1		9	9
r_{19}	2				3						3	3
Score		421	219	226	304	299	165	175	317	154	433	346
Relative weight %		13.8	7.2	7.4	9.9	9.8	5.4	5.7	10.4	5.0	14.2	11.3
Rank		2	8	7	5	6	10	9	4	11	1	3

Fig. 2. EQFD 1

Where, the (Smi) is a score of each metric, (Ij) is the importance weights of each requirement, (Cij) is the correlation strength between each requirement and the metric, and Wmi is the relative weight of each metric.

Via *RM* matrix, the results of the calculations show the metrics that make more impact on the environment. Below is an example of how to calculate the relative weight of each metric (Wm):

Sm_1=5×9+5×9+5×9+5×9+4×9+4×9+4×3+3×9+4×0+3×0 +4×9+3×9+3×0+3×9+4×1+3×3+3×9+2×0+2×0 = 421.

In this same way, the rest of the metric scores were calculated. Through equation 3, the calculation of the relative weight of m_1 is:

$Wm_1 = m_1 / (m_1 + m_2 / m_{11}) = (421/3059) \times 100 = 13.8\%$.

The results of EQFD1 show that type of material (m_{10}), energy consumption (m_1), and carbon dioxide (CO_2) (m_{11}) are the most important metrics that make an effect on the environment and needed to be improved.

2. Building EQFD2

After the relative weights of engineering metrics are calculated through EQFD1. EQFD2 is built by correlating the components of the refrigerator $C = \{c_1, c_2 \ldots cn\}$ with the metrics, as shown in Figure 3. Through the identified components of the chosen product $C = \{c_1, c_2, \ldots, cn\}$, and the calculated relative weight of each metric, the *CM* matrix is built to correlate metrics (M) with components (C), the correlation strengths depend on the effect of each metric to the components. The correlation is rated on a scale consisting of 1, 3, and 9 similar to the steps which have been achieved with the *RM* matrix. The relative weight of each component will be calculated through the following equations. The row score of each component (Sci) is:

$$Sci = \sum_{J=1}^{n} (Wmj \times cij) \quad (4)$$

Then, the relative weight of each metric (Wm_i) is calculated as follows:

$$Wci = (Sci / \sum_{Si=1}^{n} Sc) \times 100 \quad (5)$$

$$\sum_{i}^{n} Wc = 100 \quad (6)$$

Where the (Sci) is the score of each component, (Wci) is the relative weight of each component, (Cij) is the correlation score between each metric and the components. The results of the calculations show the components that have the most effects on the environment, as shown in Figure 3. The components c_1, c_3 and c_6 come with high relative weight values. It means these components have the most effect on the environment; thus they became the focus of eco-design improvement.

EQFD 2		Components (*C*)									
Metrics (*M*)	Relative weight	c_1	c_2	c_3	c_4	c_5	c_6	c_7	C_8	c_9	c_{10}
m_1	13.8	9	1	9	9	1	9	9	3	1	
m_2	7.2	9	1	3	9		3	9	9	1	
m_3	7.4	9		3	3		1	3	3		
m_4	9.9	9	3	9	3	1	9	9	1	1	3
m_5	9.8	9	9	9	1	1	9	3	3		9
m_6	5.4	3	1	9			9	1	1	1	9
m_7	5.7	3	9	9	3	1	9	3	1		1
m_8	10.4	9	1	3	3		3	9	3	9	9
m_9	5.0	9	3	1	3		3	1		9	3
m_{10}	14.2	3	1	9	1		9	9	3		3
m_{11}	11.3	9	1	9	9	1	9	9	1	1	3
Score		748.4	247	710	430	51	706	679	263	186	357
Relative weight %		17.1	5.7	16.2	9.8	1.2	16.1	15.5	6.0	4.2	8.2
Rank		1	8	2	5	10	3	4	7	9	6

Fig. 3. EQFD 2

3. Discussing the Results of EQFD1 and EQFD2

The results of EQFD1 show the type of material (m_{10}) as the most engineering metric related strongly to the environment. Thus, it will be the focus of the improvement to meet the environmental requirements through the selection of alternative material that has less environmental impact. Also, the results of EQFD2 identified the components that have the most effect on the environment, they were the compressor (c_1), doors (c_3) and outer frame (c_6). These components will be analyzed and assessed in terms of the type of material via SolidWorks software, which is supported by the LCA tool. The compressor as a part of the refrigerator will not be assessed because it is a complex part that contains different materials. Thus, engineers can focus more on its electrical power. This criterion can be considered to select the compressor as an environmentally friendly product. In addition, the components that have the most effect on the environment will be assessed to support the decision-makers about where to improve.

