ISSN 0511-5728
The West Indian Journal of Engineering
Vol.41, No.2, January 2019, pp.77-83

Redesign of a Furniture Industry Component: A Sustainable Design Approach

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(Received 05 October 2018; Revised 07 January 2019; Accepted 18 January 2019)

Abstract: *Sustainability has been a recent trend in the manufacturing industry, owing to environmental concerns. Product designers are now looking at effective approaches for sustainable product design. Design for X (DFX) tools and techniques have widely been used over the years to streamline the design and manufacture processes. Design for environment (DFE) is becoming of critical use in the preliminary phases of the product design process in order to render cost-effective and environmentally friendly products. This can be enhanced by deploying computer-aided design and engineering (CAD/CAE) tools which have the ability to manipulate the product concepts in a virtual environment. The efficacy of this approach is demonstrated through a case study involving the redesign of a component selected from the local Caribbean market. The SolidWorks package was used to generate CAD models which were further analysed by using the Simulation and Sustainability modules. The guidelines of Design for Manufacture and Assembly (DFMA) and DFE were also utilised in the redesign. The research shows that DFX tools and techniques, namely CAD/CAE and DFE, can be combined in a single platform to effectively redesign products to meet functional and environmental requirements.*

Keywords: *DFX tools, product redesign, product sustainability, case study*

1. Introduction

Manufacturing organizations are showing increased interest in sustainability due to the environmental concerns, namely global warming and resource depletion, which arose in the last few decades. Sustainable design is a comprehensive, holistic approach for creating products and systems that are gentle on the environment, socially equitable and economically viable (Vinodh 2010). It is defined as a design approach which strives to increase quality while reducing or eliminating negative environmental impact (McLennan 2004). Sustainable product design considers both functional characteristics and environmental impact at the product design stage (Hosseinpour et al. 2015). Several external pressures, including environmental interest groups and environmental laws and regulations, demand that companies provide more sustainable products with minimal material usage, minimal energy consumption, and without producing hazardous wastes. Becoming environment-friendly also provides several internal incentives to companies, including improvement of product quality, reduction in costs, management of risks and the acquisition of an eco-friendly social image (Alblas et al. 2014).

Product designers are in need of methods and tools that accelerate and streamline sustainable design. Design for X (DFX) is a generic term describing product design approaches where X denotes manufacture, assembly, environment, disassembly, recyclability, life-cycle, and maintainability (Kuo et al., 2001). DFX tools range from broad guidelines to specific software tools. Many case studies have reported the benefits achieved by utilizing DFX approaches (Huang and Mak, 1998). In this context, the paper presents a product redesign case study to ensure the sustainable design of a component currently used in the assembly of a computer keyboard shelf by a Caribbean computer furniture fabricator.

The main focus of the paper is to demonstrate a case study in which product sustainability is realised using integrated DFX tools, specifically computer-aided design and engineering (CAD/CAE) tools and DFE principles. The product redesign exercise starts with CAD modelling of the selected component followed by a sustainability analysis in the four prominent spheres of environmental impact namely, carbon footprint, water eutrophication, air/water acidification and total consumed energy in the selected component’s material sourcing, manufacturing, use and end of life. The environmental impact of the selected component is assessed using the Sustainability module of the SolidWorks package. Moreover, engineering analysis using the Simulation module of the SolidWorks package enabled the assessment of the structural integrity of the design. The results facilitated the redesign of the component in an iterative manner. Furthermore, the component modelling and computer-aided engineering (CAE) analysis were conducted on the same CAD platform, which further facilitated an improvement in assembly efficiency.

2. Literature Review

The literature has been reviewed from the perspective of sustainable design and integration of DFX tools and approaches. Checklists, quality function deployment (QFD) and life cycle assessment (LCA) methods have widely been used to limit the environmental impact of products during the design stage (Hosseinpour et al., 2015). Checklists are easy to implement at the early stages of the product design process but are impractical in providing design details (Hosseinpour et al. 2015). The effectiveness of QFD based tools relies greatly on the experience and knowledge of designers (Masui et al., 2003). Moreover, LCA tools are difficult to use in the early design stages if details of the final product are unknown (Yang et al., 2012).

