Methods for managing uncertainty in material selection decisions: Robustness of early stage Life Cycle Assessment

by

Anna L. Nicholson

Bachelor of Science in Industrial Engineering
Bachelor of Industrial Design

North Carolina State University, 2004

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Signature of Author………………………………………………………………...……………………
Technology and Policy Program, Engineering Systems Division
Mechanical Engineering
[January 26, 2009]

Certified by…………………………………………………………………………………..………….
Randolph E. Kirchain
Assistant Professor of Materials Science and Engineering, and Engineering Systems
Thesis Supervisor

Certified by…………………………………………………………………………………..………….
Timothy G. Gutowski
Professor of Mechanical Engineering
Thesis Reader

Accepted by……………………………………………………………………………………………..
David E. Hardt
Professor of Mechanical Engineering
Graduate Officer, Department of Mechanical Engineering

Accepted by……………………………………………………………………………………………..
Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program

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Abstract

Utilizing alternative materials is an important tactic to improve the environmental performance of products. Currently a growing array of materials candidates confronts today's product designer. While life-cycle assessment (LCA) methods provide quantitative input into this selection decision, their implementations are evolving and disparate. The goal of this paper is to explore several major analytical variations of LCA implementations and the implications of these variants across a range of application contexts. Specifically, this thesis examines analytical variations in valuation method and treatment of recycling by exploring allocation methods that affect product end-of-life. An abstracted case study across a range of materials is presented, including materials that exhibit a spectrum in variation of environmental performance and material degradation between primary and secondary applications. To date, research has shown that the amount of recycled material delivered by, or used in, the life cycle of a product will affect the environmental burdens of other product life cycles. However, explicit consideration has not been given to the question of whether end-of-life allocation methods can lead to different materials selection decisions in early stage product development cycles. Similarly stemming from this question is the issue of, if so, how do these allocation methods differentially favor certain material classes? Results indicate that the choice of analytical method as well as its underlying parameters can have substantial impact on individual metrics that determine environmentally preferred material and that there are sets of analytical variation over which strategic results are strongly affected.

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1 Introduction: The Challenge of Environmentally Informed Materials Selection

Industries today deal with a range of environmental pressures that are diverse, dynamic, and demand new levels of accountability, financial commitment, and supply chain capabilities. Environmental pressures stem from four key sources, including regulations, resource accessibility, ethical responsibility, and consumer demand for environmentally-minded products. In terms of filtering down to an operational level, these concerns challenge industries to conduct business in ways that are sustainable, or minimize impact on the natural environment and human health while improving societal interests [1]. Materials selection decisions exhibit great influence on the environmental performance of firms through their effect on processing technology, product form, and supply chain configuration. Consequently, materials dictate a product's environmental profile via the burden associated with extraction and refining, transformation from material to product, product performance characteristics during use, and potential recovery at end-of-life. Given their fundamental impact, effective tools to inform the environmental implications of materials selection are critical to enabling the transition to a sustainable enterprise.

Of the methods available to incorporate environmental information into the materials selection process, the most general and broadly discussed is Life Cycle Assessment (LCA)[1]. Other environmental assessment methods include the recently popular carbon footprint analysis, a method of quantifying and presenting emissions data for the whole life cycle of products, and environmental flow analysis, based on material and energy flows [2], [3]. 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[2] endemic to materials selection?

The literature offers many examples where LCA is used to assess the environmental profile of materials ranging from simple commodities such as kraft paper [4] to complex product systems such as automobiles [5]. LCA is also used to analyze such complex operations as seafood [6] and biofuel production systems. However, issues such as differences in defining system boundaries, scope, and data uncertainty have constrained the widespread acceptance of LCA methods. In particular, a LCA study is time consuming, data-intensive and expensive to conduct. The acquisition of data by direct measurement is usually problematic, often requiring a tradeoff between accuracy and cost. Normally, a large sample size taken over an extended period of time is necessary to provide a rigorous estimate but time and economic constraints may make such a sample impossible to obtain. Often LCA studies are rendered obsolete in decision making processes due to these time and economic constraints [7].

Despite recent attempts at standardization, there remain persistent doubts about the general robustness of LCA results, often due to uncertainties about data quality [8]. This is particularly

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[1] The key elements of LCA will be detailed in the following section.
[2] Primarily, uncertainty arises due to lack of knowledge about the true value of a quantity. It is distinguishable from variability, which can be attributed to the natural heterogeneity of values. Uncertainty can be reduced by more accurate and precise measurements. Variability cannot be reduced by further measurement, although better sampling can improve knowledge about variability. In this thesis, "uncertainty" encompasses uncertainty and variability.

significant in the LCA of products such as biofuels due to the wide range of available feedstocks and processing options. The extent of the environmental benefits resulting from the use of an alternative fuel such as a biofuel depends greatly on the net energy balance of the fuel system life cycle. Figure 1 shows a fuel system life cycle for biofuel produced from a crop such as soybeans. Net energy is the difference between the calorific value of a fuel and the cumulative energy inputs (excluding feedstock energy content) needed for its processing, storage, and transportation. In effect, net energy is a measure of the capacity of an alternative fuel to displace conventional energy sources; therefore it also has a profound influence on the environmental benefits of fuel substitution.
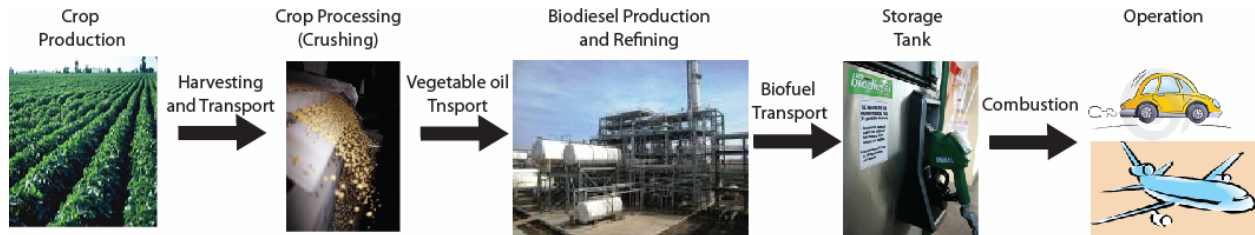
Figure 1: Life cycle of biofuel production. Stages of life cycle include feedstock recovery, feedstock transportation, biofuel production, biofuel transportation, and biofuel utilization

Many life-cycle studies attempt to account for the primary energy and mass flows in biofuel production and several conclude that biofuels are environmentally preferable to conventional petroleum based fuels in terms of net energy value and life cycle carbon dioxide production [9] [10]. However, variations in data and assumptions used among these LCA studies have resulted in a wide range of estimates when accounting for uncertainties around issues such as farming energy and yields, conversion technologies, emissions from fertilizer use, and land use emissions included in the life cycle energy calculations. There are several studies which attempt to represent these sources of uncertainty around biofuel production in LCA [8]. One such study analyzes the life cycle greenhouse gas emissions of alternative jet fuels compared with conventional jet fuel from crude oil [11]. The results are illustrated in Figure 2, which shows a considerable range of biofuel carbon dioxide emissions relative to conventional jet fuel when taking these production uncertainties into account.
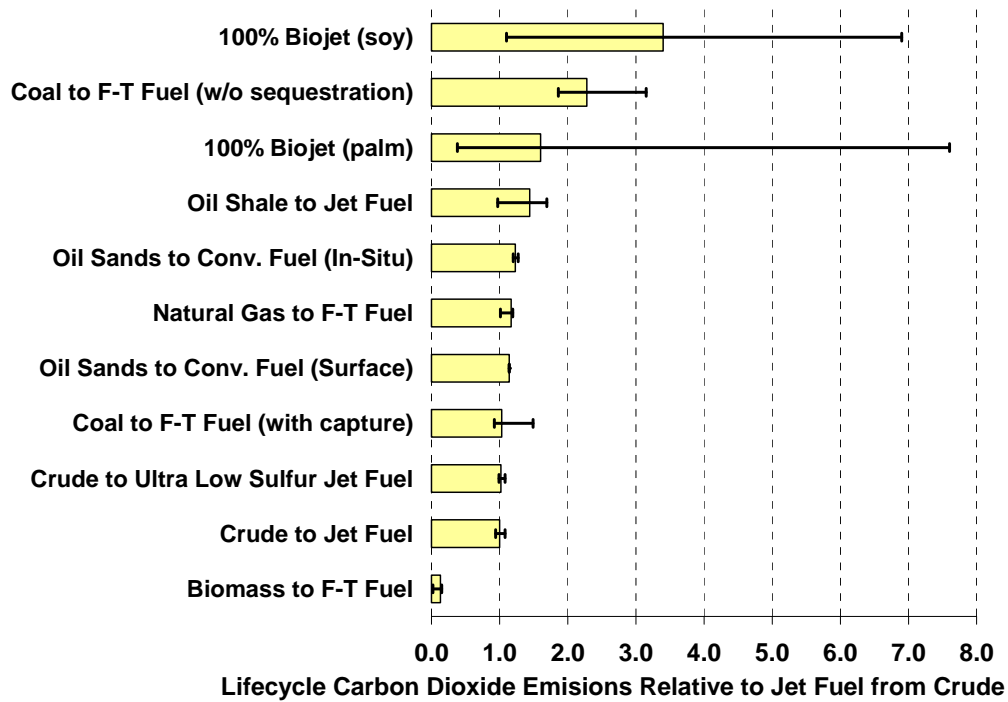
Figure 2: Comparison of life cycle carbon dioxide emissions between alternative jet fuel sources and conventional jet fuel [11]

