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ENABLING ENVIRONMENTALLY-INFORMED MATERIALS SELECTION DECISIONS: ROBUSTNESS OF EARLY STAGE LIFECYCLE ASSESSMENT

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ENABLING ENVIRONMENTALLY-INFORMED MATERIALS SELECTION DECISIONS: ROBUSTNESS OF EARLY STAGE LIFE-CYCLE ASSESSMENT

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Abstract

This paper explores the robustness of materials selection decisions when using various life-cycle assessment methods. Improving the environmental performance of vehicles is a topic of growing concern met by today's designer. One approach to this goal is through vehicle mass reduction, enabled through the implementation of a growing array of material candidates. While LCA methods are available to provide quantitative input into this selection decision, LCA applications are evolving and distinct. Specifically, this paper surveys the major analytical variations of LCA implementations and explores the implications of one major variant when applied to an automotive materials selection case study involving aluminum. This case study examines analytical variations in treatment of recycling by exploring allocation methods that affect product EOL. Preliminary results indicate that the choice of analytical method can have real impacts on individual metrics and there are sets of analytical variation over which strategic results are strongly affected.

Introduction: The Challenge of Environmentally Informed Materials Selection

Corporate regulations, resource availability, ethical responsibility, and consumer demand for environmentally-beneficial products and services currently challenge industries to conduct operations in ways that protect the natural environment, human health, and societal interests – ways that are sustainable [1]. Within the family of decisions about product and production, no single decision has greater fundamental impact on environmental performance than the selection of materials, influencing the choice of production technology, product form, and configuration and distribution of the supply chain. As such, materials establish the environmental profile of their associated extraction and refining, the characteristics of transformation into product, the product performance during use, and the potential for recovery at end-of-life (EOL). Consequently, effective tools to inform the environmental implications of materials selection decisions are critical to realizing sustainable industry.

Of the methods available to incorporate environmental information into the materials selection process, the most general and broadly discussed is life cycle assessment[1]. LCA requires the analyst to extensively characterize each stage of a product's or process' life, presenting a challenge for typical materials selection decisions occurring early in product development cycles, when options are ample, but data is scarce. As a result, a critical question emerges concerning the effectiveness of LCA to support materials selection decisions: Can LCA results resolve the environmental performance of materials alternatives given the level of uncertainty endemic to materials selection?

[1] The key elements of LCA will be detailed in the following section.

The analyses in this paper explore this question in the context of a case of materials choice for automotive structural materials. Specifically, these analyses characterize the robustness of the LCA result to variation in analytical treatment of EOL processing. The following sections briefly review the LCA method and describe the case study that will be explored.

Background: Life Cycle Assessment

The LCA framework is widely used to evaluate the environmental performance of product systems, offering a way to explore options that potentially will reduce life-cycle environmental impact. The International Organization for Standardization (ISO) LCA framework is depicted in Figure 1, showing the major conceptual stages of the LCA process. The Goal and Scope Definition stage is used to outline study objectives and necessary system boundaries. The next stage, Inventory Analysis, quantifies all material and energy inputs and outputs. The Impact Analysis stage then translates this inventory into impacts on ecological and human health. However, many LCA studies stop short of the Impact Analysis step due to its subjective, controversial nature and instead focus on assembling and analyzing life-cycle Inventory Analysis data. Determining the appropriate weighting method to apply depends on the strategic intent of the LCA study, and is left to the LCA decision-maker. It is this notion of explicit and implicit trade-offs that occurs when apportioning and weighting an inventory in terms of environmental effects that serves as motivation for testing the robustness of the LCA methodology.