Current efforts at sustainable product design focus on integrating eco-design tools. Hosseinpour et al. (2015) proposed a benchmark based method for sustainable product design. The method integrates QFD, benchmarking, and LCA to conduct the evaluation of the environmental impact of the product. A CAD/CAE simulation methodology was also used to determine the parameters of the benchmark products and finite element analysis (FEA) was performed to validate the design parameters. Vinodh and Rathod (2014) presented an integrated technical and economic model to evaluate the reusability of products or components using LCA methodology and Monte Carlo simulation technique. The authors showed that the developed model was capable of assessing the reusability of products and the use of simulation reduced uncertainties in input data and parameters and increased the effectiveness of the model. Soft computing and artificial intelligence approaches are also being explored for sustainable product design. Mutingi et al. (2017) proposed a fuzzy grouping genetic algorithm (FGGA) approach to evaluate modular designs in terms of sustainability parameters, namely design fitness, cost fitness, and green fitness.

It has been noted by several researchers that engineering analysis in a CAD environment facilitated eco-friendly product redesign (Wu et al., 2007; Vinodh, 2010). In addition, sustainable product design using CAD facilitated the organisation to achieve business benefits such as reduced cost and time which would, in turn, improve profitability (Vinodh, 2010). Russo (2011) stated that CAD platforms are ideal for sustainable design because product assemblies are already organised and the information on materials, manufacturing processes, and mass-properties is easy to integrate. Further, the study proposed an integrated approach for sustainable product design linking CAD, FEA, and LCA tools. Vinodh and Rajanayagam (2010) proposed an integrated approach using a CAD-based sustainability analysis and Design for Manufacture (DFM) guidelines to implement a sustainability concept at the early stages of product design with minimal environmental impact.

The theory of DFE has proven successful in the development of eco-friendly products as well as reducing environmental impact. DFE aids in sustainable product development which states that resources must be used in such a manner so as to ensure their availability for future generations (Giudice et al., 2006). Moreover, application of DFE guidelines in product design process can improve product life cycle by reducing the overall cost as well as the impact of manufacturing and disposal on the environment (Chowdary and Gittens, 2008). Noteworthy DFE guidelines to enhance the product sustainability include having multifunctional parts, use of the same material for neighbouring parts, and easily located high-value parts ensuring the ability of the product to be recyclable at the end of its life cycle (Fiksel, 1996).

A large number of case studies and research articles on DFX applications have been published over the years. Huang and Mak (1998) reported that multiple DFX tools should be used to attain overall optimum solutions. In this regard, the author developed a DFX shell to serve as a generic platform for the integration of DFX tools. Holt and Barnes (2010) suggested the integration of DFX tools as an enabler of concurrent engineering. The authors also revealed that although DFX techniques are popular, they are used discretely in the product design phases as opposed to concurrently. Chowdary and Harris (2009) deployed DFMA and DFE principles in conjunction with market research, product research and QFD to drive reductions in overall product costs by decreasing part numbers and assembly time. Chowdary and Kanchan (2013) suggested the use of DFE guidelines and CAD/CAE tools as enablers for integration in product design and development. The efficacy of the proposed methodology was validated through a case study using a desktop organizer selected from the Caribbean market. Computer-aided design (CAD) and DFE integration was also used by Chowdary and Phillips (2014) in the development of a tennis ball retriever concept to demonstrate the agility in the design of new products.