Moreover, there are co-products from the biofuel production process must be taken into account when determining life cycle environmental impact. Co-products are artifacts from the biofuel production process such as distiller's dried grains and solubles and crude glycerin [9]. There are essentially four methods to estimate energy credits for co-products. First, the energy content of co-products can be used to estimate energy credits. A second method of allocating co-product energy values is to use the relative market values of the biofuel and its co-products. One can also allocate energy use among multiple products on a mass basis: however, this method is not always a good indicator of a product's energy value. A fourth method is based on the replacement value of co-products, which assumes energy credits to be equal to the energy required to produce a substitute for the biofuel co-product values. Wong demonstrates in Figure 3 how the application of different co-product allocation methods can vary the LCA result for a soybean derived biofuel. The discrepancy between allocation methods is further pronounced when considering the implications of land use change from crop production on life cycle greenhouse gas emissions.

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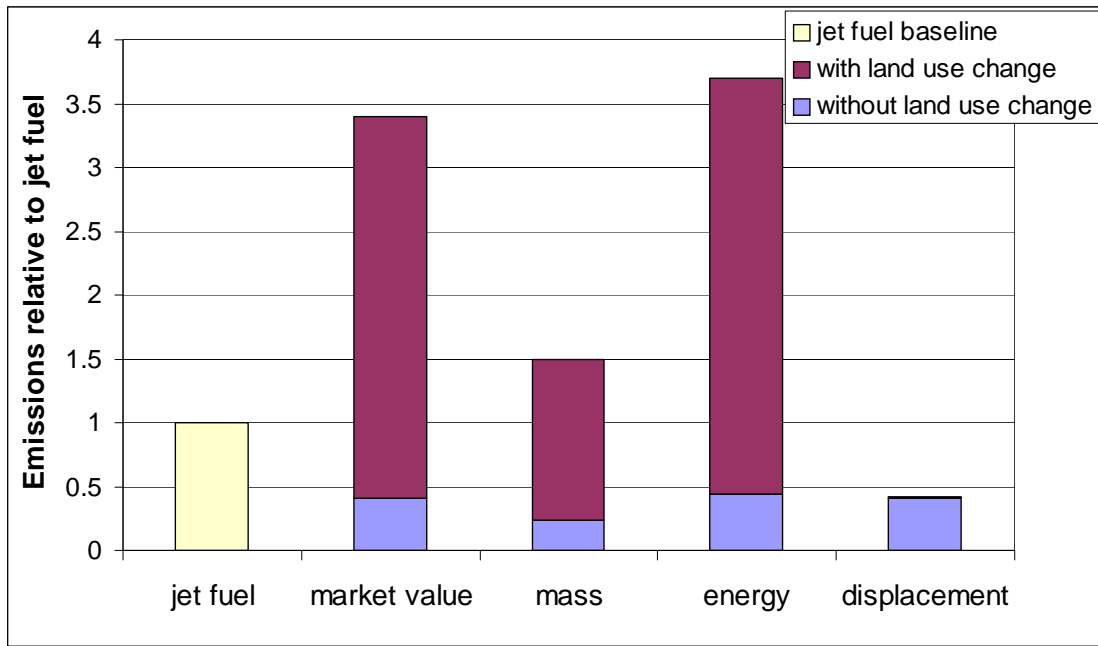
Figure 3: Life-cycle GHG emissions of biofuel produced from soybeans compared with jetfuel, based on different allocation methods [11]

In other case studies, it has been shown that different LCA valuation methods will give different results in terms of preferred product or material. (e.g. [12], [13], [14]). Ekvall showed that LCA assessments of paper recycling arrive at different conclusions, partly due to methodological differences in the inventory analysis of LCA [15]. This study emphasized that ideally recycling should be assessed in connection with other waste management practices, such as incineration and landfilling, and emphasized that environmental gain of paper recycling depends on what material is replaced. Other studies that demonstrate how different LCA assumptions can lead to different preferred material include [16], showing that environmentally preferred choice of material in an automobile fender design depends on one's valuing of energy, resource use, and global warming.

1.1 Thesis Outline

This thesis attempts to address the question of how key sources of methodological variation within the LCA method can impact the environmentally preferred material result. Within this context, uncertainty stemming from allocation issues is examined more in-depth to try to characterize how various assumptions about its application can consistently influence the LCA study result.

Chapter 1 first provides an overview of the Life Cycle Assessment framework and highlights key sources of methodological uncertainty that can affect the robustness of the result. The second part of the chapter discusses the effectiveness of methods such as LCA when used for informing the decisions occurring in early stage product design.

Chapter 2 provides an overview of co-product allocation in the LCA method. The second section introduces the relevant background of end-of-life allocation methods and provides the basis for the questions explored in the second case study in Chapter 4.

Chapter 3 presents the work that was performed to map fundamental areas of uncertainty in LCA method. The first case goes through the investigation of key questions critical to exploring the

robustness of the LCA method: (1) variation in the method of impact assessment, (2) uncertainty in product specification, (3) uncertainty in product use, and (4) uncertainty in end-of-life processing. Chapter 4 transitions into a second case study that specifically examines the last point of the first case study -- end-of-life allocation methods, the main exploration of this thesis.

Next, Chapter 5 provides a discussion of the results developed in case study II. Chapter 6 summarizes the main ideas developed in the thesis, key contributions and broader implications of the work.

1.2 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. A life-cycle sequence for a product considers all the stages a product goes through from "cradle to grave," as illustrated in Figure 4. This means that the environmental impacts from raw material manufacture, production, use and disposal as well as transport between these stages are calculated.
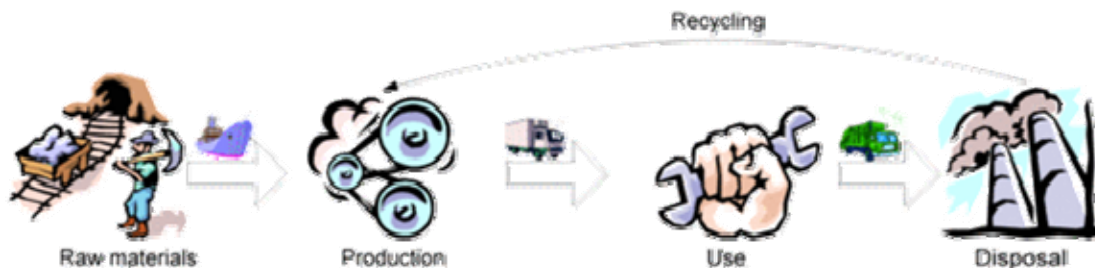
Figure 4: Illustration representing various stages of a product life-cycle from cradle to grave [17]

The International Organization for Standardization (ISO) LCA framework is depicted in Figure 5, 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 and defines a study functional unit. System boundaries determine which processes will be included in an LCA study, and are partly based on subjective choices. Boundaries considering time horizon, geographical area, between the current life cycle and related life cycles of other technical systems, and between the technological system and nature must therefore be established. A functional unit tells what kind of function is delivered by the studied system. For instance, the function of a ceramic mug might be as a container of two cups of hot coffee three times a day. In this way, different products that fulfill the same function may be compared in terms of their environmental impact. The next stage, Inventory Analysis, quantifies all material and energy inputs and outputs to the system being studied. The Impact Analysis stage then translates this inventory into impacts on the natural world. For example, in one prevalently used Impact Analysis method, the inventory is explained in terms of its impact on resource use and 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.
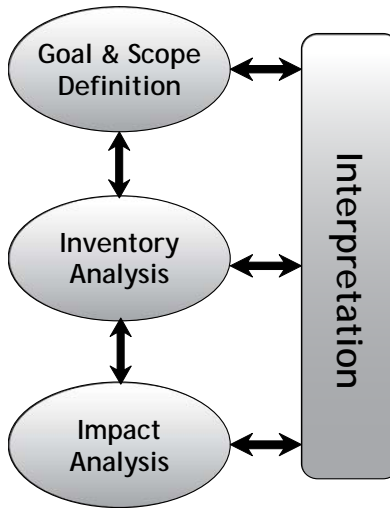
Figure 5: ISO 14040 framework for LCA [18]

Decision theory indicates the partitioning and weighting required to translate a LCA inventory into a measure of environmental performance is critical from a framing perspective [19]. Analysts approach the "Interpretation" phase of LCA using a variety of methods to weigh the results of the phases of the process, and each method for weighting relies on its own distinct, embedded assumptions regarding environmental valuation. Often this leads to a mindset where there exist "right" and "wrong" weighting methods, creating a dualistic way of thinking from which a "best" indicator must be chosen [20]. Fundamentally, determining the appropriate method to apply depends on consistency with strategic intent of the LCA study, and is therefore a task relegated to the LCA decision-maker. It is this notion of explicit and implicit trade-offs that occur when apportioning and weighting an inventory in terms of environmental effects that serves as motivation for testing the robustness of the LCA methodology.

