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Integrating DFMA and Sustainability Assessment for Mini-Fan Redesign: A Comparative Case Study

M. F. Rosli[1]*, M. S. M. Effendi[1], M. L. Abd Latif[1], M. K. Asmawi[1] and Suhaimi Shahrin[1]

[1]Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), Kampus Tetap Pauh Putra, 02600 Arau, Perlis, Malaysia.

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ABSTRACT

The environmental performance of small consumer products can be improved when manufacturability and life-cycle considerations are incorporated before detailed design is fixed. This study integrates Design for Manufacturing and Assembly (DFMA) principles with a screening-level, CAD-based sustainability assessment to compare a baseline mini-fan with a redesigned alternative. The baseline assembly was modelled in SolidWorks 2020, and the main housing, battery casing, and base were modified through geometric simplification and material-volume reduction. Both alternatives were evaluated using identical manufacturing processes and regional settings. The redesign reduced product mass from 99.00 to 88.88 g (10.22%). The software outputs also indicated reductions of 67.16% in carbon footprint, 66.94% in water eutrophication, 67.37% in air acidification, and 67.16% in total energy consumption. The findings demonstrate the value of combining DFMA-informed geometry review with rapid environmental screening to compare alternatives before tooling and prototype production. However, the results are comparative rather than a complete life-cycle assessment because the archived dataset does not report the material database version, transport assumptions, use-phase profile, end-of-life scenario, or uncertainty analysis. The redesign supports resource-efficient product development and contributes to SDG 9 and SDG 12.

Keywords: Computer-aided sustainability assessment, Design for manufacturing and assembly, Mini-fan, Product redesign, Sustainable product development.

1. INTRODUCTION

Sustainable product development now requires environmental criteria to be treated as design inputs rather than post-design checks. Recent circular-economy research emphasises that product architecture, material choice, manufacturing route, use characteristics, and end-of-life options are interdependent; consequently, decisions made during concept development can lock in both resource demand and environmental burden [1]. Product-concept metrics likewise show that material, production, use, and end-of-life performance should be assessed before detailed geometry and tooling commitments restrict redesign opportunities [2].

Recent ecodesign reviews report a shift from isolated environmental checklists towards integrated methods that combine product-development activities, life-cycle information, quantitative indicators, and organisational decision processes [3]. Early-stage tools are especially valuable when they translate complex sustainability requirements into criteria that designers can compare across alternatives; examples include the Sustainability Fingerprint and structured management practices for sustainable product development [4, 5]. Contemporary Design for

*Corresponding author: farizuan@unimap.edu.my

Excellence literature further positions environmental performance, circularity, manufacturability, quality, and cost as interacting design objectives rather than separate optimisation tasks [6].

Design for Manufacturing and Assembly (DFMA) provides a practical engineering basis for addressing part geometry, material use, process suitability, handling, insertion, and assembly complexity. Recent reviews confirm that DFMA remains most effective when applied early, although many reported applications still focus on relatively simple mechanical products and rely on incomplete or case-specific metrics [7, 8]. Studies integrating DFMA with sustainability show that redesign can reduce part count, cost, assembly effort, material consumption, and selected environmental indicators, but the magnitude and direction of improvement depend on the product architecture and assessment boundary [9, 10].

Environmental assessment during iterative design presents a complementary challenge. Parametric life-cycle assessment (LCA) methods can link changing design variables to environmental outputs and enable faster optimisation than a conventional one-off assessment [11]. Recent eco-design methodologies similarly advocate adaptable databases and software interfaces so that designers can obtain quantitative feedback while materials and processes are still being revised [12]. Nevertheless, life-cycle decision support remains sensitive to system boundaries, data quality, uncertainty, and the risk of simplifying complex trade-offs into a single preferred alternative [13]. Systematic reviews of LCA in circular design therefore recommend transparent assumptions, sensitivity analysis, and a clear distinction between screening studies and complete life-cycle assessments [14].