Moreover, Chowdary (2014) proposed an approach where computer aided design and engineering (CAD/CAE) and design for environment (DFE) integration were combined with a fuzzy QFD tool to prioritise product sustainability. Suresh et al. (2015) integrated DFE and DFMA for the sustainable development of a component from the automotive industry. Vinodh (2010) used CAD and CAE analysis to determine the sustainability and environmental impact of an existing product as measured in terms of parameters such as carbon footprint, energy consumption, water eutrophication and air acidification. Moreover, the study concluded that the conduct of the sustainability analysis in a CAD environment enabled the re-design of the existing product making it more eco-friendly. Both Vinodh (2010) and Suresh et al. (2015) suggested that for future research, the sustainability methodologies be performed for different organisations across different sectors in several countries to augment and strengthen the practical applications. Product sustainability is currently not a widespread practice in the Caribbean region, but the recent onset of environmental troubles and exhaustion of natural resources has uncovered the need for sustainable product design. This can be accomplished through implementation of DFX tools at the early stages of the product design process.

From the literature review, it can be seen that although many researchers integrated eco-friendly product design approaches and DFX tools, the concurrent application of DFX tools to optimise the redesign of products in CAD environment has not been thoroughly investigated. The use of DFX tools has also not been implemented in the Caribbean industry so this present case study will supplement the past and future research in this direction.

3. Research Methodology

Figure 1 depicts the logic flow methodology of the study. It starts with the literature review on DFX tools and sustainable product design. Step 2 starts with the selection of the local firm and identification of a product for investigation. In step 3, the generation of the CAD/CAE model of the bracket is performed using the SolidWorks package. Then in step 4, within the SolidWorks environment, the sustainability analysis of the bracket is conducted to assess the environmental impact. Based on the sustainability results, the redesign of the bracket is accomplished in step 5. Moreover, in order to support the bracket redesign process, CAE model results are taken into consideration. Furthermore, to prove the merits of the selected bracket redesign, the sustainability analysis is again conducted to assess the environmental impact in step 6. Lastly, the study inferences are reported in step 7.

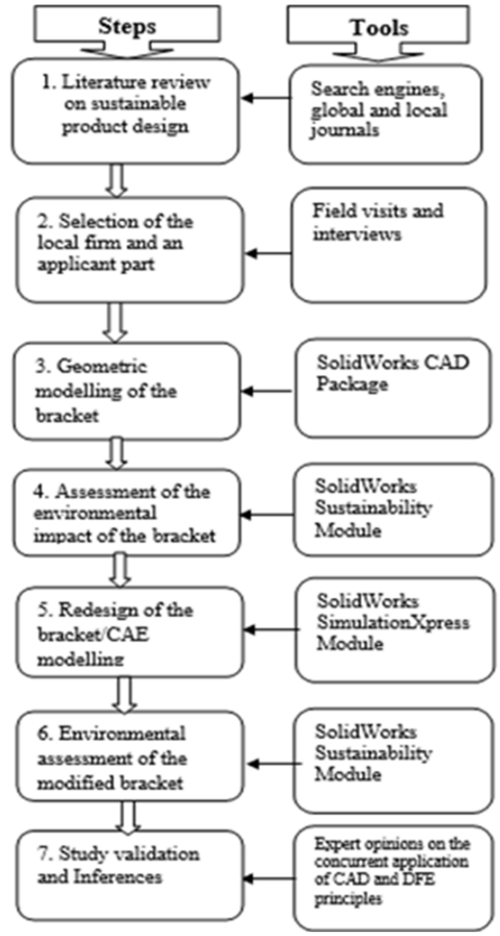

Figure 1. Research Methodology

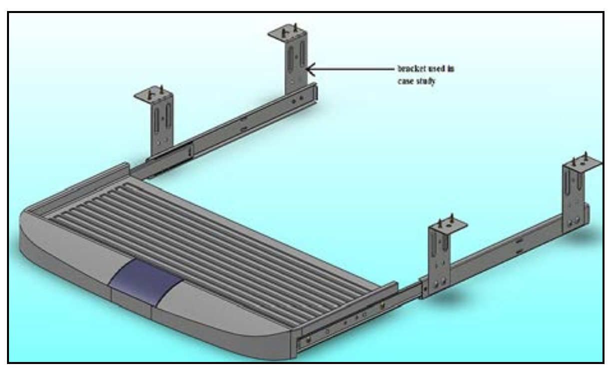

Figure 2. Keyboard shelf assembly showing the brackets to be redesigned in the case study

4. Case Study

4.1 Case Component and Background

A bracket from a keyboard shelf assembly supplied by a local manufacturing company is selected as the case component. The location of the bracket is shown in Figure 2.