1.3 Literature Review: Sources of Variation and Uncertainty in LCA

As with any analytical approach, the robustness of life-cycle assessment is affected by both uncertainty in the underlying data and the quantitative implications of specific methodological approaches. This section will summarize the literature on the sources and implications of uncertainty within LCA. Before moving to that, it is first useful to explore previous work that has documented both the pervasive nature of this issue and the lack of adequate methods or practice to address the effects of uncertainty within LCAs. LCA results are usually presented as point estimates, which strongly overestimate its reliability, and make use of deterministic models, which do not address the variability and uncertainty inherent in input variables. This may lead to decisions that are unnecessarily costly, or mislead public perception about the environmental profile of a product or process [21]. These are long-since acknowledged problems. As noted by Vigon ([22], as cited in [23]), LCA practitioners lack systematic approaches for determining data quality, and need improved techniques for sensitivity and uncertainty analysis. Although this matter is often mentioned, real uncertainty assessments are rarely performed. In a review of thirty recent LCA studies, only fourteen (47%) mentioned uncertainty, two (7%) performed qualitative uncertainty analysis, and one (3%) performed quantitative uncertainty analysis [24]. This is not surprising, since there is a lack of consensus concerning methodology. While the recent ISO standards recommend the use of uncertainty methods [18, 25-27], they give little guidance for practical implementation. In recent years, initiatives to understand, incorporate, and reduce uncertainty in LCA have made progress. For example, a SETAC-Europe LCA working group on data availability and data quality has developed a framework for modeling data uncertainty and the Danish Environmental Protection

Agency has proposed a data collection strategy for reducing uncertainty in LCI [28],[29]. Some LCA software platforms, such as SimaPro, provide the ability to analyze uncertainty using Monte Carlo analyses [30]. Also, the Ecoinvent LCA databases include quantitative uncertainty distributions for parameters in many processes, such as the variability and stochastic error of the figures which describe the inputs and outputs due to measurement uncertainties, process specific variations, temporal variations, etc. [31], [32].

In the following section, different types of uncertainty appearing in the LCA methodology are presented. Specifically, this section first considers uncertainty around data used in the LCA inventory process and then methodological uncertainty. Within the methodological uncertainty section, uncertainty around framing, allocation, and impact assessment is explored.

1.3.1 Data

The robustness of life cycle assessment is affected by dependence on data from different countries, different operations, different sources, data that is often not collected for LCA purposes [33], and more or less subjective methodological choices. The quality and availability of data for the inventory stage varies widely and is an expressed concern in the impact assessment process [23]. In usual practice, data are collected from a variety of sources: production sites, engineering texts, regulatory reports for industries, or industry literature. In many cases, data are not available directly from the most accurate source-production sites. These data are usually considered proprietary. The result is considerable variation in accuracy among numerous individual data points and the potential for out-of-date information. In addition, averages or even point estimates from different sources may be extrapolated for an entire industry. LCA data are also static by nature. Inventory data need regular updating, and the difficulty in projecting future performance and innovation should be considered.

Data inaccuracy
Data inaccuracy concerns the empirical accuracy of measurements that are used to derive the numerical parameter values [34]. Measurements can be subject to random error, which results from imperfections in measuring instruments and observational techniques, or systematic error, which results from an inherent flaw or bias in the data collection or measurement process [21].

Data gaps
Due to the often complex data requirements needed to assemble a comprehensive LCI, missing parameter values may leave the model with data gaps [34]. Other issues contributing to gaps in data include:
- Data confidentiality
- Complexity of system
- Products at early stage of market development
- Context of product unknown
- Lack of knowledge around processes and components

Misrepresentative data
Data gaps may be avoided by using representative data [34], typically data from similar processes. However, this data often does not accurately represent the age, geographical origin, or technical performance of the original system or process, all important factors of consideration when determining environmental impact.

1.3.2 Framing

According to the definition of the ISO standard the system boundary is "the interface between a product system and the environment or other product system" [18]. Complex systems like industrial and fuel production systems have practically no final limit. One can trace back materials and energy indefinitely depending on the level of detail used. Therefore, every assessment must limit its analysis at some point. Different studies having different system boundaries may have different results and this detail must be taken into account when comparing them. In fact, several LCA studies examined this flexibility in the past. For example, Lee et al. present the example of washing machine studies, including and excluding the services (heating, lighting, compressed air, etc.) of the manufacturing plant and resulting different conclusions [35]. Consequently, the boundary conditions and system definitions in an LCA have great influence on the study results, as do framing issues related to time-scale and spatial considerations.

1.3.2.1 Temporal Framing

Variations over time are relevant in both the inventory and impact assessment, as processes and factors in the environment vary naturally over short and long time scales. Examples are process emissions, wind speed, and temperature. Another aspect is the chosen time horizon to combine potential effects, which, for instance, applies to global warming potentials, photochemical ozone creation potentials [36], and emissions from landfills [37].

1.3.2.2 Spatial Framing

Variability stems from inherent fluctuations in the real world. Although there are natural variations between different geographical and industrial sites, environmental interventions are usually summed up in the impact assessment, regardless of the spatial context. Examples of factors that vary over space are background concentration and human population density [36].

1.3.2.3 Conceptual Framing

Choices are unavoidable in LCA. Because there is often not one single correct choice, there is uncertainty in choice: for instance, of functional unit, system boundaries, characterization method, weighting method [36], marginal or average data [38], or technology level [13].

1.3.3 Impact assessment

Impact assessment attempts to examine the potential environmental consequences of a product system based on the collected inventory data. In other words, this step applies quantitative measures to value the relative severity of different environmental changes. To do so, impact assessment seeks an association or relationship between an inventory data set and particular environmental issues using defined impact categories. For each category endpoint, the environmental and human health sciences have usually identified several compounds or stressors that are related to adverse effects for that endpoint (e.g., sulfur dioxide and nitrogen oxides for acid rain.). These compounds are then targeted for inventory data collection for particular categories. Then, a category-specific model is used with simplifying assumptions to convert the inventory data into a numerical category indicator. This category indicator is intended to portray an overall load from the system, a life-cycle stage, or an operation on the specific category.

There are three different operational weighting methods for valuing different types of environmental impacts[3]. One is *distance-to-target*, and the underlying rationale can be explained as follows:

> "the quotient between the current levels of emissions in a geographical area (often a country) and the level that is considered critical (target level) indicates how severe a certain kind of emission is. A contribution to the overall flow of a certain substance where current emissions are far above the target level is thus given more weight than contributions to flows where the distance-to-target is smaller. A critical element in this class of methods is the target levels and how these are determined" [20].

In distance-to-target methods, the targets are normally related to either political/administrative target levels or "critical" or "sustainable" levels. However, the problem then becomes how to define the targets. For example, targets may be related to the environmental quality, environmental interventions and threats, or on flows within the technical system. Targets may also vary based on differing areas of protection and/or differing time frames (short term targets, long term targets and targets without any specified time frame). Ultimately targets are decided by different stakeholders with perhaps dissimilar goals, and may not always be compatible with each other [39]. Two types of valuation techniques using distance-to-target methods include Ecoscarcity 97 and EDIP [20].

Another type of valuation method uses an expert panel to weigh environmental consequences. For example, the Eco-Indicator 99 method includes a damage modeling of impacts on ecosystems, human health, and finite resources. Damages were weighted by a panel consisting of LCA experts and LCA users. When applying the method, a practitioner can choose one or more weighting sets based on three different cultural perspectives (individualist, hierarchist, and egalitarian) and connected views of nature (benign, tolerant, and ephemeral), or an average of the three. Figure 6 illustrates the Eco-Indicator 99 impact assessment methodology [20].

A third class of valuation method is driven by economics, where monetization is used to reduce complex data to numerical values. In these methods, the economic value of resources and emissions is determined by market prices, government allocation, and contingent valuation. For example, the Environmental Priority Strategies (EPS) impact assessment method assesses the added economic value from all types of impacts and assigns an environmental load unit to each resource, emission, and activity on a per unit mass basis [40].