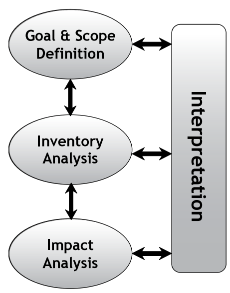

Figure 1. ISO 14040 framework for LCA [2]

<u>Exploring Materials Selection using LCA: Generic Vehicle Life Cycle</u>

To address the robustness of the LCA methodology, the authors have previously used LCA to compare implications of material selection on the life cycle of a generic vehicle. Specifically, a Base Case and Comparator vehicle, differing only in choice of material application to vehicle structural panels, were evaluated in terms of environmental impact using different LCA valuation methods. Figure 2 and Figure 3 show the impact of changing the underlying assumptions about vehicle use on the percent difference between the Base Case and Comparator analysis as defined by Equation (1) using three LCA impact methods; Cumulative Energy Demand (CED), Environmental Priorities System (EPS), and Eco-Indicator 99. These figures compare the "crossover" time between the Base Case and Comparator vehicles; the elapsed lifetime at which the environmental burden associated with material production and use of one material alternative equals that of the other. Specifically, these plots show how percent difference changes with variation in vehicle lifetime, vehicle fuel economy of the Base Case vehicle, and average driving distance per year.

$$\%\,difference = \frac{(Comparator - BaseCase)}{BaseCase} \qquad (1)$$

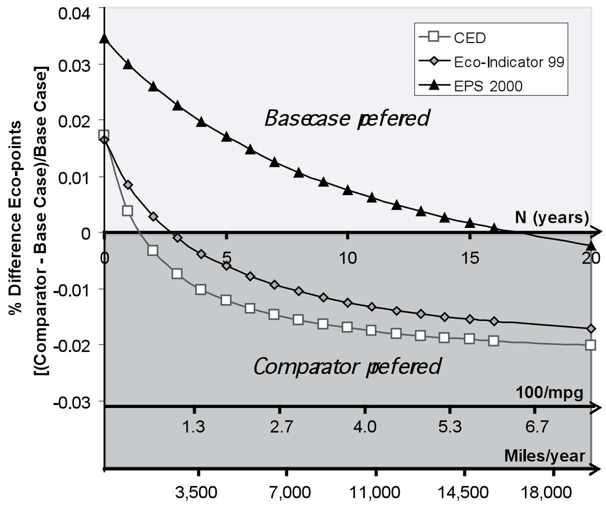

Figure 2. Comparison of Comparator and Base Case vehicles using Eco-Indicator, EPS, and CED varied across intensity of use (i.e. measured in terms of vehicle life, fuel consumption, and miles/year) – includes production, use, maintenance, and EOL

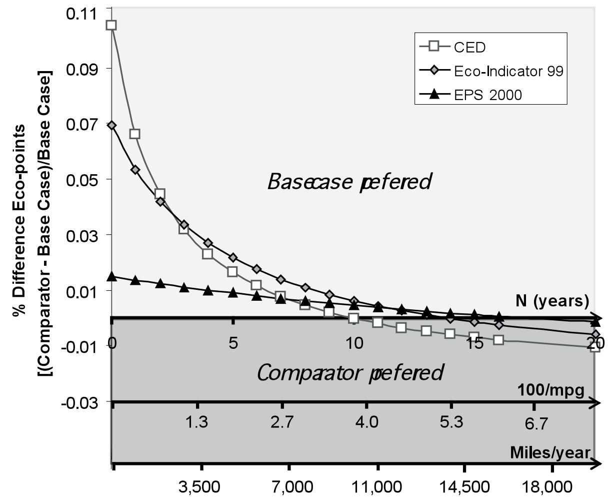

Figure 3. Comparison of Comparator and Base Case vehicles using Eco-Indicator, EPS, and CED varied across intensity of use (i.e. measured in terms of vehicle life, fuel consumption, and miles/year) – includes production, use, and maintenance (excludes EOL)

Figure 3 differs from Figure 2 insofar as it excludes the impacts and benefits of the EOL phase from the analysis. Given the small impact of EOL processing, the dominant implication of this is to change the magnitude of benefits associated with recycling EOL materials that are allocated to the two materials alternatives. In the end, these figures demonstrate that the manner in which the benefit for EOL recovery is calculated and allocated has a *strong* effect on the relative magnitude of impacts associated with two alternatives. It is this implication that serves as the motivation for exploring how the robustness of the result is changed when making different assumptions regarding treatment of EOL.