4.2 CAD/CAE Modelling of Existing Bracket

The bracket of the computer shelf was modelled using the SolidWorks package and is shown in Figure 3. Then, the CAE model was created using the SolidWorks Simulation module to simulate the performance of key product components under practical loading conditions and constraints, permitting the assessment of the stress, displacement and factor of safety distributions for such parts. Basic design criteria used for the redesign of the bracket are as follows:

- No stress developed under the loading conditions must exceed the yield point for the material. Surpassing the yield point of the material will result in unwanted plastic deformation of the part.

- Displacement should be kept to a minimum under loading conditions. The lower the displacement of the part, the sturdier the design and the less flexing the assembly will experience under load.
- A factor of safety (FOS) of 1.0 indicates that the material has just begun to exhibit plastic deformation. As a result, the minimum factor of safety should have a value that is greater than 1.0. Higher FOS is always favourable.

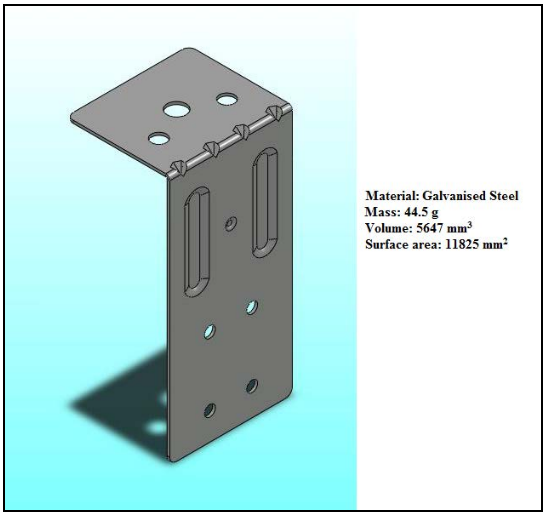

Figure 3. 3D CAD model of the bracket

A review of available desktop computer keyboards indicated that a typical keyboard has a mass less than 1 kilogram (kg). The keyboard shelf selected for this case study was however rated at a maximum capacity of 6.80 kgs. In light of this, the CAE analysis was conducted to simulate the worst-case loading conditions on the brackets with the slides of the shelf assembly fully extended and supporting a uniformly distributed load of 6.80 kgs at the location of the keyboard tray. The simulation also accounted for the masses of the various components of the assembly that were directly supported by the four (4) brackets. Though time-consuming, the finest mesh settings were applied when analysing the virtual model of the assembly to provide the most accurate CAE results.

The results of the initial CAE analysis are shown in Figure 4. It was revealed that the forward brackets are placed under more stress than the aft brackets during the applied worst-case loading scenario. Taking this into consideration, the stress, displacement and minimum FOS results obtained for a single forward bracket would be used to provide comparisons between the alternative bracket designs.

4.3 Sustainability Analysis of Existing Bracket Design

The SolidWorks Sustainability module was used to assess the environmental impact of the selected bracket. The material has been selected as galvanised steel. The surface area, volume and mass are computed. The manufacturing process has been specified as progressive die stamping. Figure 5 shows the results of the sustainability analysis. The four examined parameters include carbon footprint, water eutrophication, air acidification and total energy consumed, as defined by Vinodh (2010).