In principle, impact assessment strives to achieve an accurate model and representative indicator, but this is inherently a subjective process in practice. The indicator's actual benefit and worth remains to be determined and understood before making decisions. As discussed in the section on data uncertainty, disparities between inherent spatial, temporal, and even toxicological characteristics of the categories in LCA all contribute to many levels of uncertainty and variability that are made more complex by inventory accounting, calculation, impact assessment, and valuation procedures. At this level, when subjective judgments are made on scientific evidence, transparency is crucial within LCA on communicating how complex modeling approaches generate these indicators. As mentioned previously, studies have shown that the selection of different impact assessment methods can lead to different results in terms of preferred product or material. For example, the application of different LCA impact assessment methods can lead to different preferred material in automotive design, showing that environmentally preferred choice of material depends on one's valuing of energy, resource use, and global warming [16].

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[3] A fourth method is valuation by proxy; for example, carbon footprint or energy use.
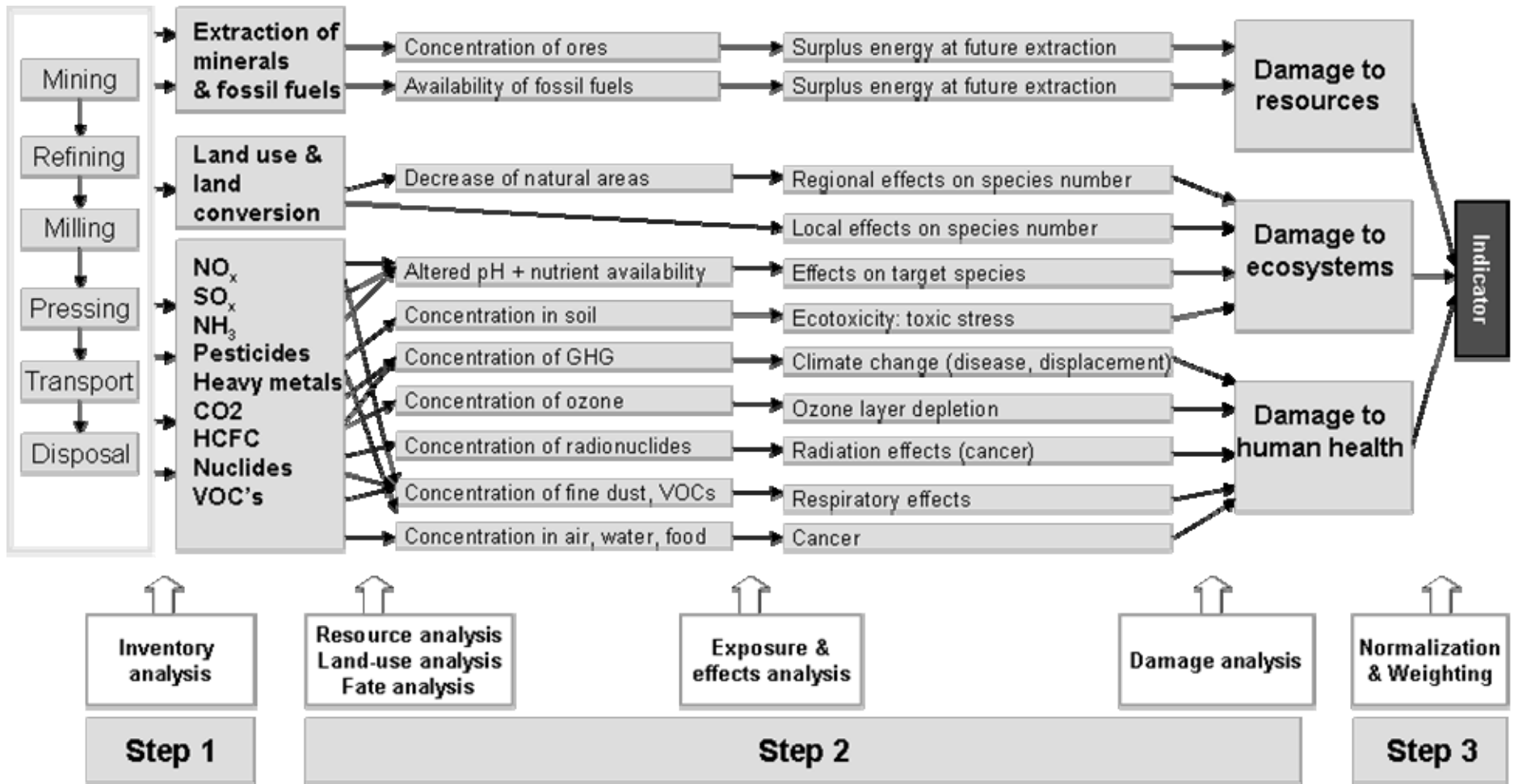
Figure 6: Eco-Indicator 99 Impact Assessment Method: A damage oriented method for Life Cycle Impact Assessment [41]

1.3.4 Allocation

When a process in a product system is related to more than one product, it presents a problem for the LCA analysis: How should its exchanges, such as the resources consumed in the process and the releases it generates, be partitioned and distributed over multiple products? For example, in the chloralkali process, both chlorine and sodium hydroxide are produced. How should the emissions from this process be allocated with respect to chlorine and sodium hydroxide when performing an LCA involving only one of these products? The allocation of these multiple products, known as "co-products," has been one of the most controversial issues in the development of the methodology for LCA, as it may significantly influence or even determine the result of the assessments [42]. A widely cited example of the problem of allocation stems from open-loop recycling; in other terms, when recycling results in material or energy being used in more than one product. In open-loop recycling, recycling processes which provide waste treatment for upstream products also provide material for downstream products. The next section further defines the problem of allocation in open-loop recycling.

In light of these sources of variation and uncertainty within the LCA methodology, this thesis seeks to explore the analytical variation of LCA in general, and more in-depth, of the issue of allocation in product systems.   Specifically, allocation in the context of open-loop recycling will be considered in an effort to characterize the robustness of the LCA result to variation in analytical treatment of end-of-life (EOL) processing.

1.4 Literature Review: Understanding Metrological Effectiveness

To date, indicators of environmental performance capable of informing the decisions of those effecting change in products, processes, and policy 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 the criteria catalogued in Table 1. Ultimately, these criteria can be summarized in a framework specifying that a successful metric must be (1) useful, (2) feasible, and (3) robust. The focus of this thesis is characterizing the robustness of LCA results, particularly as defined by criteria 15 and 16 in Table 1.

Table 1: Criteria mentioned in the literature to evaluate the effectiveness of environmental metrics

Criteria		Discussed in
	USEFUL	
1.	Simple, easy to apply (user friendly)	A, E, F, H
2.	Understandable, easy to interpret, evaluate	A,C,E, F, H
3.	Useful (appropriate to task and goals/objectives, relevant)	A, E,C, H
4.	Diagnostic	F, H, I
5.	Facilitate the use of econometric and statistical tools	I
6.	Responsive to change, contribute to prediction, analyze trends, ("able to measure progress over time")	H, K
7.	Have associated reference value, benchmarkable	F, K
8.	Private/protective of data	A
9.	Allows for cross-company, other meaningful comparisons (geographic units, facility, industry, process)	E, C, F, H
10.	Consistent with other relevant indicator sets	E, F
11.	Can be integrated with other information (economic, forecasting, information systems)	F
12.	Represent environmental conditions & impacts & responses	F
	FEASIBLE	
13.	Cost effective, based on available, accurate data	A,E, C, F, H,K
14.	Based on data regularly updated of known (good) quality	F, G, I
	ROBUST	
15.	Reproducible, verifiable	A, E, K
16.	Nonperverse	A
17.	Modular/Stackable (can be aggregated to different scopes, scales)	A
18.	Based on international standards, with consensus on validity	F
19.	Clear system boundaries	B
20.	Clear uniform definition of indicator & uniform data collection	G
21.	Objective	C
22.	Subjective elements explicit	B
23.	Stakeholder involvement in indicator development, and/or responsive to stakeholder expectations	E, C, K

References used in **Error! Reference source not found.**:

A: [43]
B: [44]
C: [45]
D: [46]
E: [47]
F: [48] referencing OECD

G: [49]
H: [50]
I: [51]
J: [52]
K: [53]
L: [54]

1.5 Exploring Materials Selection using LCA: Central Research Question

To first order, this thesis explores the broader question of the robustness of material decision making when using the LCA methodology, specifically considering: (1) variation in the method of inventory evaluation, (2) uncertainty in product specification, (3) uncertainty in product use, and finally, as mentioned above, (4) uncertainty in end-of-life allocation. Exploring these issues of uncertainty demonstrate that methodological variation within LCA can have a significant impact on preferred material. Next, uncertainty within product end-of-life allocation was selected for more in-depth consideration. To date, research has shown that the amount of recycled material delivered by, or used in, the life cycle of a product will affect the environmental burdens of other product life cycles [55]. However, no one has explicitly explored the question of whether end-of-life allocation methods can lead to different materials selection decisions in early stage product development cycles. Furthermore, if this is the case, how do these allocation methods differentially favor certain material classes?

