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Procedia CIRP 122 (2024) 115–120

www.elsevier.com/locate/procedia

31st CIRP Conference on Life Cycle Engineering (LCE 2024)

Enhancing life cycle assessment framework to support product ecodesign through index decomposition analysis

Amos Wei Lun Lee[a,b,]*, Yee Shee Tan[b], Jonathan Sze Choong Low[b]

[a]*National University of Singapore (NUS), 9 Engineering Drive 1, Singapore 117575, Republic of Singapore*
[b]*Advanced Remanufacturing and Technology Centre (ARTC), Agency for Science, Technology and Research (A*STAR), 3 Cleantech Loop, #01/01 CleanTech Two, Singapore 637143, Republic of Singapore*

* Corresponding author. *E-mail address:* amoslee@u.nus.edu

Abstract

In ecodesign, life cycle assessment (LCA) has not only been used to evaluate a product's environmental sustainability but also serves as a tool for designers to identify areas for sustainability improvement. Conventionally, this is achieved by ranking all contributing LCA variables to identify high-impact areas. However, interpreting and translating this information into actionable design variables can be challenging. An LCA variable can be influenced by multiple design variables, each of which might affect the design's environmental sustainability to varying degrees. Presently, there is a lack of tools capable of analysing the influence of each design variable. To bridge this gap, this study proposes an LCA disaggregation methodology that uses Index Decomposition Analysis (IDA) to assess the environmental sustainability significance of the considered design variables. Using the methodology, designers can make informed decisions that prioritise design effort on design variable with the greatest potential for enhancing the product's environmental sustainability. The proposed methodology is demonstrated through a case study involving the design of a desk fan cover, considering material choice, geometry, and manufacturing process as key design variables.

Keywords: Index decomposition analysis; Decomposition analysis; environmental sustainability; product ecodesign; Hotspot analysis

1. Introduction

Ecodesign describe the incorporation of environmental sustainability consideration in the design process [1]. When implemented in the design stage, it can have far-reaching implications for the entire product life cycle affecting up to 80% of a product's environmental impact [2, 3]. Recent years have seen an increase in interest to implement ecodesign in product design [4]. This can be attributed to the years of successful communication with consumers becoming increasingly aware of the contribution of their consumption decision has on climate change and are willing to pay more for sustainable options [5, 6]. Besides public demand for sustainable products, there has also been increasing pressure from governing bodies to reduce manufacturing emission to limit the rise in global temperature to 2°C in the year 2100 [7]. Driven by both government and public appetite for more sustainable product options, manufacturers are incentivised to invest in the redesigning of their products to be more sustainably made.

Designers can incorporate ecodesign into product design through a multitude of different approaches [8]. One of the most commonly used approach is to devise design strategy to lower the life-cycle greenhouse gas or life cycle emission base on the product's life cycle assessment (LCA) [9, 10]. In this approach, the LCA of the design will need to be conducted first. Subsequently, the LCA variables will be ranked in accordance with their contribution to the design's life-cycle emission. Top ranking variables that have significant contribution to the design's life cycle emission will then be identified and be branded as hotspots. From here designers can devise design

10.1016/j.procir.2024.01.016

solutions to improve the environmental sustainability of the products, typically, by targeting these hotspots.

With the aforementioned approach, one of the main challenges lies in the interpretation and translation of the identified hotspot to actionable design variables. For example, while the current approach might list the contribution of Material A as the top contributor of a design it does not provide additional information on the weight of the influence design variables such as geometry or material choice has on the design's sustainability across its life cycle. This information is important in guiding the optimal design strategy that can be taken as the contribution by each LCA variable can be influenced by multiple design variables and affect various stages of the design's life cycle. Currently, there is a lack of an analysis methodology that provides designers with such insights. Designers have to rely on their personal experience and domain expertise to interpretate and conceive design strategy from the identified hotspot.

To close the gap, this work proposes an LCA disaggregation methodology that uses Index Decomposition Analysis (IDA) to assess the environmental sustainability significance of the considered design variables. The main objective of the methodology is to provide designers with an additional layer of analysis that can be used to focus design effort on design variables that have the greatest potential in enhancing the product's environmental sustainability.