Methods

Understanding Metrological Effectiveness: Robustness

To date, LCA indicators have not been specifically evaluated for their practical and effectual merit. General efforts within the literature to define the dimensions of merit for environmental metrics have resulted in criteria that can be summarized in a framework specifying that a successful metric must be (1) useful, (2) feasible, and (3) robust [3-6]. The focus of this paper is characterizing the robustness of LCA results.

In order to test the robustness of materials selection decisions when using different LCA EOL allocation methods, a vehicle materials selection case study from a prior study was used to provide a complete and detailed bill of materials for analysis [7]. Environmental impact assessment results were computed using the Eco-invent V1.3 database and the CED impact methodology. Results were then permuted to test for change in result due to variation in the EOL method. The figure of merit will be the extent of change required to change the elected materials selection decision.

EOL Allocation Methods

Currently ISO 14040 standards do not explicitly address the issue of EOL accounting in open loop recycling and there exists a diverse set of methods to address recycling benefits or "credits" and burdens at product EOL. One method is to employ system boundary expansion to include all products affected by the secondary material flow of the original product, which can be overly cumbersome or infeasible in terms of data collection [8]. For metals that can be reused many times, boundary expansion can introduce large sources of uncertainty. A conceptually robust method, developed by Franklin Associates, requires the LCA analyst to assume recovery rates and predict the total number of times recycling will occur, given the incarnation of future products [9]. This paper explores the implications of various EOL allocation schemes on the elected materials selection decision. Table I outlines the different allocation methods analyzed herein in relation to the life cycle cascade represented in Figure 4.

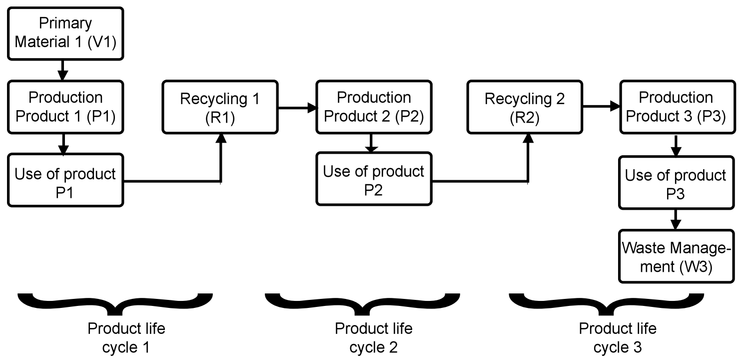

Figure 4. Simplified system boundaries illustration of product material flows and processes involving open loop recycling [10]

Table I. Allocation methods for addressing EOL treatment in LCA

Method	Description	Formula
Cut-off method	Loads directly caused by product are assigned to that product [10].	L1 = V1, L2 = R1, L3 = R2 + W3
Loss of quality (1) method[2]	Assigns load to products in relation to their relative loss of quality in each step; virgin material production, final waste management and recycling are necessary for material function [10].	$L1 = \frac{Q1}{Q1+Q2+Q3}(V1+R1+R2+W3)$ $L2 = \frac{Q2}{Q1+Q2+Q3}(V1+R1+R2+W3)$ $L3 = \frac{Q3}{Q1+Q2+Q3}(V1+R1+R2+W3)$
Loss of quality (2) method	Assigns load to products in relation to their relative loss of quality in each step; virgin material production and recycling to upgrade losses in material quality are necessary for material function [10, 11].	$L1 = \frac{Q1-Q2}{Q1}(V1+R1)$ $L2 = \frac{Q2-Q3}{Q1}(V1+R2)$ $L2 = \frac{Q3}{Q1}(V1+W3)$
Waste treatment method	Waste treatment is an unavoidable consequence of raw material extraction and processing [10, 12].	L1 = V1 + W3, L2 = R1 L3 = R2
Burden on last product method	Material lost through waste treatment must be replaced through virgin material production [10, 12].	L1 = R1 L2 = R2 L3 = V1 + W3
Closed loop approximation method	Applicable to materials such as metals that do not experience significant losses in quality when recycled [13].	$L1 = L2 = L3 = \frac{V1}{3} + \frac{W3}{3} + \frac{(R1+R2)}{3}$
50/50 method	Virgin material production and waste treatment are allocated to the first and last products in equal proportions [10, 14].	$L1 = \frac{V1+W3}{2} + \frac{R2}{2}$, $L2 = \frac{R1+R2}{2}$ $L3 = \frac{V1+W3}{2} + \frac{R2}{2}$
Substitution method	Recycled aluminum substitutes primary aluminum; accounts for the load of producing (X% = 10%) lost aluminum and recycling burdens [15].	L1 = (100%-X%)(R1) + X%(V1+W3)