In order to test the robustness of materials selection decisions when using different LCA methods, first a vehicle materials selection case study was developed to provide a complete and detailed bill of materials for analysis. Environmental impact assessment results were computed using SimaPro 7.0 LCA software and the Eco-invent and ETH-ESU 96 databases. Results were then permuted to test for change in result due to: (1) variation in the method of impact assessment, (2) uncertainty in product specification, (3) uncertainty in product use, and (4) uncertainty in end-of-life processing. The figure of merit is the extent of change required to change the elected materials selection decision. The latter part of the thesis examines LCA robustness to different assumptions about end-of-life allocation. While EOL allocation methods have been evaluated for specific products such as waste wood [56], this thesis examines where the variation in results may be most amplified over a range of relationships between material characteristics, such as the ratio between primary and secondary energy use or the number of project lifecycles. Characterizing this space will allow LCA decision-makers to understand how choice of EOL allocation method affects the environmental performance of the elected material candidate when using LCA to choose between different materials.

The best way to help practitioners and ensure a comparable standard of LCA studies would be to agree on a framework for data quality management and uncertainty analysis [57]. However, taking the considerations from the previous chapter into account, it seems difficult to develop a framework that outlines in detail what should be done and how. Of greater use would be a framework that points out the important aspects of uncertainty in LCA to the practitioner, guides through the considerations one must make regarding for instance desired results, time and resources, describes what one can do to address different issues, and describes how to do it. This thesis should be useful in developing such a framework.

The analyses in this thesis explore analytical variations in the allocation of impacts associated with open-loop recycling in LCA implementations and the implications of these variants across a range of application contexts. Specifically, these analyses characterize the robustness of the LCA result to variation in analytical treatment of end-of-life (EOL) processing.

2 Methods

2.1 Allocation of co-products

A current problem in LCA is how to deal with material and energy flows which affect other processes or product life cycles not included in the system being analyzed. An example of the problem of co-product allocation is illustrated in Figure 7, which shows the co-production of caustic soda, chlorine and hydrogen [58]. In this example, the electrolysis of sodium chloride results in caustic soda, chlorine, and hydrogen. Because each of these three materials is created from the same source, how should the environmental impact of total production be allocated to these functional flows? For example how are the air emissions from this process to be allocated with respect to chlorine and sodium hydroxide when performing an LCA involving only one of these products? The allocation of these multiple products, known as "co-products," has been one of the most controversial issues in the development of the methodology for LCA, as it may significantly influence or even determine the result of the assessments.
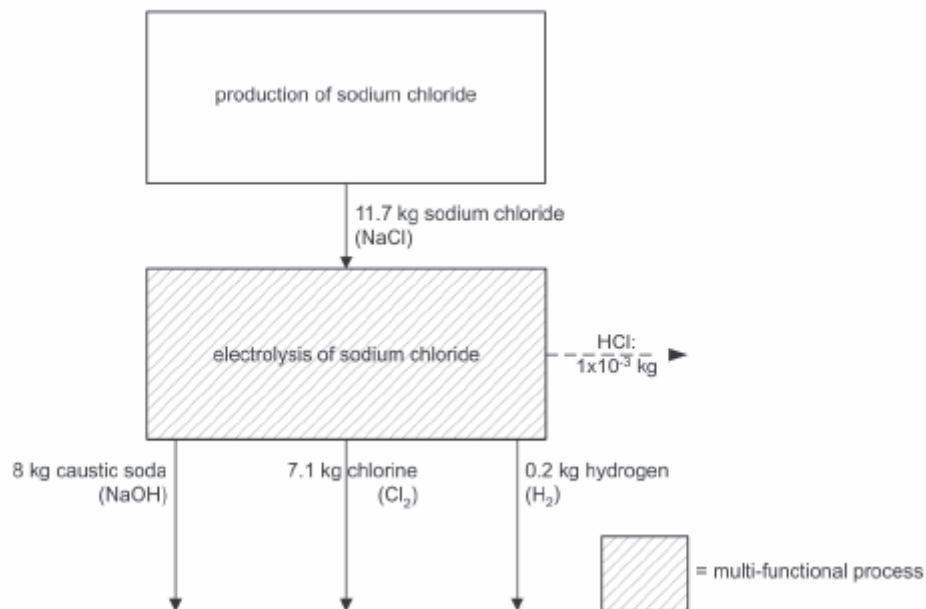
Figure 7: Co-production process of caustic soda, chlorine and hydrogen (numbers are hypothetical)

If unavoidable, allocation is needed to partition the burden of environmental impact caused by raw material extraction, recycling and the final disposal of a material over different product systems according to some notion of proportionate shares. Generally, allocation should: 1) be based on causal relationships and 2) wherever possible should be avoided by system expansion or subdivision of unit-processes. When such relationships cannot be used as the basis for allocation, ISO recommends in step 3) that allocation be based on economic relationships [26]. However, exactly how this economic allocation is performed remains unspecified, or at least for many practitioners, the decisions to be made and their consequences are still unclear.

Many different approaches to this allocation problem have been suggested in the literature [42] [59], [60], [61] ,[62]. Additionally, the choice of approach can have a real impact on the results of an LCI [63], [36], [55]. A special case of allocation in LCA is the issue of open-loop recycling. While co-production processes are simple enough to understand the in terms of economic or mass allocation procedures, recycling processes often create more complex problems, both conceptually and mathematically. The next section explores the issues associated with co-product allocation at product end-of-life in open-loop recycling.

2.2 Allocation at product end-of-life

A key issue affecting the robustness of the LCA methodology when assessing the environmental performance of a material centers around the issue of allocation when recycling materials. Recycling can be considered bi-functional in the way that it represents both waste treatment and secondary material production. Changes in the amount of recycled material delivered by, or used in, the life cycle of a product will affect the environmental burdens of other product life cycles. Consequently, the way in which environmental impacts are distributed among materials as they are recycled into new products has been widely criticized. There exist many uncertainties about allocating environmental burden at a product's end-of-life, when a material can be potentially be recycled several times. This "open-loop" recycling is the case for products whose materials are recycled into products other than the end-of-life product, as illustrated in Figure 8.   Figure 8 shows a simplified diagram of the process and material flows in a product life cycle cascade. Product 1 (P1) is produced from the primary raw materials extracted in step V1. At the end of P1's life, all of its material then recycled into product 2 (P2). Again, at the end of P2's useful life, all material is then recycled into product 3 (P3). Once P3 is used, it is then disposed of in some manner such as landfilling or incineration and leaves the cascade of product recycling.

The problem illustrated by Figure 8 is the lack of knowledge around what P1 was before being transformed into P2, and similarly, what P3 will be after P2 is recycled. Without this specific product knowledge, how, then, should the burdens associated with recycling, primary material extraction, and final disposal be apportioned among the three products in this example? Partially this uncertainty is due to the lack of specificity in the allocation procedures for recycling in ISO 14041 standards dealing with recycling in LCA, especially for open loop recycling [18]. Additionally, processes in the original product production chain are sometimes joint processes that are shared by more than one product system [26] and consequently have to be allocated to different product systems. Other difficulties stem from the complex nature of recycling systems, especially if reuse and remanufacturing processes are involved [64]. Another challenge to allocating burdens in recycling is based on the somewhat perverse notion that human industrial activities create positive environmental impacts.
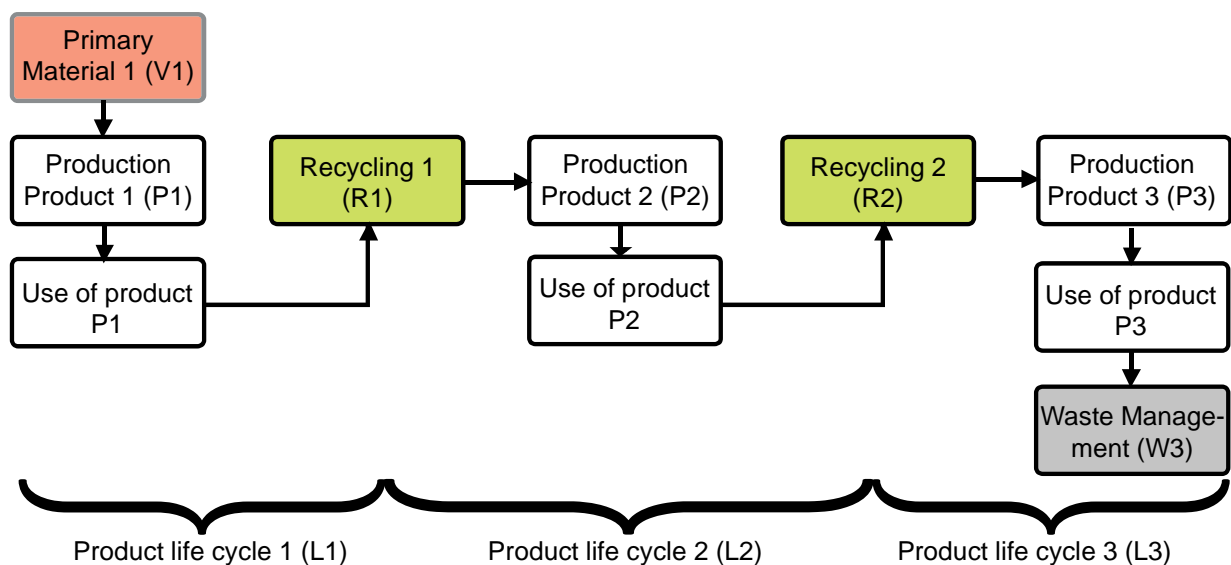
Figure 8: Simplified system boundaries illustration of product material flows and processes involving open loop recycling [42]