D. *Development of A CAD Model for Impact Assessment*

1. Geometrizing and Modeling the Refrigerator

Using SolidWorks software, components of the refrigerator are modeled and disassembled to conduct the analysis and assessment of the components. The parts of the refrigerator are shown in Figure 4.

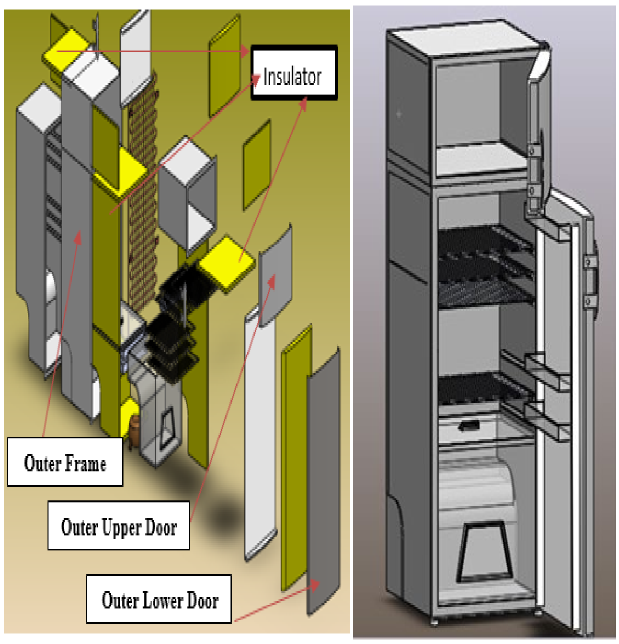

Fig. 4. Exploded view of the refrigerator

2. Assessment of the Refrigerator's Component

According to the results of EQFD1 that shown the type of material is related strongly to the environment. Besides, the results of EQFD 2 identified that the doors and outer frame were the most components that affect strongly the environment. The material of the upper door has been chosen to be assessed environmentally using SolidWorks sustainability. The type of material that is used to make this part of the refrigerator is AISI 304 with a sheet metal process (Rolling). Through SolidWorks sustainability, the component is assessed for its all life cycle stages. The assessment process was done through five main menus: material menu, manufacturing processes menu, transportation menu (train, truck, boat, or plane), and end of life menu, in addition to manufacturing and use stage locations. Figure 5 shows the environmental assessment sustainability report of AISI 304 material which includes the results of the assessment process. Each pie chart consists of four key impacts, carbon footprint (CO2), total energy consumption, air acidification (SO2), and water eutrophication (PO4), which resulted in key parameters that are, material type, manufacturing process, use, and end of life stages. At the bottom of each chart, the total amount of individual impacts are presented. Furthermore, the material financial impact is at the bottom of the graph. The results of the assessment process are shown in Figure 5.