Section 2 describes the theoretical background of LCA and IDA. Section 3 describes the proposed LCA disaggregation method in detail. Sections 4 demonstrate a proof of concept on the viability of the methodology through a case study. Section 5 and 6 discuss the capability of the proposed methodology and conclude the paper respectively.

2. Theoretical Background

2.1. Life cycle assessment (LCA)

This subsection introduces features and parameters of LCA to facilitate the usage of the proposed methodology. As such further discussion related to the LCA framework will not be presented here; reader interested in a more comprehensive overview can refer to ISO14040:2006 [11] and ISO 14044:2006 [12]. According to ISO14040:2006, LCA involves the compilation and evaluation of a product system's inputs, outputs, and potential environmental impacts over its entire life cycle [11]. The life cycle of a product system consists of five stages: raw material extraction, production, distribution, usage, and the end-of-life (EoL).

The environmental impact of each resource flow in the product's life cycle is being represented by multiplying the activity data with its corresponding emission factor. The collection of the product's activity data and the emission factors is known as the life cycle inventory (LCI). In this work, the environmental impact of each resource flow will be referred to as an LCA variable. There are generally four different types of LCA variables (Figure 1). Table 1 provides examples of each type of LCA variables along with the constituent of the LCA variable.

In a LCA study the environmental sustainability contribution attributed to the production of resources (Material, water, energy) utilize in any stage of the product system's life cycle will falls under its raw material extraction stage [13, 14]. The environmental sustainability contribution of the remaining life cycle stages is made up of emission associated with the handling of waste that is produced from activities within the respective life cycle stage.

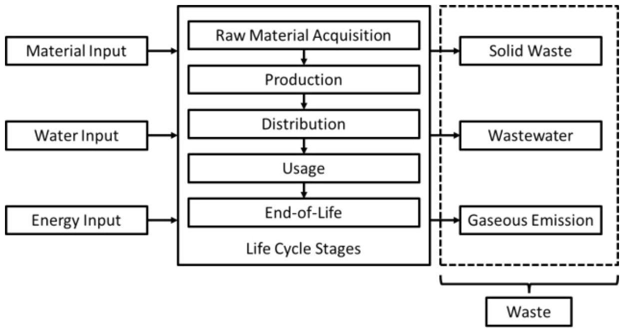

Figure 1 Resource flow in LCA

Table 1 Examples of LCA variables.

LCA Variable Type	Variable Constituents
Material	Activity data of the material input Emission factor of the production of material
Water	Activity data of the water input Emission factor of the production of water
Energy	Activity data of the energy input Emission factor of the production of energy source
Waste	Activity data of the waste produced Emission factor of the end-of life treatment of waste

2.2. Index decomposition analysis (IDA)

Developed in the 1980s, IDA is an analytical technique that was developed to analyse the electricity consumption trend of industry [15]. With the implementation of IDA, practitioners can find out the contribution by the overall activity level as well as the contribution from the activity mix and activity energy intensity of each industrial sector to the overall electricity consumption trend of the industry [15]. Since its initial introduction, researchers has extended the use of IDA to analyse consumption trend in other areas such as material, water, and non-energy resource requirements [15]. Besides consumption trend recent work has also seen IDA being applied to uncover the uncertainties in LCA results [16] and to analyse the carbon emission of buildings [17].

This work will be utilising the additive form of the logarithmic mean Divisia index (LMDI) method from the Divisia index to support the IDA. The chosen method uses an arithmetic mean weight function to express the arithmetic change of the aggregate indicator that is being decomposed [15, 18].

3. Proposed Methodology

The objective of the proposed LCA disaggregation methodology is to help designers analyse and identify design variables that should be prioritized to improve the environmental sustainability of current/existing design. The workflow of the proposed methodology is provided in Figure 2. To implement the methodology, the user would need to provide 2 different inputs. The first input is the LCI of the design. Next, the user would also be required to prepare the list of modifiable design variables that they would like to investigate. In the context of this work, design variables are not limited to the physical attribute of the product but also includes process variables that could influence the design of the product of interest. Examples of design variables include the product's chosen material, geometry, manufacturing process, and EoL processes. Despite the number of design variables that can be considered, designers should only identify design variables that they can influence. In this work the environmental sustainability of the designs will be quantified by the global-warming potential measure by the equivalent carbon dioxide (kg CO_2e).

