A Ratio Estimation Method For Streamlining LCA of Polymer Materials for Eco-design

B. Song[a], W.C. Lui[b], W.F. Lu[b]

a. Life Cycle Engineering Programme,
Singapore Institute of Manufacturing Technology
71 Nanyang Drive, Singapore 638075
bsong@simtech.a-star.edu.sg

b. Centre for Design Technology
Faculty of Engineering,
National University of Singapore,
10 Kent Ridge Crescent, Singapore 119260

Keywords: Streamlined LCA, Polymer Materials, eco-design, environmental impacts

ABSTRACT

The indicators from Life Cycle Assessment (LCA) are required for eco-design decisions in material and process selections. For polymer materials, such an analysis can take months to develop the LCA model and build up the data inventory for each type of materials. This has become an impediment to the development of an eco-design decision tool that will allow the designers to evaluate the life cycle impacts of optional polymer materials and related components for the product under development. The work of this paper focuses on the exploration of methods to drastically simplify the LCA model and data requirements for polymer material assessment. In particular, a ratio estimation method is presented and discussed.

1. Introduction

Current and emerging legislations on environmental protection require the consideration of life cycle sustainability in product design decisions. Impacts on eco-system quality, human health, and nature resources form the critical decision metrics. The methodology to quantify the impacts is Life Cycle Assessment (LCA), which considers the “cradle” to “grave” life cycle of a product, material, or a process with respect to technological, economical, and environmental indicators [1].

Eco-design decisions on material selections are made against major regulations, i.e., the WEEE [2], RoHS [3], and EuP [4]. To establish the facts, a LCA analysis is required [5]. For polymer materials, such an analysis for each polymer material involves about 700 different substances, which makes it extremely time consuming and costly to develop the LCA model and build up the data inventory. This has become an impediment to the development of an eco-design decision tool that will allow the designers to evaluate the life cycle impacts of optional materials and related components for the product under development. As a result, it is necessary to study ways that can drastically simplify the LCA model and data requirements for polymer material assessment.

2. LCA Results for 4 Types of Polymer Materials

In order to study the ways to streamline the data requirements by LCA of polymer materials, LCA models and for the manufacturing process and landfill treatment have been developed for 4 polymer materials: Polypropylene (PP), Polystyrene (PS), Polyvinylchloride (PVC), and Polyethylene (PE). All the life cycle inventory (LCI) data used are from GaBi 4 database system [6]. Three categories for Life Cycle Impact Assessment (LCIA) are defined based on Eco-Indicator 99 [7], namely eco-system quality, human health, and resources. The eco-system quality measures the effects of Acidification, Ecotoxicity, Land conversion and land use. The human health concerns with the diseases and life years lost due to premature death from environmental causes. The effects cover Climate Change, Ozone Layer Depletion, Carcinogenic Effects, Respiratory Effects and Ionizing Radiation. The resources include the surplus energy required in future to extract lower quality mineral and Fossil fuel resources. The depletion of agricultural and bulk resources, such as sand and gravel, is considered under the land use. LCA score for each category are calculated based on the emission of by-products from the processes in scope. The following steps are involved:

a. Classification: review of the inventory to decide on which impact categories the emissions from the manufacturing and landfill process would contribute to;
b. Flow: This is a GaBi concept that represents an actual material or energy flow of actual processes, technical procedures or groups of procedures. Each flow generates different emissions which contribute to different environmental impacts.
c. Weighting: used to evaluate balances by aggregating balance results and enabling macro level comparison.

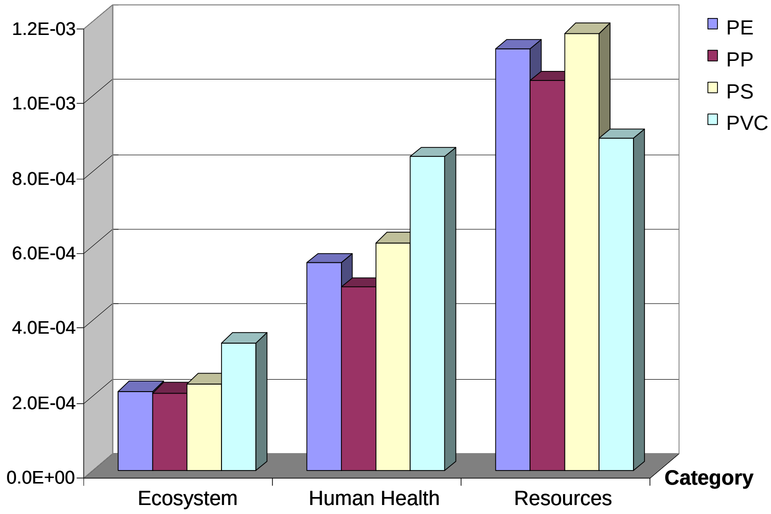

Figure 1: Normalized LCA Scores under the three main categories

The LCA scores of the materials are shown in Figure 1.