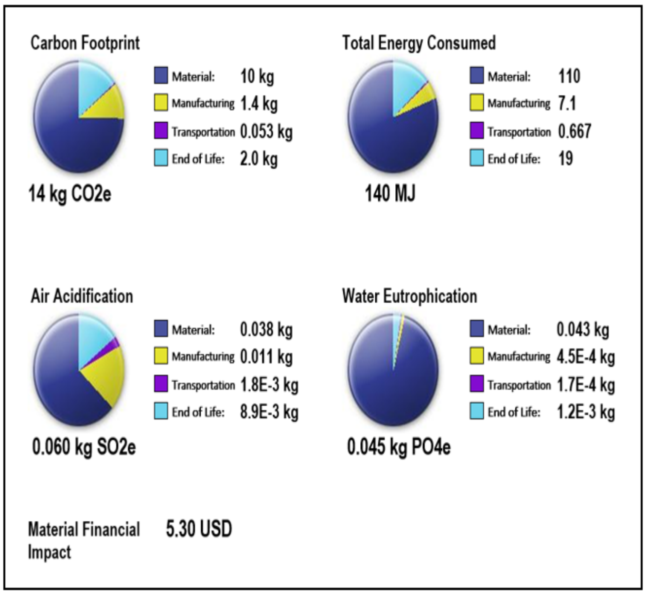

Fig. 5. Sustainability report for environmental impacts of AISI304

3. Environmental Impact Assessment of Benchmarking

The only way to assess whether the material of the components is more sustainable or not is required to be assessed with other different materials. Hence, the impact assessment of the original material will be compared with other materials. In the assessment, the original material AISI304 is compared with another four materials, galvanized steel, aluminum, ABS plastic and Polypropylene (PP) to choose the safer material that contributes to reducing the environmental impacts. In this research, they were presented as different scenarios (alternatives).

Scenario 1. Galvanized Steel

The results of the environmental impacts, carbon footprint, energy consumption, air and water pollution after using galvanized steel, processed by sheet metal process are summarized in Figure 6. Also, five parameters were considered (material, manufacturing, usage, transportation and end of life) in the assessment. The results show that galvanized steel overall achieved fewer environmental impacts compared to the original material (stainless steel AISI304). The improvement was in a 42% reduction in carbon footprint, a 36% decline in total energy consumption, a 50% fall in air acidification, and a 94% drop in water eutrophication.

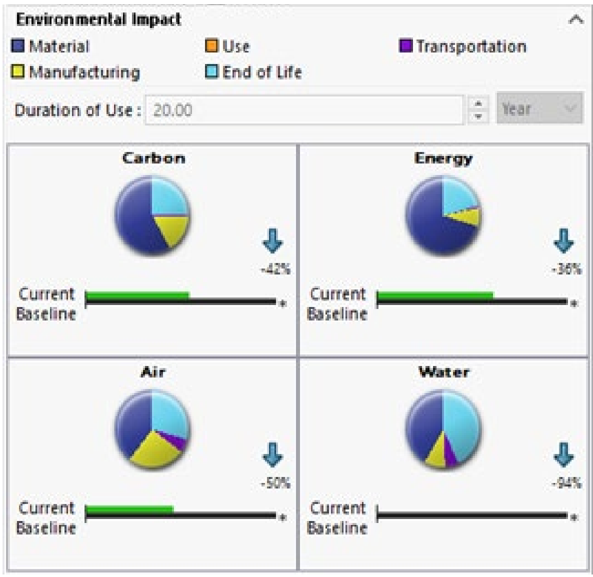

Fig. 6. Environmental impacts of galvanized steel compared to AISI 304

Scenario 2. Aluminum Material

The results of the assessment after using aluminum compared to the AISI304 stainless steel are shown in Figure 7. The results indicate that aluminum as non-metallic material achieved relative reductions in carbon emissions, energy consumption and water eutrophication. It shows that relative improvements were realized as the carbon footprint was reduced to 19%, and the total energy consumed was reduced to 8%. However, water eutrophication significantly improved by 94 %. On the other hand, air acidification increased by 31%. Further, financial impact improved by 70%.

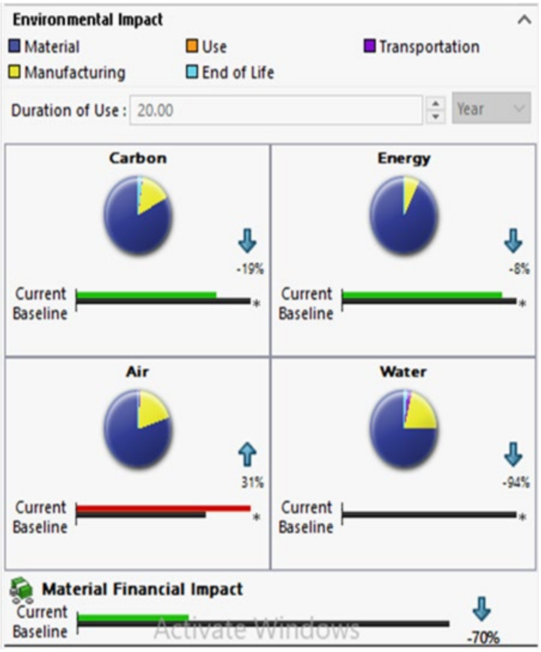

Fig.7. Environmental impacts of aluminum compared to AISI304

Scenario 3. ABS Plastic

Figure 8 shows the environmental assessment of the ABS plastic, manufactured by extrusion molded process. It achieved a significant reduction in the overall environmental impacts compared to the original material (stainless steel AISI304), where the five indicators point out that the highest improvements were on carbon footprint. It was improved by 62%, total energy consumed improved by 40%, water eutrophication improved by 95%, and air acidification went down to 60%. Also, the financial impact indicator improved by 53%.