2.2.1 End-of-life Allocation Methods

When dealing with recycling in LCA, there are various proposed allocation methods in the literature to deal with the uncertainty of ascribing environmental burden at a product's end-of-life. The Closed Loop method refers to the recycling of material within the product system to directly offset the production of virgin material. In reality the assumption of complete substitution is not valid since most recycling processes alter material quality. Also, it has been demonstrated that increased recycling does not necessarily mean that the market will absorb the surplus recyclate. [65]. The shortcomings of the Closed Loop method are partially addressed by the Substitution method, represented in Figure 9. The Substitution end-of-life allocation method assumes that recycled material can substitute for primary material and accounts for the burden of producing material that is "lost" due to degradation, as well as recycling burdens [66].

Figure 9: Schematic of substitution end-of-life allocation method [66]

Another manner of modeling open-loop recycling in the literature is the Cut-off method. As shown in Figure 10, the product material is a blend of recycled (secondary) and virgin (primary) material. When the material leaves the system boundary, the subsequent recycling burden is accounted for in the next product system. This approach therefore is only sensitive at the material-level but not at the product-level, and therefore does not discriminate between future recyclable versus non-recyclable material applications.

Figure 10: Schematic of "Cut-off" allocation, representing a blend of virgin and recycled material

Yet another end-of-life allocation method is Value Corrected Substitution, or Loss of Quality. Virgin material is substituted in the same manner as the substitution method. However, a value correction associated with the loss of quality of the material reflects the potential limited application of the recycled material when compared with the virgin material. Usually this value correction factor corresponds with the different economic values of secondary and primary materials of different qualities [64], [42]. Ekvall also explores the concept of market based allocation based on product price elasticities [55].

$$\frac{\text{Price (recycling)}}{\text{Price (virgin)}} = \frac{2}{3}$$
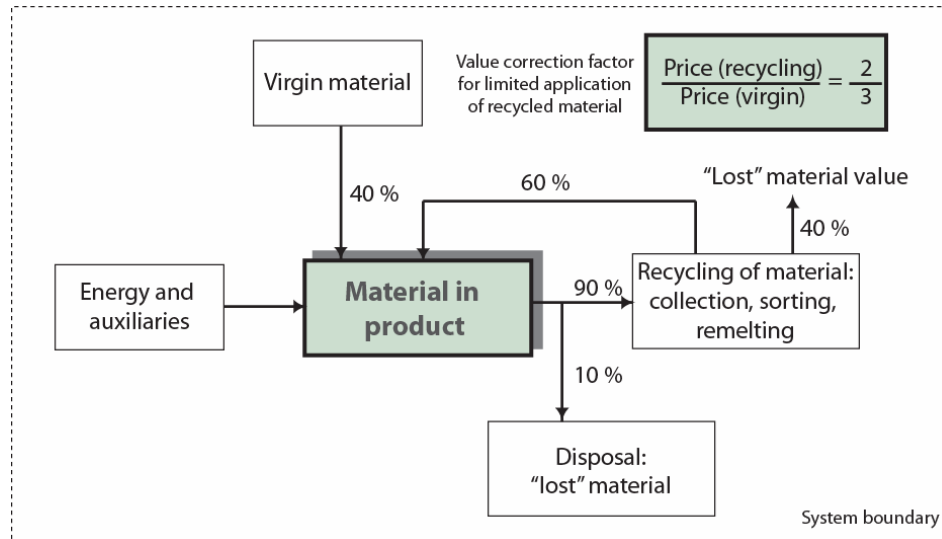
Figure 11: Schematic of value corrected substitution allocation. Depending on the price-ratio of virgin and recycled material, a fraction of the value of the recycled material is lost to reflect its limited range of application.

Overall, a negative consequence of these flexible ISO14041 end-of-life allocation rules is that different results may be obtained from otherwise equivalent studies. In order to address this problem, the procedural standards demand an independent examination of the applied method and the study results, critical review, as well as a report with a transparent communication of the study and its results.

2.3 Impact Assessment Methods

The impact assessment frameworks surveyed in this thesis include Eco-indicator 99, Environmental Priorities System (EPS) 2000, and Cumulative Energy Demand (CED). Eco-indicator bases its damage assessment through an evaluation of impacts on human health, ecosystem quality, and damage to resources. These damage categories were weighed by an expert panel based on three different viewpoints -- individualist, egalitarian, and hierarchist -- each with distinct assumptions regarding cultural perspectives and impact timeframe [67]. EPS correlates environmental impacts with financial consequences by estimating a social "willingness to pay" for effects on human health, biodiversity, resource depletion, ecosystem productivity, and recreational and cultural values. CED calculates the total primary energy use through a life cycle and weighs results by type of resource consumed.

3 Case Study I: Environmentally Informed Materials Decisions in the Automobile

This case study maps fundamental areas of uncertainty in LCA method by investigating key questions critical to exploring the robustness of the LCA method: (1) variation in the method of impact assessment, (2) uncertainty in product specification, (3) uncertainty in product use, and (4) uncertainty in end-of-life processing. Specifically, an automotive materials case study was developed to examine these issues.

3.1 Base Case Selection: Generic Vehicle Development

To evaluate the robustness of LCA to analytical variation in support of materials selection decisions, an automotive materials selection case study was developed. Specifically, the case involved vehicle life cycle considerations ranging from material production, operation, maintenance and repair to end-of-life. Burdens associated with vehicle part manufacturing and assembly were omitted due to limited information availability and their relatively small life cycle contribution compared to material production and vehicle operation [68]. Development of a novel, complete description of a vehicle at the level necessary to conduct a LCA was beyond the scope and resources of this thesis. Four candidate vehicle descriptions were identified in the literature. The composition of these candidates are compared in Figure 12 [5, 68-70]. Although the distribution of materials is similar across all four designs, 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 for this study because of its comprehensive bill-of-materials [5].
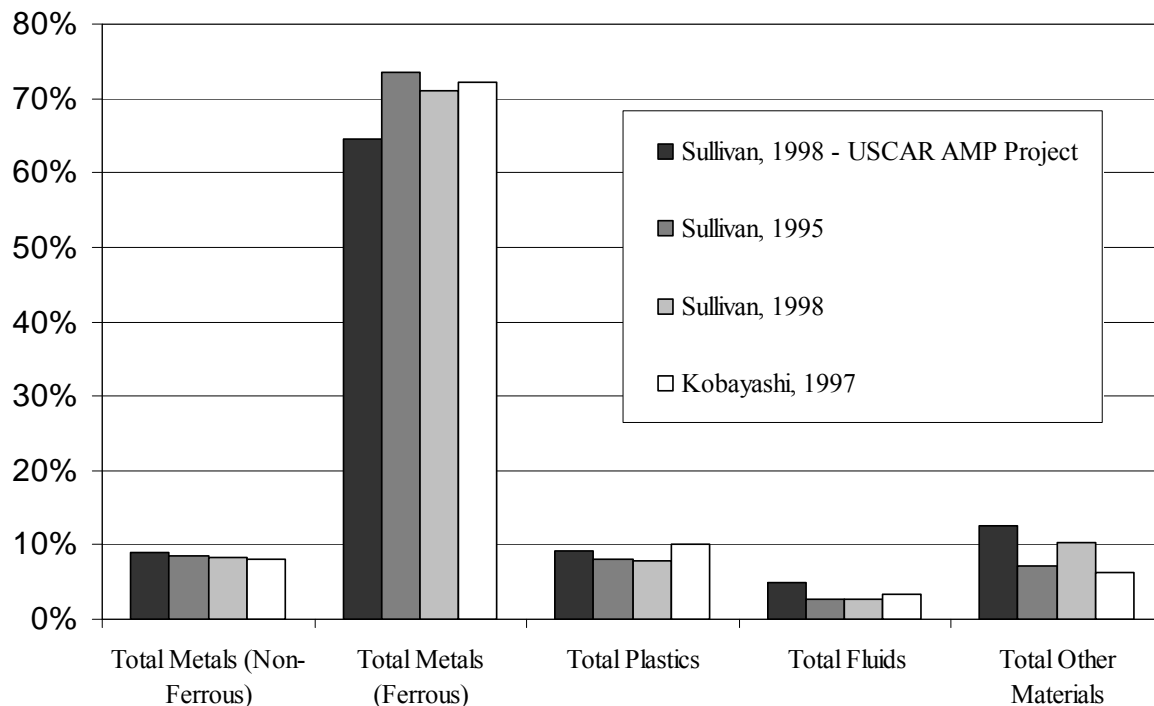
Figure 12: Comparison between material compositions used in vehicle LCA studies