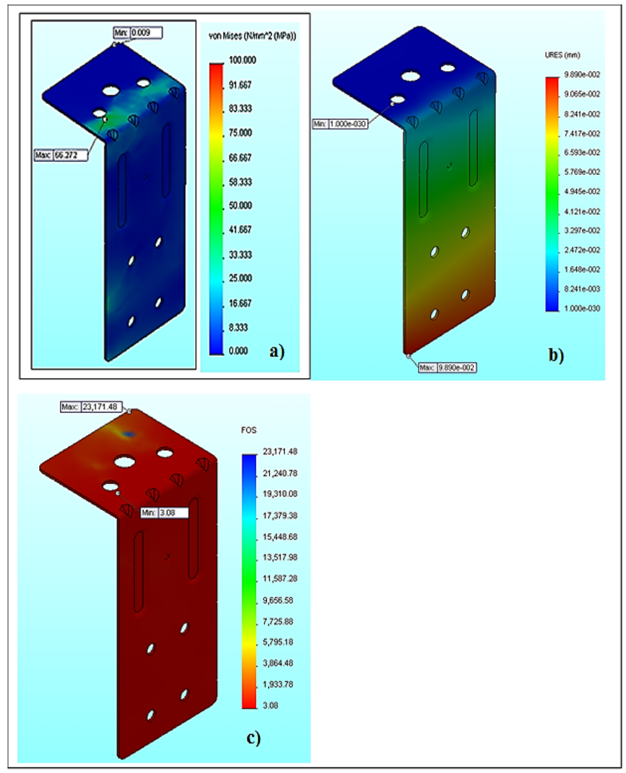

Figure 4. FEA analysis of the existing bracket a) Stress b) Displacement c) Factor of Safety

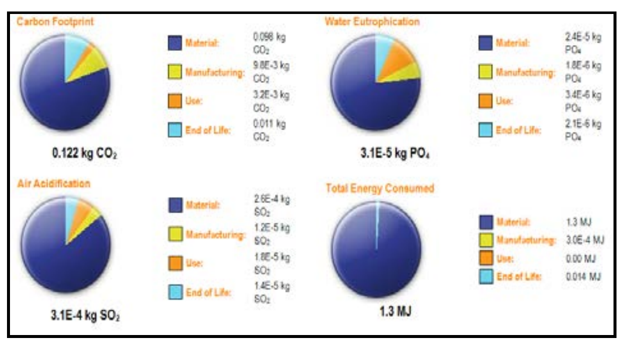

Figure 5. Sustainability analysis results for existing keyboard shelf bracket

4.4 Bracket redesign

In order to improve the design sustainability and assembly efficiency of the bracket in the keyboard assembly, an alternative component design was proposed based on the simulation results. An alternative design was developed with the intent to strike a balance between part performance and environmental impact. The material selected for the redesign was galvanised steel of 2 mm thickness. The bracket width was reduced to 15 mm to lower component volume and mass and reduce the environmental impact of the design. The final dimensions of the bracket are 92mm x 38mm x 15mm. Moreover, after discussing with the managers of the case study unit, the product structure guidelines (Giudice et al., 2006) and ease of assembly and disassembly guidelines (Boothroyd et al.,2002; Giudice et al., 2006) were also followed while designing the alternative bracket. The 3D CAD model of the alternative bracket design can be seen in Figure 6. The results of the CAE and sustainability analysis conducted on this alternative design are shown in Figures 7 and 8.

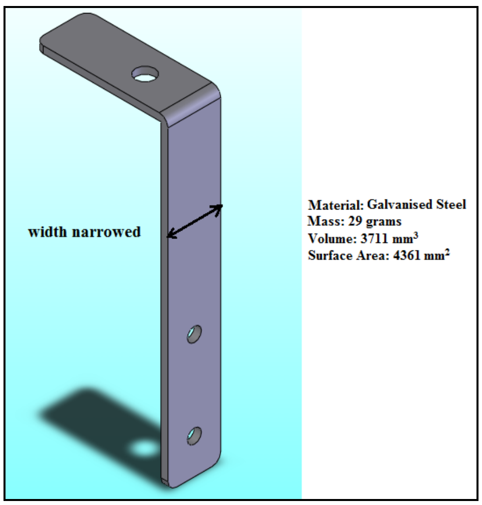

Figure 6. 3D CAD model of the redesigned bracket

5. Results and Implications

5.1 Development/Deployment of Guidelines

In the present case study, DFX tools were integrated to achieve the sustainable redesign of a furniture component. CAD/CAE tools enabled the testing of the design in a virtual environment which facilitated the redesign of the component making it more sustainable. This involved CAE analysis in the SolidWorks Simulation module to ensure design integrity and sustainability analysis in the SolidWorks Sustainability module to ensure the design exhibits minimum environmental impact.