3.1. LCA Decomposition

Following the proposed workflow for the LCA disaggregation methodology, the first step is to decompose the LCA of the design. In this process, users will define the emission constituents (EC) that influence the environmental sustainability contribution of the said LCA variables. While the variable constituents listed in Table 1 for each LCA variable can serve as a starting point for the user, there is opportunity to develop a more comprehensive list of EC depending on the design variables that is being considered. The main output from the LCA decomposition process is to generate a list of EC for each LCA variable that is being considered as describe by equation (1).

$$V^x = \prod_{z=1}^{n} Q_z^x = Q_1^x \cdot Q_2^x \cdot \ldots \cdot Q_n^x \quad (1)$$

V represents the emission factor of the LCA variable, x represents impact category that is being investigated, Q represent the input of the EC, n is the total number of variables in the LCA variable.

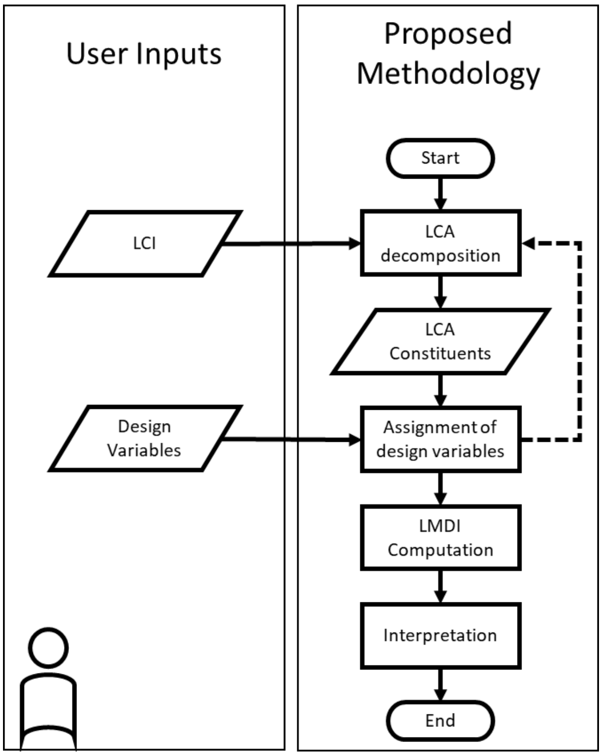

Figure 2 Proposed workflow for the LCA disaggregation methodology

3.2. Assignments of design variables

The second step in the proposed methodology is the assignment of design variables. In this process, users will identify and assign the design variable that assert the greatest influence for each of the identified EC. Each identified design variables need to be assigned to at least one EC to be included in subsequent analysis. It should be noted that not all EC has to be labelled. EC that are not influenced by any of the considered design variable can be left unassigned. At the end of the process equation (1) will transform into equation (2) where the subscript D will be used to represent the assigned design variables. D can take any value or name depending on the discretion of the user.

$$V^x = \prod_{z=1}^{n} Q_{z,D}^x \quad (2)$$

3.3. LMDI Computation

Subsequently, the influence of each design variable will be computed using the additive form of the LMDI method for each LCA variable. The additive form is selected as it presents the decomposition results in terms of the difference contributed by each variable [15]. This allows for the consolidation of the contribution by variables across different LCA variables that are assigned with the same design variable. The remainder of the sub-section will present the mathematical equations involved as well as the assumptions taken. Figure 3 provides an illustration of the input and output of the LMDI computation.