3.2 Alternative Materials Comparator: Mass Reduction Using Aluminum Closures

To understand the robustness of the LCA method to support materials selection decisions, it was necessary to develop and analyze an alternative materials comparator. The selected comparator differs from the Base Case in that it is modeled to have closures with all structural components made from aluminum. Conceptually, this differs from the USAMP Base Case which used mild steel closure structures. To create the Comparator bill-of-materials, the Base Case bill-of-materials was modified by reducing the mass of steel and increasing the mass of wrought aluminum, each by a quantity equivalent to the mass of a full set of closures (four doors, hood, decklid, and fenders) made of the respective materials. Table 2 summarizes baseline vehicle and vehicle use assumptions. Specifically, the Base Case was modeled as containing 108 kg of mild steel associated with the closures. The Comparator was modeled to have a primary mass savings of 40 kg from substituting an assumed 68 kg of aluminum closures. Both values were based upon closure designs provided by a major US automaker. Notably, this mass differential would be expected to be less for many current vehicles due to the increased utilization of high strength steels. Because the focus of this work is not the case itself, but rather the robustness of the method, the Base Case vehicle was modeled as having mild steel closures to maintain consistency with the source study.

For the Base Case vehicle, fuel economy is 23.6 mpg with a vehicle mass of 1532 kg [5]. Total vehicle miles traveled was assumed to be 120,000 miles over an 11 year period for both alternative designs. For the Comparator vehicle, industry data was applied to calculate fuel economy savings due to weight savings at a rate of 6% reduction in fuel consumed per mile driven to a 10% reduction in vehicle mass [71].

Material substitution can lead to vehicle mass reduction directly (i.e., primary mass savings), but is also expected to enable corresponding secondary mass savings. Although total mass savings associated with materials substitution is ideally an iterative process that evaluates specific mass reduction candidates, in general, automakers use secondary weight savings factors from 1.3-1.75 [72]. For example, a factor of 1.5 indicates 100 kg of primary mass savings yields 50 kg of derived secondary weight savings. This analysis explores the implications of allocating secondary weight savings to mild steel, and compares performance with the Base Case. Sensitivities around secondary weight savings factors were also explored. Eco-indicator 99, EPS 2000, and CED, discussed above, were used to explore the effects of different impact assessment methods on the Base Case and secondary weight savings scenarios.

Table 2: Baseline vehicle assumptions

Design	Use	End-of-life
• Base case: 108kg mild steel panels • Comparator: 68kg aluminum panels (40kg primary mass savings, 20kg secondary mass savings)	• 11 years • 23.6 mpg • 10,909 miles/yr	• High value/hazardous components removed • 95% ferrous metals recovered • 90% non-ferrous metals recovered • ASR land filled

3.3 Results

Table 3 compares the baseline results for the Base Case and Comparator vehicle evaluated using both the Eco-Indicator 99 method and Cumulative Energy Demand (CED) method. As a point of reference the reported life-cycle energy values for the USCAR AMP study vehicle are included. Total life cycle energy results (i.e., the CED method) for the Base Case vehicle differ from the USCAR AMP study by 2%. Notably, results for vehicle production and use differ from reported USCAR AMP value by 20% and 3%, respectively. Although the USCAR AMP study discusses the application of end-of-life credits, the positive value reported for end-of-life activities suggests that such credits were accounted for elsewhere in values reported in that work. As such, a more appropriate comparison likely comes from comparing the total of production and end-of-life: 142 MJ for Base Case versus 136 for USCAR AMP. These values differ by about 4%. The relative distribution of production and use impacts (i.e., use phase accounts for approximately 85% of the total) in these results is consistent with the studies mentioned above.

The Comparator results differ from the Base Case with an 11% higher vehicle production value and an 82% larger end-of-life credit. Use phase impacts for the Comparator vary by 2.4%, indicating a lower lifetime fuel consumption.

As shown in Table 3, when applying an environmental impact assessment method, such as Eco-Indicator 99, the overall distribution of results can shift significantly with use accounting for 75% of total impact. Nevertheless, the rank order of the Base Case and the Comparator design are unaffected.

The goal of this study has not been to evaluate the specific environmental merits of the two options being compared. Instead the question at hand is how sensitive is the result to changes in underlying analytical assumptions. To that end the following section will explore the impact of such changes on the relative standing of the two materials alternatives being considered: Base Case and Comparator. The figure of merit for that comparison will be the percent difference in the life-cycle result between the two alternatives, defined as:

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

Looking at Table 3, the Comparator has a life-cycle impact approximately 2% less than the Base Case when evaluated under the baseline conditions.

Table 3: Base case results showing Eco-Indicator 99 (EI 99) and CED by vehicle life cycle stage

	Metric	Production	Use	End-of-Life	Total
USCAR AMP (GJ)	CED	133.7	838.6	2.7	975.0
Base Case (GJ)	CED	160.8	815.4	-18.4	957.8
Comparator (GJ)	CED	178.4	796.0	-33.4	941.0
Percent Difference:		10.9%	-2.4%	-81.5%	-1.8%
Base Case (Eco)	EI 99	1007	2458	-172	3293
Comparator (Eco)	EI 99	1080	2401	-231	3250
Percent Difference:		7.2%	-2.4%	-34.3%	-1.3%

3.3.1 Sensitivity Analysis

The life-cycle literature is full of discussions about various inherent uncertainties within the LCA method. These include core issues such as incomplete or inappropriate inventory data, insufficient or inconsistent data on the translation of releases into environmental harm, and the incorporation of human values to establish the relative importance of specific harms. The author feels that for LCA to be broadly applied, the above issues will either need to be solved fundamentally or those firms that continue to apply LCA will have to implicitly or explicitly accept these limitations.

However, even when this happens, there still remains a question as to whether LCA is able to support materials selection decisions at the early design stages when they happen; is the LCA result able to resolve the performance of key technological alternatives, and, is that resolution robust to the extent of uncertainty present at early design. To that end, the focus of this work is to understand the impact of uncertainty in the way the problem is specified on the underlying result. This section details three preliminary analyses to examine this question, the robustness of the LCA result to 1) changing the impact assessment method; 2) uncertainty in product use characteristics, and 3) uncertainty in product specification.

3.3.1.1 Variation in the Impact Assessment Methodology

Figure 13 compares differences in the life-cycle result between the two materials alternatives when evaluated using the three valuation methods being studied: CED, Eco-indicator, and EPS. Since it is not appropriate to compare absolute results across such methods, the results of each have been normalized such that the difference in impact of materials production is 100 points.
The first clear observation from these results is that for the baseline conditions, all three methods indicate material production for the Base Case vehicle leads to lower impact, while the Comparator is associated with a lower impact during the vehicle use phase. Specifically, CED indicates a lower Base Case material production by 11%, Eco-Indicator by 7%, and EPS by 2%, while all three methods show a 2% impact reduction during the vehicle use phase. Probably the most notable difference among the results emerges in the evaluation of the impacts associated with end-of-life. While Eco-indicator and CED attribute a significantly larger credit (i.e., more negative points) to the Comparator, the EPS suggests that end-of-life activities associated with both alternatives lead to a nearly identical impact.
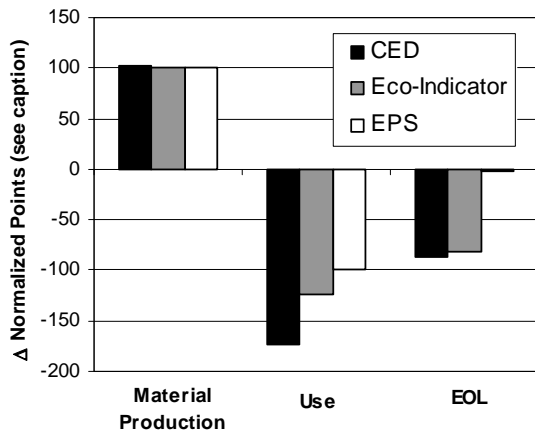
Figure 13: Normalization factor: CED = 172, Eco-Indicator = 0.72, EPS = 8.9
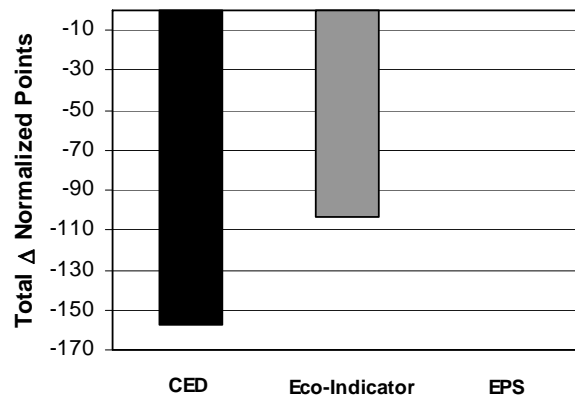
Figure 14: Total life cycle Eco-points for CED, Eco-Indicator, and EPS