Several guidelines were applied to the deployment of the research methodology. These are as follows:

a) DFE Guidelines

- Waste source reduction: The mass of the bracket was reduced in the alternative design which may limit the waste generated per unit of production.

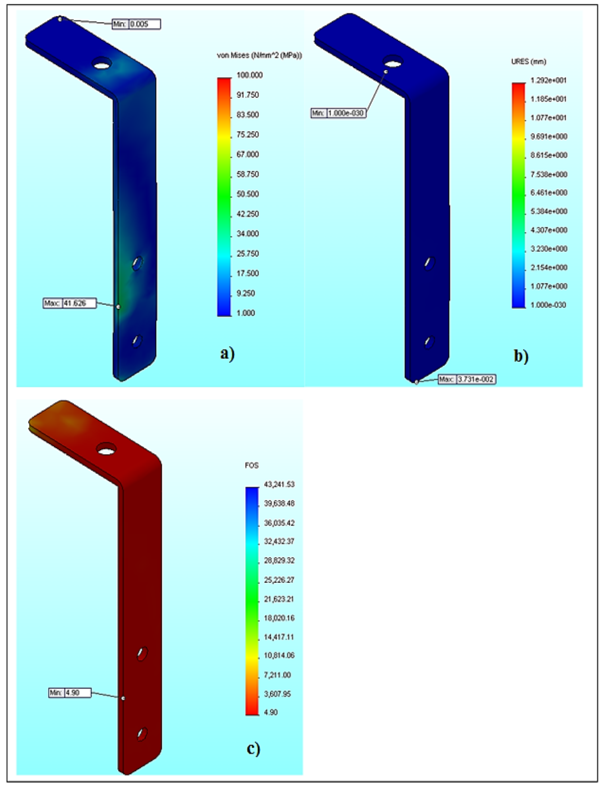

Figure 7. FEA analysis of the redesigned bracket a) Stress b) Displacement c) Factor of Safety

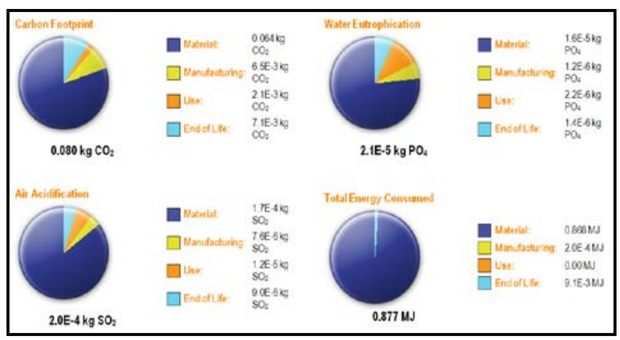

Figure 8. Sustainability analysis results for redesigned bracket

- Toxic substance reduction: No toxic substances used in the alternative design.
- Energy use reduction: The total energy consumed to produce, transport, store, maintain, use, recycle and dispose of the bracket was reduced by 33%.
- Design for disassembly: Number of fasteners reduced by 50% which may facilitate material recovery at product end-of-life.
- Design for recyclability: The material used is recyclable.
- Design for remanufacture: Less stamped features are present in the alternative design to minimise manufacturing costs.

b) Product Structure Guidelines

- Minimise the number of parts: The alternative bracket design uses a single self-threading screw for attachment to the desktop and a single fine thread screw for attachment to the outer slides.
- Design for parts orientation and handling: Alternative bracket design is symmetrical, has no hidden features, no sharp edges and can be easily oriented for assembly.
- Design for ease of fabrication: Less stamped features are present in the alternative design to minimise manufacturing costs.

c) Fastener Guidelines

- Minimise the number of fasteners: Number of fasteners reduced in the alternative bracket design by the adoption of single attachment points.
- Eliminate adhesives unless compatible with both parts joined: No adhesive used.

d) Ease of Assembly and Disassembly Guidelines

- Simplify the design and reduce the number of parts: Number of fasteners reduced from 4 to 2 and the design is simplified by reducing the number of stamped features.
- Design for disassembly: The slightly decreased material thickness ensures that the self-threading and fine thread screws will have to be manually driven through fewer rotations in order to secure this bracket to the rest of the assembly.