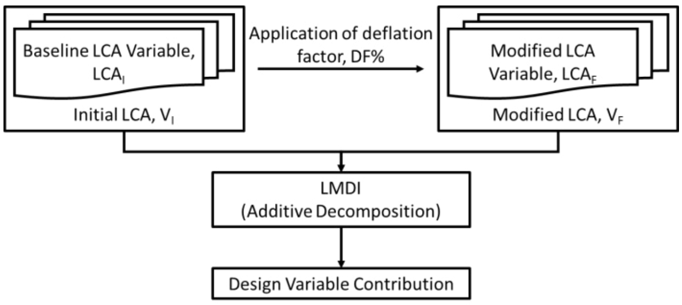

Figure 3 LMDI computation

To compute the LMDI, two sets of input will need to be provided. The first set of data will be the LCA of the design which will be referred to as the baseline LCA from here on out. The second set of data comes in the form of a modified LCA. The modified LCA represents the ideal state of the design with where the LCA of the design LCA is at its minimum. It is computed by applying a deflation factor (DF) to all EC that are assigned a design variable as describe by equation (3). The DF essentially describes the maximum reduction potential of the LCI constituent among the design options. For example, in a scenario with five material options, the DF for embodied carbon is the percentage difference between the baseline and the lowest alternative. Thus, the value of DF can and will likely be unique for each EC.

$$Q_{z,D}^{x,F} = Q_{z,D}^{x,I} \times \left[1 - \frac{DF}{100}\right] \quad (3)$$

In the equations, the superscript F indicates variables that are extracted from the modified LCA while the superscript I represents variables extracted from the baseline LCA.

Next, the LMDI for each LCA variable will be computed using the additive decomposition method. When implemented the difference in the emission factor of the LCA variables between modified and baseline value will be represented by the changes attributed by each of the LCA variable's EC as describe by equation (4). The computation of the contribution for each EC to the emission factor of the LCA variable is describe by equation (5).

$$\Delta V^{x} = V^{x,F} - V^{x,I} = \sum_{z=1}^{n} \Delta V_{Q_{z,D}^{x}} = \Delta V_{Q_{1,D}^{x}} + \cdots + \Delta V_{Q_{n,D}^{x}} \quad (4)$$

$$\Delta V_{Q_{n,D}^{x}} = \frac{V^{x,F} - V^{x,I}}{\ln V^{x,F} - \ln V^{x,I}} \ln \frac{Q_{z,D}^{x,F}}{Q_{z,D}^{x,I}} \quad (5)$$

3.4. Interpretation

The last step in the proposed methodology is the interpretation of the LMDI results. In this process, the difference in the LCA for the selected impact category between the baseline and modified LCA will be reflected by the contribution of the considered design variable as represented by equation (6). The contribution of the design variable is obtained by amalgamating EC across every LCA variable with the same assigned design variable. From the computed contribution of each design variables, designers can critically assess and identify design variables that has the most significant influence in affected the environmental sustainability impact of the design.

$$\Delta LCA^{x} = LCA^{x,F} - LCA^{x,I} = \sum_{p=1}^{L} D_{p}^{x} \quad (6)$$

4. Case Study

To demonstrate the implementation of the proposed methodology, the design of a desk fan cover was used as a case study. Figure 4 shows the CAD drawing and the design description of the desk fan cover. In this hypothetical case study, the main objective is to identify the design variable that has the greatest influence in lowering the cradle-to-grave carbon footprint of the desk fan cover. As such carbon emission of the design would be the impact category that is being investigated. The three-design variables of concern in this case study are the choice of material, choice of manufacturing process, and the geometry of the design. For the case study, the designer has the option of choosing between acrylonitrile butadiene styrene (ABS) and polylactide (PLA) for the material of the design as well as choosing between injection moulding or additive manufacturing by fused filament fabrication for the choice of manufacturing process.

Material	Volume	Manufacturing Method
Acrylonitrile butadiene styrene (ABS)	3.14 X 10^{-5} m^3	Injection Moulding

Figure 4 CAD drawing of the front and back of a desk fan cover

4.1. Design's LCI

The distribution and usage phase of the product LCA is excluded in this case study as they are out of the control of the designers and do not have active input to the product LCA. Table 2 provides a compilation of the assigned design variables for each EC in the LCA stage that is considered.