Circular product design extends environmental assessment beyond impact reduction to the preservation of product and material value. Computational frameworks demonstrate that higher circularity does not automatically guarantee a lower overall environmental burden because alternative recovery pathways can introduce trade-offs across the value chain [15]. Product-level indicator reviews also show substantial variation in definitions, calculation boundaries, and data requirements, which limits direct comparison between circularity scores [16]. Consequently, redesign decisions should combine quantitative environmental indicators with explicit consideration of durability, repair, disassembly, reuse, remanufacturing, and recycling.

Recent research has organised these considerations into product-development strategies and maturity models. Circular product design studies identify multiple-use cycles, design for repair and disassembly, material compatibility, and life-extension strategies as important additions to conventional ecodesign [17]. Maturity-based approaches help organisations determine whether such practices are systematically embedded across the stages of new-product development [18], while implementation studies emphasise the need to align circular objectives with stakeholder roles, information flows, and decision gates [19]. Multi-hierarchical frameworks and DfX-based methods further connect circular objectives with design strategies across product life-cycle phases [20, 21].

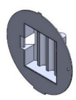
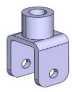
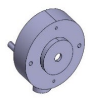
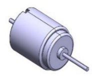
Against this background, small consumer-product case studies remain useful because they expose how early geometric changes affect material use and software-generated environmental indicators under controlled assumptions. Recent redesign frameworks advocate structured comparison between baseline and alternative concepts [22], while comprehensive analyses of sustainable product design factors stress the combined importance of technical, environmental, economic, and organisational criteria [23]. Current eco-design scholarship also calls for practical, repeatable workflows that link circular-economy principles to everyday engineering decisions [24]. The present study therefore, compares a baseline mini-fan with a redesigned alternative in which the main housing, battery casing, and base were modified. Performance is evaluated using product mass and four SolidWorks Sustainability outputs: carbon footprint, water eutrophication, air acidification, and total energy consumed. The study addresses SDG 12 through resource-efficient redesign and SDG 9 through computer-aided product innovation.

2. MATERIAL AND METHODS

2.1 Case Study and Baseline CAD Model

The case study used a small tabletop mini-fan, represented as a complete three-dimensional assembly in SolidWorks 2020. The baseline model comprised ten listed components: the main housing, base, rear cover, front cover, blade, battery cover, battery casing, top connector or neck, housing case, and motor. Table 1 presents the component breakdown used to identify redesign opportunities. The analysis was conducted at the assembly level to assess changes to individual parts in the context of the complete product.

Table 1: Baseline mini-fan component breakdown.

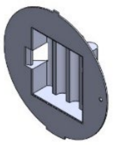
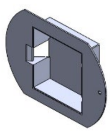
				
Housing	Base	Rear cover	Front cover	Blade
				
Battery cover	Battery casing	Top connector (neck)	Housing case	Motor

2.2 DFMA-Oriented Redesign Procedure

The baseline assembly was examined using recent DFMA guidance, with attention to non-functional material, unnecessary geometric complexity, process compatibility, and the ease with which features could be manufactured and assembled [7, 8]. Three components were selected because the archived design study identified them as major contributors to material use and because their geometry could be modified without changing the motor, blade, front cover, rear cover, or intended product layout. The selected components were the base, main housing, and battery casing.

The redesign removed external bulk, simplified local features, and retained the interfaces required for assembly. These interventions are consistent with integrated DFMA-sustainability studies in which geometry and assembly decisions are evaluated together with material and environmental outcomes [9, 10]. Table 2 summarises the design changes, and Figure 1 compares the complete assemblies. The available dataset did not contain measured handling time, insertion time, assembly cost, tooling cost, or a standard DFA index. The DFMA outcome was therefore assessed qualitatively from the documented design interventions and quantitatively from product mass and sustainability indicators; no claim of part-count reduction is made.

Table 2: Components selected for redesign.

Baseline part	Redesigned part	Design intervention
		Base: reduced external bulk while retaining the support and neck interface.
		Main housing: reduced material volume and introduced a more compact front geometry.
		Battery casing: simplified the frame geometry and enlarged the central opening.

(a) (b)

Figure 1: Complete mini-fan assemblies: (a) baseline design and (b) redesigned alternative.