5.2 Analysis of results

Design improvements were revealed through comparison of the alternative design results to the original model as highlighted in Table 1. From these results, it is clear that ample improvements were made to the redesigned product. Moreover, parametric refinement of the virtual prototypes through CAD/CAE and DFE served to strengthen the design and boost its sustainability.

Substantial improvement in environmental impact was displayed by the alternative design. Approximate reductions of 51%, 50%, 51% and 52% were observed for the metrics of carbon footprint, water eutrophication, air acidification and total energy consumed respectively. Moreover, the performance metrics of maximum stress, maximum displacement and a minimum factor of safety were significantly superior to those obtained for the original benchmark investigation. An approximate increase of 45% was observed for maximum developed stress. Maximum displacement increased by 37% with a minimum factor of safety declining by approximately 29% to a value of 4.9. These results highlight an improvement in the part performance at the reduced environmental impact.

Based on the case study, it can be deduced that the integration of DFX tools (specifically CAD, CAE and DFE) enables the sustainable development of keyboard shelf bracket.

Table 1. Comparison of results of the baseline and the proposed alternative design model

	Parameter	Benchmark	Final Design Iteration	Improvement (%)
General	Material	Galv. Steel	Galv. Steel	n/a
	Surface Area (mm^2)	11825	4361	63%
	Volume (mm^3)	5647	3711	34%
	Mass (g)	44.5	29	35%
Environmental	Carbon Footprint (kg CO_2)	1.22×10^{-1}	0.80×10^{-1}	34%
	Water Eutrophication (kg PO_4)	3.13×10^{-5}	2.08×10^{-5}	34%
	Air Acidification (kg SO_2)	3.04×10^{-4}	1.99×10^{-4}	35%
	Total Energy Consumed (MJ)	131.43×10^{-2}	87.73×10^{-2}	33%
Performance	Maximum Stress (MPa)	66	42	36%
	Maximum Displacement (mm)	9.9×10^{-2}	3.7×10^{-2}	63%
	Minimum Factor of Safety	3.1	4.9	58%

5.3 Industrial Implications

The presented method enables the assessment of the environmental impact of a product at the design stage. The case study was conducted to ensure sustainable product design by the concurrent application of DFX tools using CAD/CAE and DFE. The study has also addressed the three sustainability requirements of environmental, social and economic feasibility. In comparison with other integrated methods presently available, this integrated sustainable approach can aid product designers in finding effective solutions to create environmentally friendly products quickly, using widely available tools and without spending much time in accessing product lifecycle data.

6. Conclusions

A case study involving a systematic procedure to enable the re-design of an existing product assembly was documented. The approach endorses the joint application of DFX tools, namely CAD/CAE and DFE, to optimise assembly efficiency, lower manufacturing costs, improve component performance and reduce environmental impact on several levels. The method was successfully applied to the redesign of a bracket selected from a typical keyboard shelf assembly. The results of the case study indicate that the redesigned bracket possess minimal environmental impact and superior structural performance. To bolster the findings, the method should be applied to redesign a greater sample of product assemblies. Assemblies with higher degrees of complexity, either having larger part numbers and/or components with more intricate features, should be studied thus creating the opportunity for more widespread deployment of the proposed procedure.

Overall, it can be stated that CAD/CAE and DFE are powerful DFX tools when applied on their own. The concurrent use of these philosophies and techniques, however, makes it possible for manufacturers to comprehensively optimise their designs for the complex demands of the present market.

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