Table 2 Compilation of the assigned design variables for the EC of each LCA variables

LCA Stage	LCA Variable	EC	Assign Design Variable
Raw Material Extraction	Input Material	Design Volume	Geometry
		Material Density	Material
		Material Embodied Carbon	Material
	Auxiliary Material	Material Mass	Manufacturing
		Material Embodied Carbon	Material
Production	Energy	Energy Usage	Manufacturing
		Grid Emission Factor	-
	Manufacturing Waste	Material Mass	Manufacturing
		Material Waste Emission	Material
End-of-life	Design EoL	Design Volume	Geometry
		Material Density	Material
		Material Waste Emission	Material

To populate the EC, a combination of software, database, and online resources was used. The Ansys Granta database [19] was use to provide input for the EC relating to the material properties, material's embodied carbon, and manufacturing energy requirements. The grid emission factor was extracted from the published data of Singapore's grid emission factor [20]. The design volume was extracted from the CAD software, Solidworks [21], while the estimation of the support material required for fused filament fabrication was modelled using the Cura software [22]. The input value of the EC used in the case study can be found in Appendix A.

4.2. LMDI Computation

Following the collection of the design's LCI and LCIA the cumulative carbon emission of the baseline design was found to be 0.431 kg CO_2e. Table 3 shows the contribution by each EC to their respective LCA variables computed from the LMDI method. The DF for the material and manufacturing process EC was selected based on the difference in value between the baseline design and design options. Regarding the geometry, designers can derive DF from various sources. This includes basing values from similar projects/designs or conducting preliminary investigation using geometry generation algorithm such as topology optimization or generative design to establish a viable DF value. From the LMDI computation, the choice of material was determined to be the design variable that has the highest potential in affecting the environmental sustainability of the design.

Table 3 LMDI computation summary

LCA Variables	ΔV^x, kg CO_2e	EC	$\Delta V_{Q^x_{n,D}}$, kg CO_2e	DF, %
Input Material Emission	-0.070	Design Volume	-0.019	20
		Material Density	-0.012	13
		Material Embodied Carbon	-0.039	37
Energy Emission	-0.048	Energy Usage	-0.048	67
		Grid Emission Factor	-	0
Design EoL Emission	-0.169	Design Volume	-0.030	20
		Material Density	-0.018	13
		Material Waste Emission	-0.121	60
Cumulative LCA			-0.287 kg CO_2e	
Contribution by design variable:		Material	-0.191 kg CO_2e	66%
		Manufacturing Process	-0.048 kg CO_2e	11%
		Geometry	-0.048 kg CO_2e	22%

4.3. Verification

To verify the assessment from the LMDI computation, three variants of the baseline design were developed. In the first design variant (design 1), the choice of material for the baseline design was switched from ABS to PLA while the manufacturing process and geometry of the design remain the same. For the second design variant (design 2), the geometry of the baseline design is altered while the choice of material and manufacturing process remains the same. Figure 5b shows the CAD drawing of the altered geometry where the number of vanes of the fan cover design is reduce from 40 to 30, this reduces the volume of the design by approximately 16%. With the third design variant (design 3), the main deviation from the baseline design lies in the choice of the manufacturing process to fabricate the design. The manufacturing process was switched from injection moulding to fused filament fabrication.

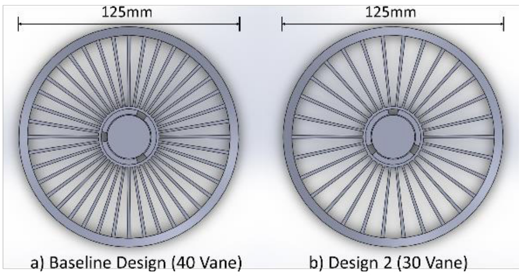

Figure 5 CAD drawing of a) Baseline design b) Design 2

After the generation of the design variant, the life cycle carbon emission for the considered life cycle stages of each design is evaluated. The LCA variables for all three-design variants are largely the same as the baseline design with the exception of design 3. In design 3, there is an addition of 2 LCA variables, the auxiliary material emission and the manufacturing waste emission. This was included to reflect the use of support structure in fused filament fabrication. The LCA for each of the design variant are compiled in Table 4. Across the design variants, design 1 which has a substitution in material has the lowest carbon emission. This is in line with the LMDI analysis of the baseline design which states that changes made to the choice of material will result in the greatest improvement in the design's environmental sustainability.

Table 4 Compilation of LCA and key information of the designs.