2.3 Sustainability Assessment and Comparison Method

The environmental comparison was conducted with the SolidWorks Sustainability module. The baseline and redesigned assemblies were evaluated using the same archived settings: injection moulding as the manufacturing process and China as the manufacturing region. Five outputs were recorded: product weight, carbon footprint, water eutrophication, air acidification, and total energy consumed. Maintaining an identical comparison basis is important in rapid eco-design because changes in material, process, geography, transport, and end-of-life assumptions can alter the modelled result independently of geometry [11-14].

For each indicator, the percentage reduction was calculated from the baseline value and the redesigned value using Equation (1).

$$R_i = [(X_{i,b} - X_{i,r}) / X_{i,b}] \times 100 \quad (1)$$

where R_i is the reduction for indicator i, $X_{i,b}$ is the baseline value, and $X_{i,r}$ is the redesigned value. The analysis is a deterministic comparison of two CAD alternatives; no replicate simulation, uncertainty distribution, or inferential statistical test was available. Consistent with current LCAoriented design guidance [12-14], the results are interpreted as screening-level evidence for relative comparison rather than as a complete product footprint.

3. RESULTS AND DISCUSSION

3.1 Design Outcome

The redesign produced visible geometric changes in all three targeted components. The new base has a smaller external footprint and a more compact support form. The main housing is shorter and has a more open front geometry, while the battery casing uses a simplified frame with a larger central opening. These changes preserve the overall product configuration and functional interfaces while removing material from regions not directly associated with the fan mechanism or protective function.

The archived records do not demonstrate a reduction in total part count. Accordingly, the main DFMA contribution is geometric simplification and material-volume reduction rather than part consolidation. This distinction is important because recent DFMA literature evaluates performance through a broader set of measures, including part count, handling and insertion time, process capability, assembly cost, and reliability [7, 8]. The present work should therefore be described as a DFMA-informed redesign supported by environmental screening, not as a complete quantitative DFA study.

3.2 Environmental-Impact Comparison

Table 3 summarises the comparison between the baseline and redesigned alternatives. Product mass decreased from 99.00 to 88.88 g, corresponding to an absolute reduction of 10.12 g or 10.22%. The software outputs also indicated lower environmental values for the redesigned model: carbon footprint decreased by 67.16%, water eutrophication by 66.94%, air acidification by 67.37%, and total energy consumption by 67.16%.

Table 3: Environmental-impact comparison between the baseline and redesigned mini-fan.

Indicator	Unit	Baseline	Redesigned	Absolute change	Reduction (%)
Weight	g	99.00	88.88	-10.12	10.22
Carbon footprint	kg CO_2	670	220	-450	67.16
Water eutrophication	kg PO_4	0.366	0.121	-0.245	66.94
Air acidification	kg SO_4	9.5	3.1	-6.4	67.37
Total energy consumed	MJ	6700	2200	-4500	67.16

Figure 2 presents the values after normalising each baseline indicator to 100%. The redesigned mass is 89.78% of the baseline value, whereas the four environmental outputs are 32.63-33.06% of their respective baseline values. Within the five reported indicators, the redesigned alternative therefore performs better than the baseline. This result does not establish the absence of broader trade-offs because performance, durability, assembly effort, user experience, and end-of-life behaviour were not included.