[2] Q1 is the quality of material in P1, Q2 is the quality of material in P2, and Q3 is the quality of material in P3. Quality ratios were computed using market pricing data for primary and scrap metals.

Case Study

Base Case and Alternative Materials Comparator Selection

To understand the robustness of the LCA method to various EOL assumptions, an automotive materials selection case study was analyzed. The case involving a Base Case and Comparator vehicle, differing only in choice of material application in closure panels. The vehicle description provided by the USAMP Life Cycle Inventory for the USCAR Generic Family Sedan Study was selected to serve as a Base Case [16]. Fuel economy was 23.6 mpg with a vehicle mass of 1532 kg [16], including 108 kg of mild steel closure panels. The Comparator was modeled with 68 kg of aluminum closures leading to a primary mass savings of 40 kg and a secondary mass savings of 20 kg. For the Comparator vehicle, fuel economy savings due to weight savings was estimated at a rate of 6% reduction in fuel consumed per mile driven per 10% reduction in vehicle mass. Total vehicle miles traveled was assumed to be 120,000 miles over an 11 year period for both alternative designs. Further details of the case can be found in [7].

Results

Figure 5 compares the results between the Base Case and Comparator vehicles using the EOL methods outlined in Table I. Results show a considerable range of variation between methods, with positive values indicating an environmental preference for the Base Case vehicle. Due to its wide application in LCA literature, the closed-loop approximation method value is noted with a dashed line to serve as a basis of comparison for other EOL methods. The negative value associated the loss of quality (2) method reveals an environmental preference for the Comparator vehicle. Table II considers the implications of EOL method on the vehicle use phase by comparing crossover point, the point at which the environmental burden associated with material production and use of the Base Case vehicle equals that of the Comparator. Each EOL method surveyed reduced the original crossover value of ten years obtained when no EOL treatment was considered. In the end, it appears that choice of EOL treatment method in an LCA has a strong effect on the magnitude of the relative environmental performance. However, for this automotive case, all crossovers remain well below current average vehicle lifetimes. As such despite this variation, the LCA result seems to be highly robust for this case.

Table II: Comparison of crossover point between Base Case and Comparator vehicles by EOL method

End-of-Life Method	Crossover point (Years)
No EOL treatment	10.0
Cut-off	5.8
Loss of quality (1)	0.8
Loss of quality (2)	-1.7
Waste treatment	5.8
Burden - last product	0.2
Closed loop approx.	2.0
50/50	3.0
Substitution	0.7

Figure 5. Comparison of Base Case and Comparator vehicles using CED varied by EOL allocation method

Conclusions

One of the key engineering challenges of the 21st century will be creating products with substantially lower environmental burden. Any fundamental solution to this challenge will require careful selection of materials and the processes used to fashion material into product. Life Cycle Assessment is a broad, flexible analytical framework to map the environmental consequence of a range of design decisions including the selection of materials. For LCA to be effective in informing materials decisions, it must provide reasonably robust answers when applied against the uncertain data endemic to early-stage design.

This paper provides a preliminary exploration into the robustness of LCA result in response to variation in end-of-life allocation method. For the case presented herein, the CED evaluation method provided significantly different distribution of relative burden for the two alternative designs when considering different allocation methods. Nevertheless, despite this significant variation the amount of vehicle use required to offset the additional burdens of Comparator vehicle production remain substantially below the typical lifetime of current vehicles. As such, the preferred material remains consistent across these analytical options.

For LCA to become widely accepted, practitioners need to develop confidence in the information that is provided. Further study is needed to continue to build that confidence., The limited results presented here indicate that material decision-makers need to be aware of the implications of end-of-life assumptions on choice of material.

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