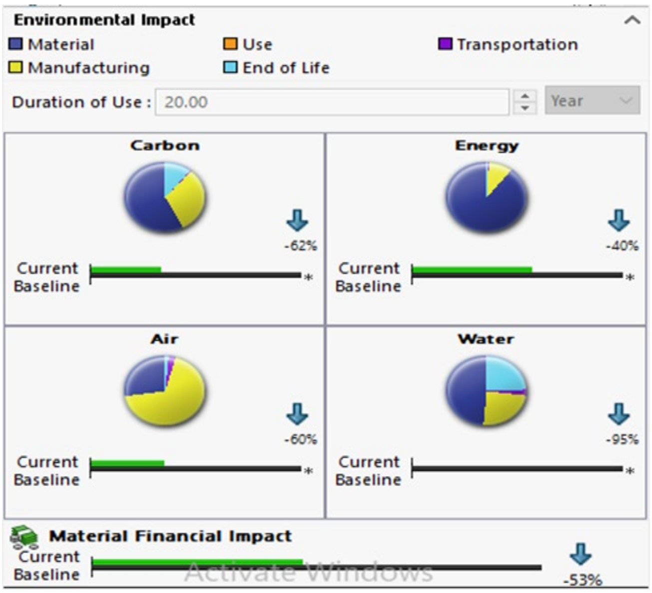

Fig. 8. Environmental impacts of ABS plastic compared to AISI304

Scenario 4. Polypropylene Polymer (PP)

Polypropylene (PP) as a polymer with the extrusion process achieves reductions in overall environmental issues compared to the AISI304. Figure 9 shows that carbon footprint reduced to 70%, total energy consumption reduced to 46%, air acidification reduced by 66%, water eutrophication went down to 97%, and the material finical impact indicator displays considerable improvement, it was improved by 62%. PP is a suitable material for manufacturing products and demonstrates it is a more environmentally friendly material [20].

Table 3 shows the comparative results of the original material stainless steel (AISI304) and the material PP.

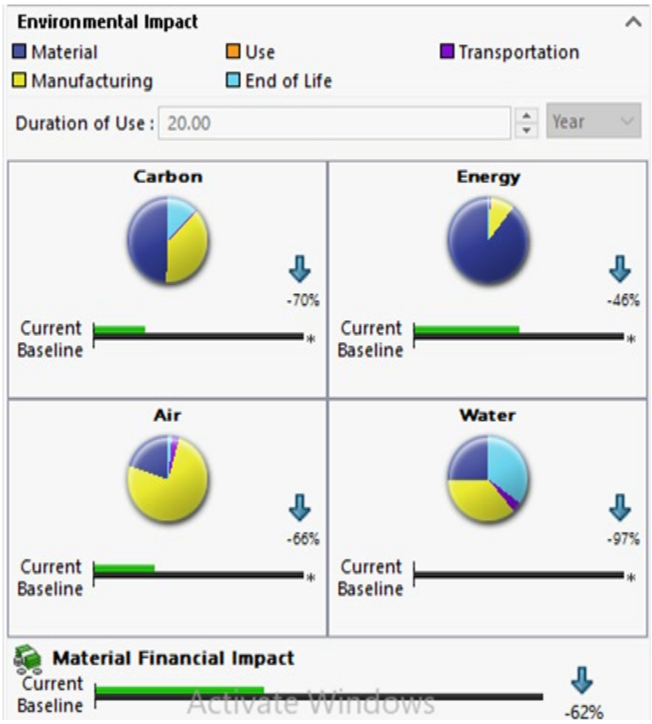

Fig. 9. Environmental impacts of PP polymer compared to AISI304

4. Applying the Assessment on the Lower Door and External Frame

The previous assessment demonstrated that Polypropylene (PP) achieved significant results compared to the original material (AISI304). The application was on the upper door of the refrigerator. Thus, this material is applied to two major components of the refrigerator, the lower door and external frame to demonstrate the applicability of Polypropylene. Tables 4 and 5 show the results of the assessment that are obtained by the SolidWorks software. Likewise, the results of the assessment demonstrate that the PP is better for the environment compared to the (AISI304) material.