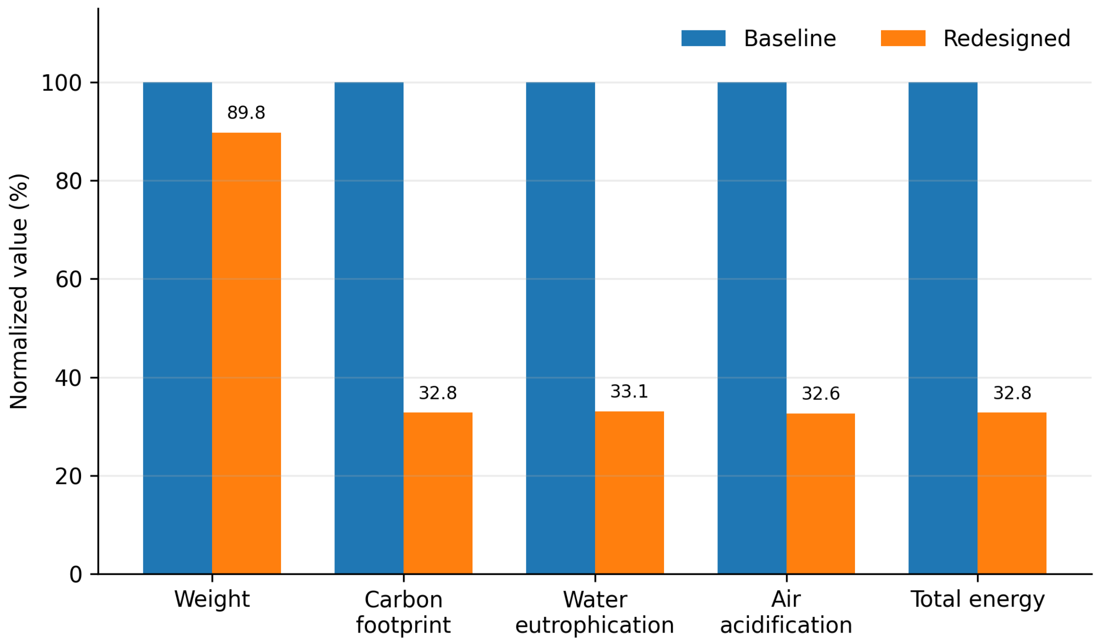


Figure 2: Normalized comparison of the baseline and redesigned alternatives, with each baseline indicator set to 100%.

3.3 Interpretation and Study Limitations

The findings support the use of early-stage redesign to identify material and environmental improvement opportunities before tooling and prototype production. They are consistent with recent DFMA-sustainability case studies [9, 10] and with eco-design frameworks that use rapid quantitative feedback to compare concepts during iterative development [11, 12, 22]. For a small consumer product, linking the CAD assembly to environmental screening provides a practical decision aid, particularly when physical prototypes and detailed supply-chain inventories are not yet available.

The modelled reductions in the four environmental indicators are much larger than the 10.22% reduction in mass. This indicates that the outputs reflect the combined effect of the software database and the assigned material, manufacturing, regional, transport, use-phase, and end-of-life parameters, rather than geometry alone. The archived dataset reports aggregate values but does not identify the exact material grade, database version, transport distances, use-phase profile, end-of-life allocation, or uncertainty range. Recent LCA and circular-design research identifies these assumptions as critical to interpretation [13-16]. Therefore, the percentage comparison is more defensible than treating the absolute values as a verified product footprint.

The study also did not measure assembly time, manufacturing cost, tooling complexity, airflow rate, acoustic performance, structural integrity, battery endurance, thermal behaviour, or durability. Future work should archive all SolidWorks input parameters, verify the reported units, conduct sensitivity analysis, calculate standard DFA and DFM metrics, and test a physical prototype. Circular-design criteria such as repairability, disassembly effort, component reuse, and end-of-life recovery should also be included [17-21, 23, 24]. These additions would determine whether the environmental gains are achieved without compromising functionality, safety, service life, or manufacturability.

4. CONCLUSION

A DFMA-informed redesign and CAD-based sustainability assessment were applied to a mini-fan. The base, main housing, and battery casing were modified to reduce geometric bulk and material volume while retaining the overall product arrangement. The redesigned assembly reduced mass from 99.00 to 88.88 g, equivalent to 10.22%. The SolidWorks outputs indicated reductions of 67.16% in carbon footprint, 66.94% in water eutrophication, 67.37% in air acidification, and 67.16% in total energy consumption. These results show that a structured combination of DFMA review and rapid environmental screening can support early comparison of product alternatives. The evidence is limited to the archived software outputs and does not constitute a complete LCA or quantitative DFA assessment. Verification of the software settings, unit scaling, uncertainty, product performance, assembly metrics, and prototype durability is required before production decisions are made. Subject to those checks, the redesigned alternative is the more resource-efficient option within the evaluated indicators and supports SDG 9 and SDG 12.

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