Design	Design Variables	Design Deviation	Carbon emission, kg CO_2e
Baseline	-	-	0.431
1	Material	Substitute ABS with PLA	0.256
2	Geometry	Reduction of design volume	0.361
3	Manufacturing Process	Substitute injection moulding to fused filament fabrication	0.406

5. Discussion

In this section, discussion centering around prospective use case and observed shortcoming of the proposed methodology will be presented. The proposed methodology can be used in a variety of design scenarios. Fundamentally, designers can use the methodology to make informed decision regarding redesign efforts as presented in the case study. This is particularly helpful for designers who have an existing design and are exploring options to improve its environmental sustainability. Even though the greatest environmentally sustainable improvement can be reaped from complete redesigning of a product by addressing every hotspot, few companies have the resource or desire to do so. With finite resources, the proposed methodology offers designers and manufacturers a tool to make informed design decision regarding the prioritization of design variable that has the greatest potential in influencing the design's environmental sustainability. Besides the usage of the methodology as described in this work, the proposed methodology will likely be suitable to explore the influence of design functions as well as the life cycle costing of a design. However, these design scenarios have yet to be explored and would likely require tweaking of the proposed methodology to facilitate their implementation.

Despite its innovation and associated benefits, the proposed methodology has revealed several shortcomings. A key limitation is the reliance on the user's ability to provide accurate DF value for each EC. The validity of the analysis is compromised if the difference in an EC between the design alternatives and the baseline surpasses the specified DF. For instance, if design 2 exhibits a volume reduction > 50% compared to the baseline, the analysis would be erroneous, design 2 would have the lowest emission instead of design 1. Selecting the appropriate DF is a nuanced task. While this may not be apparent in the case study with a small number of design alternatives, in scenarios with more options and greater unknowns in design solutions, determining the DF value becomes challenging. If the DF is too high, designers risk receiving unattainable recommendations, and if it's too low, the assessment could be erroneous.

In addition, the current approach of using the modified LCA in the LMDI computation is far from ideal. The implementation of a DF to obtain a modified LCA is essentially the creation of a best-in-class scenario. This approach is flawed, as it does not account for the randomness of material properties where EC such as "Material Density" and "Material Embodied Carbon" fluctuates differently from the perceive baseline rather than increase or decrease in unison.

6. Conclusion

In conclusion, this work proposed a life cycle assessment disaggregation methodology that uses index decomposition analysis to assess the environmental sustainability significance of the considered design variables. Following this methodology, designers will disaggregate the LCA of the baseline design, identifying and associating design variables with specific emission constituents. Subsequently, the influence of each design variable will be quantified using the additive form of the LMDI method, using baseline and modified LCA as input. The methodology empowers designers to explore the influence of the considered design variables on the environmental sustainability of the design. This information enables designers to prioritize those variables with the most substantial impact, facilitating the creation of a design with the greatest environmental sustainability improvement. This was demonstrated in the case study, where the design resulting from the most influential design variable (material), exhibited the lowest carbon emissions.

With increasing concern over climate change, designers are pressured to minimize environmental impact. While design improvements can enhance sustainability, not all variables have equal influence. In the case study, emission reductions vary across alternative designs. Understanding the influence of design variables is crucial, particularly in situations where resources are limited, and designers cannot afford to investigate multiple variables.

For future works, the proposed methodology, specifically the LMDI computation process will be further enhanced to address the shortcoming stated in section 5. This could involve the use of a design analysis system to recommend DF value and introducing sampling to the creation of the modified LCA to bolster the robustness of the LMDI analysis. Another area of exploration would be to adapt the proposed methodology to explore hotspots in the functional design variables or to explore hotspot in the life cycle costing of a design.

Appendix A. Design description

Table 5 Design variable specification

	Baseline Design	Design 1	Design 2	Design 3	Units
Design Volume	3.14×10^{-5}		2.63×10^{-5}	3.14×10^{-5}	m^3
Design Material	ABS	PLA	ABS		-
Material Density	1,100	1,240	1,100		kg/m^3
Material Embodied Carbon	3.59	2.28	3.59		kg CO_2e/kg
Material Waste Emission	6.8	2.7	6.8		kg CO_2e/kg
Manufacturing Process	Injection Moulding			Fused filament fabrication	-
Energy Usage	0.178	0.154	0.149	^{a}0.058	kWh
Grid Emission Factor	0.4057				kg CO_2e/kWh
Material Mass (Auxiliary)	-			0.0023	kg

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