TABLE 3. COMPARISON RESULTS FOR UPPER DOOR COMPONENT

Upper door	**AISI304**	**PP**	**Reduced values**	**Relative Reduction**
	Sheet metal	**Extrusion**		
Weight (G)	2198.88	773.55	1425.33	64.82%
Natural Gas Consumption (BTU/Lbs)	1400	410	990	70.71%
Carbon Footprint CO2 (kg)	14	4.2	9.8	70.00%
Total Energy Consumed (MJ)	140	73	67	47.86%
Air Acidification SO2 (kg)	0.06	0.021	0.039	65.00%
Water Eutrophication PO4 (kg)	0.045	$1.5*10^{-3}$	0.0435	96.67%
Material Financial Impact (USD)	5.3	2	3.3	62.26%

TABLE 4. COMPARISON RESULTS FOR LOWER DOOR COMPONENT

Lower door	**AISI304**	**PP**	**Reduced values**	**Relative Reduction**
	Sheet metal	**Extrusion**		
Weight (G)	7146.36	2514.04	4632.32	64.82 %
Natural Gas Consumption (BTU/Lbs)	1400	410	990	70.71%
Carbon Footprint CO2 (kg)	42	11	31	73.81%
Total Energy Consumed (MJ)	440	240	200	45.45%
Air Acidification SO2 (kg)	0.176	0.048	0.128	72.73%
Water Eutrophication PO4 (kg)	0.146	$4.4*10^{-3}$	0.1416	96.99%
Material Financial Impact (USD)	17.20	6.7	4632.32	64.82%

TABLE 5. COMPARISON RESULTS FOR OUTER FRAME COMPONENT

Outer frame	**AISI304**	**PP**	**Reduced values**	**Relative Reduction**
	Sheet metal	**Extrusion**		
Weight (G)	6.3*104	14706.11	$4.83*10^{4}$	76.7%
Natural Gas Consumption (BTU/Lbs)	1400	410	$9.90*10^{2}$	70.7%
Carbon Footprint CO2 (kg)	8500	1300	$7.20*10^{3}$	84.7%
Total Energy Consumed (MJ)	$8.8*10^{4}$	$2.8*10^{4}$	$6.0*10^{4}$	68.2%
Air Acidification SO2 (kg)	35	5.7	$2.93*10^{1}$	83.7%
Water Eutrophication PO4 (kg)	26	0.525	$2.55*10^{1}$	98%
Material Financial Impact (USD)	3051.50	778.20	$2.27*10^{3}$	74.5%

V. DISCUSSION

Through EQFD1, the metrics that have a direct relationship to the environment are realized. The type of material has come with the first rank. Also, the results of EQFD2 show that the compressor of the refrigerator has priority for the assessment, and as it is a complex part containing several materials, it is difficult to assess this part environmentally. The doors took the second rank and the outer frame took the third rank for the priority of improvement. According to the results of the assessment, it is clear that Polypropylene (PP) which has been used for the assessment process for the refrigerator components, upper door, lower door, and outer frame is the safest material for the environment, which it is achieved a significant improvement compared to the original material (AISI304). Therefore, the obtained results can make reductions in the environmental impacts and motivate decision-makers to use Polypropylene (PP) for manufacturing products.

VI. CONCLUSION

The primary idea of this article is to discover an ideal direction of how to improve existing products in view of the environment. This paper presents a new method for eco-design that focuses on the integration of EQFD into CAD software to reduce the negative impacts on the environment. The assessment of the environmental impacts comprised energy consumption, gas emissions, air acidification, water eutrophication, and material financial impact for the entire life cycle stages of a product. LCA was used to conduct the assessment through CAD sustainability software.

The methodology of this paper proved the ability to support engineers to evaluate and improve existing products. A refrigerator was selected as a case study to demonstrate the applicability of the methodology. The used material for the existing refrigerator is stainless steel (AISI304), which is considered an original material in this research. It was compared in the assessment to other materials, galvanized steel, aluminum, ABS, and Polypropylene (PP). Among the evaluated materials, the results show that Polypropylene (PP) is a better material for the environment.

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