3. The Ratio Estimation Method to Simplify LCA Model for Polymer Materials

Based on characterization and analysis of the data for full LCA within the scope, a ratio method that can be used to simplify the LCA data requirements is developed.

3.1 Estimation of Sub-category Flows from By-product's Weight

In LCA scoring, the total number of flows of each sub-category is taken as the sum of the individual flow of its respective by-products, i.e.,

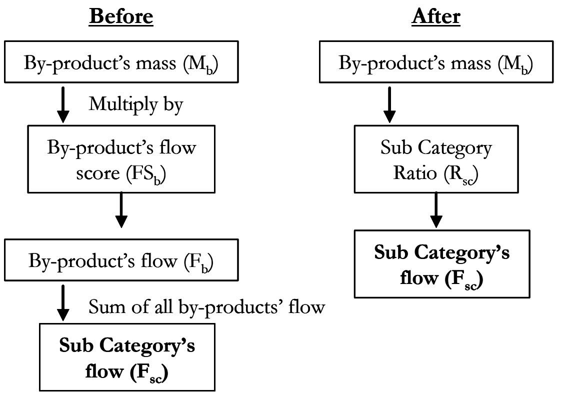

Figure 2. Sub Category's Flow computation before and after simplification

$$F_{sc} = \sum \left(M_b \times FS_b \right) \qquad (1)$$

where F_{sc} = Number of flow of a sub category, FS_b = Flow score of a by-product, and M_b = Mass of a by-product.

To simplify the calculation, it is possible to calculate F_{sc} by any of its by-product's weight with a ratio, i.e.,

$$F_{sc} = M_b \times R_{sc} \Rightarrow R_{sc} = F_{sc} / M_b \qquad (2)$$

where R_{sc} = Sub category ratio. Figure 2 shows the steps involved before and after simplification. LCA data for three polymer materials, PP, PS, and PVC, are used to verify the method. In order to find a common ratio over the three materials, the ratio of individual by-products of a material is calculated. For example, the mass of Nitrogen Oxides (emission to air) for PP is 1.00 x 10^{-2}; flow score of Nitrogen Oxides (emission to air) under Acidification is 5.71; the number of flows contributed by Nitrogen Oxides (emission to air) is 1.00 x 10^{-2} * 5.71 = 5.71 x 10^{-2} ; and the number of flows of Acidification is 6.86 x 10^{-2} . Therefore, the ratio for Nitrogen Oxides (emission to air) of PP under Acidification is 6.86 (6.86 x10^{-2}/1.00 x10^{-2}). The common ratio applicable to all materials shall be the average of all three. For example, the ratio for Nitrogen Oxides (emission to air) under Acidification of PP, PS and PVC are 1.20, 1.17 and 1.17 respective. Therefore, the common ratio for Nitrogen Oxides (emission to air) under Acidification is (6.86+6.67+6.70)/3 = 6.75. The same steps are applied to each and every of the by-products under all sub categories and the results are shown in Appendix C1.

After obtaining the entire R_{sc} for the individual by-products, it is necessary to know which R_{sc} has high potential in estimating the number of flow for its sub-category. The percentage error is calculated as follows:

$$\%(error) = \frac{F_{sc} - EF_{sc}}{F_{sc}} \times 100\% \quad (3)$$

where $EF_{sc} = R_{sc} \times M_b$, and EF_{SC} = Estimated number of flows of sub category.

3.2 Estimation of main category LCA score from by-product's weight

After obtaining the sub-category scores, related sub-category scores are summarized to calculate the main category score on Ecosystem quality, Human health and Resources, i.e.,

$$S_{mc} = \sum \left(F_{sc} \times W_{sc} \right) \quad (4)$$

where S_{mc} = LCA score of main category, F_{sc} = Number of flows of sub category, and W_{sc} = Weightage of sub category. To simplify the calculation, it is possible to calculate S_{mc} by any of its by-product's weight with a ratio, i.e.,

$$S_{mc} = M_b \times R_{mc} \Rightarrow R_{mc} = S_{mc} / M_b \quad (5)$$

where R_{mc} =main category ratio. Figure 3 shows the steps involved before and after simplification. The percentage error is calculated as follows:

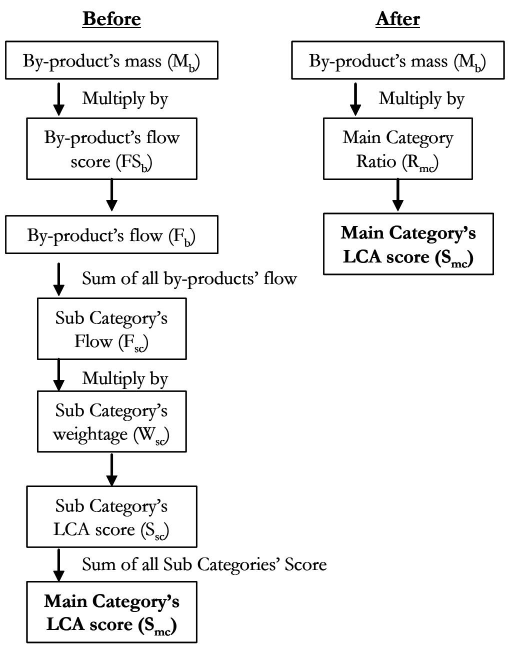

Figure 3: Main Category's LCA score computation before and after simplification

$$\%(error) = \frac{S_{mc} - ES_{mc}}{S_{mc}} \times 100\% \quad (6)$$

where $ES_{mc} = R_{mc} \times M_b$, ES_{MC} = Estimated LCA score of main category.

3.3 Estimation of main category LCA score from sub category flows

The last ratio estimation method is to use the number of flows in a sub-category to find out its respective main category LCA score. For example, if the number of flows for Acidification effects is known, it is possible to use this data to find out the LCA score for Ecosystem quality. Hence, it is necessary to find a common ratio between sub category flows and main category LCA score. To find the common ratio, we can assume the following:

$$S_{mc} = F_{sc} \times R_{mc2} \quad (7)$$

where R_{mc2} = Main category ratio 2. For instance, the number of flows of Acidification effect for PP is 6.86 x 10^{-2} and the LCA score for Ecosystem quality is 2.09 x

10^{-4}. Therefore, the ratio for Acidification effect of PP under Ecosystem quality is 3.04 x10^{-3} (2.09 x10^{-4}/6.86 x10^{-2}). To obtain the entire R_{mc2} for all the subcategories, it is necessary to know which R_{mc2} has a high potential in the estimation of the LCA score for its respective main category. The percentage error is calculated as follows:

$$\%(error) = \frac{S_{mc} - ES_{mc}}{S_{mc}} \times 100\% \quad (8)$$

where $ES_{mc} = R_{mc2} \times F_{sc}$.

3.4 Application of the Metho on PE

The methods are applied to estimate the LCA scores of PE. In comparison with full LCA scores for PE, the results based on R_{mc}, and R_{mc2} show that the average percentage errors of all estimations are 2.11% and 7.38%. This concludes that the estimation of the main category LCA scores is achieved with high accuracy.

4. Further recommendation and conclusion

The case study on PE indicates that the method gives a very good estimation on the full LCA implementation. With 20% to 30% of the original data, an estimate of 90% and above can be achieved. With the use and combination of both methods, smaller estimation error can be achieved. Such a simplification makes it easier and faster to consider the environmental impact of a product at the design stage. The reliability of the estimation method can be improved with more experiments on plastic products using available data (Polycarbonate, Nylon and etc).

References

[1] International Organization for Standardization - ISO 14040: environment management – life cycle assessment- principles and framework. Geneva, 1997.

[2] Makela, T., Directive 2002/96/EC on Waste Electrical and Electronic Equipment – WEEE, 4th International Electronics Recycling Congress, Keynote, Basel, 2005.

[3] Directive 2002/95/EC on the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment, Official Journal of the European Union, 13.2.2003

[4] M. Papadoyannakis, The EuP Directive: a framework for continuous improvement of the environmental performance of energy-using products. Procs. of 13th CIRP International Conference on Life Cycle Engineering, Leuven, 2006

[5] G.A. Keoleian, The application of life cycle assessment to design, Journal of Cleaner Production, vol. 1, No. 3-4, 1993

[6] GaBi 4, Software and database for life cycle engineering, PE International, Germany (www.pe-international.com).

[7] M. Goedkoop, R. Spriensma, the Eco-Indicator 99, a damage oriented method for life cycle impact assessment, Methodology Annex, PRe Consultants B.V., June 2001.