3.3.1.2 Secondary Weight Savings

Realized secondary weight savings is strongly affected by the specifics of the particular vehicle being altered as well as the magnitude of primary weight savings. As such, the actual amount of secondary weight savings is not known at the early strategic stages of product development when materials choices are made. To understand the impacts of this uncertainty, Figure 15 explores the effects of secondary weight savings and fuel intensity on the relative LCA result for the two technology alternatives (as defined in Equation (2)). The environmental "benefit" attributed to secondary weight savings varies with vehicle fuel intensity, or conversely, fuel economy. As fuel intensity rises, the opportunity to achieve greater environmental savings becomes more sensitive to secondary weight savings. Nevertheless, this analysis would suggest that the LCA result (for the Eco-Indicator method) is robust to secondary weight savings assumptions across the range of values investigated for this case. A similar result was observed for the CED method.
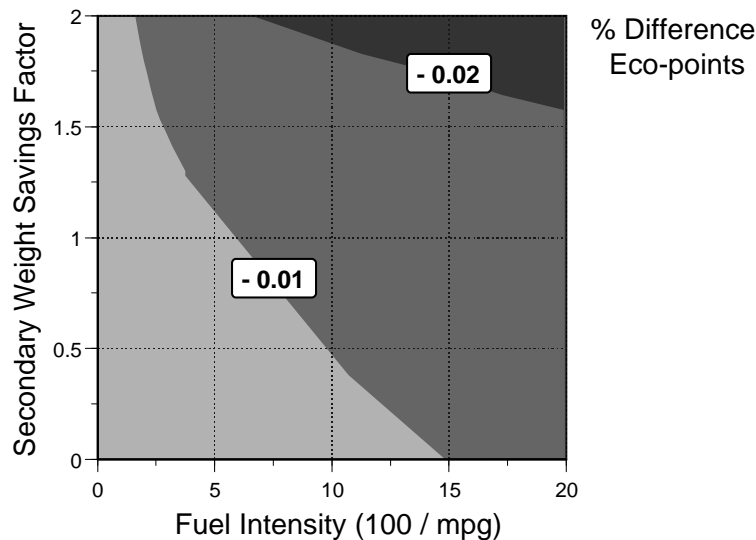
Figure 15: Comparison Relationship between secondary weight savings, fuel intensity, and percent difference in eco-points (Eco-Indicator 99)

3.3.1.3 Uncertainty in Product Use and End-of-Life Allocation Methods

Figure 16 and Figure 17 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 (3). Specifically, these plots show how percent difference changes with variation in vehicle lifetime, vehicle fuel economy (expressed as gallons per 100 miles) of the Base Case vehicle, and average driving distance per year. 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. Analysis results represent changes to any one of these values, while holding the others constant at baseline conditions. Since all three of these factors convolve to determine use phase impact (in the form of fuel consumption), it possible to represent their impact on this triple axis plot.

Each of the results in Figure 16 exhibit a distinct pattern, beginning at a positive value at the y-axis and then declining sub-linearly until eventually becoming negative as the quantity being varied increases. This behavior derives directly from the structure of the life-cycle burdens associated with the two materials alternatives. The Base Case vehicle utilizes materials with lower impacts during production, while the Comparator vehicle creates less impact during use. As the use phase becomes more intensive (as is the case when all variables are increased), the Comparator provides a relative decrease in impact (i.e., its use phase impact grows more slowly than the Base Case).

The implications of the analytical differences exhibited by the three impact assessment methods (as discussed in the previous section), are shown clearly in Figure 16. Specifically, from the y-intercept it is clear that both the CED and Eco-Indicator methods place similar relative value on the production of the two alternatives. However, the higher value placed on production relative to use that emerges from the Eco-Indicator method leads to its more gradual slope in Figure 16. The consequence of this difference is that the use phase must be more intense (i.e., longer or more miles traveled per year), before the Comparator is able to offset its higher impact production. In a similar fashion, the large value placed on production impacts by EPS 2000 leads to both a high intercept and gradual slope.

In the end, it would appear that CED and Eco-Indicator results are very robust for automotive materials selection in this case. Although both exhibit a sign change (i.e., the preferred material changes) across the range of analysis, those conditions leading to a preferred Base Case are significantly outside of the range of modern consumer automobiles. Although a baseline lifetime was selected of 11 years to maintain consistency with the USCAR AMP study, evidence suggest that vehicle lifetimes are exceeding 15 years [73]. Similarly, miles driven per year continues to grow [74]. The EPS 2000 result presents more challenge. Although the Comparator exhibits net lower environmental impact for the baseline conditions, that benefit is small. Furthermore, the preferred technology inverts for conditions only slightly less intense than the baseline.
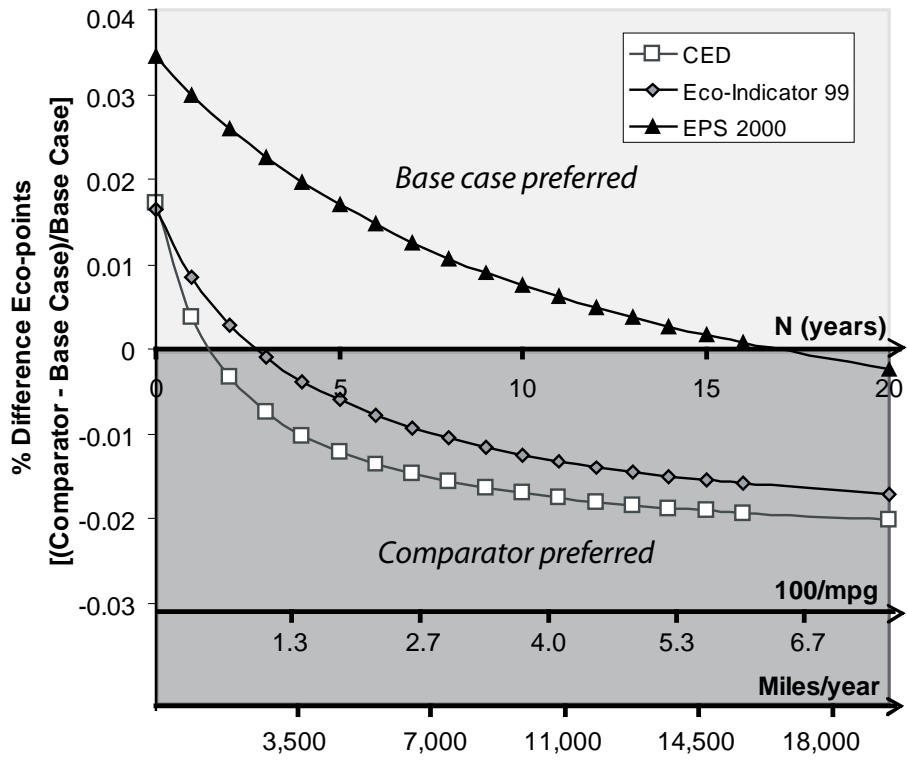
*Figure 16***:** *Comparison of Comparator and Base Case vehicles using Eco-Indicator, EPS, and CED varied across intensity of use (i.e. measured in terms of vehicle life, fuel consumption, and miles/year) – includes production, use, maintenance, and EOL*

Figure 17 differs from Figure 16 insofar as it excludes the results of the end-of-life phase from the analysis. Given the small impact of end-of-life processing, the dominant effect of this is to change the allocation rules for dealing with the benefits of recycling end-of-life materials. 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 end-of-life. Chapter 4 discusses in further depth the implications of using different end-of-life allocation methods on material choice.
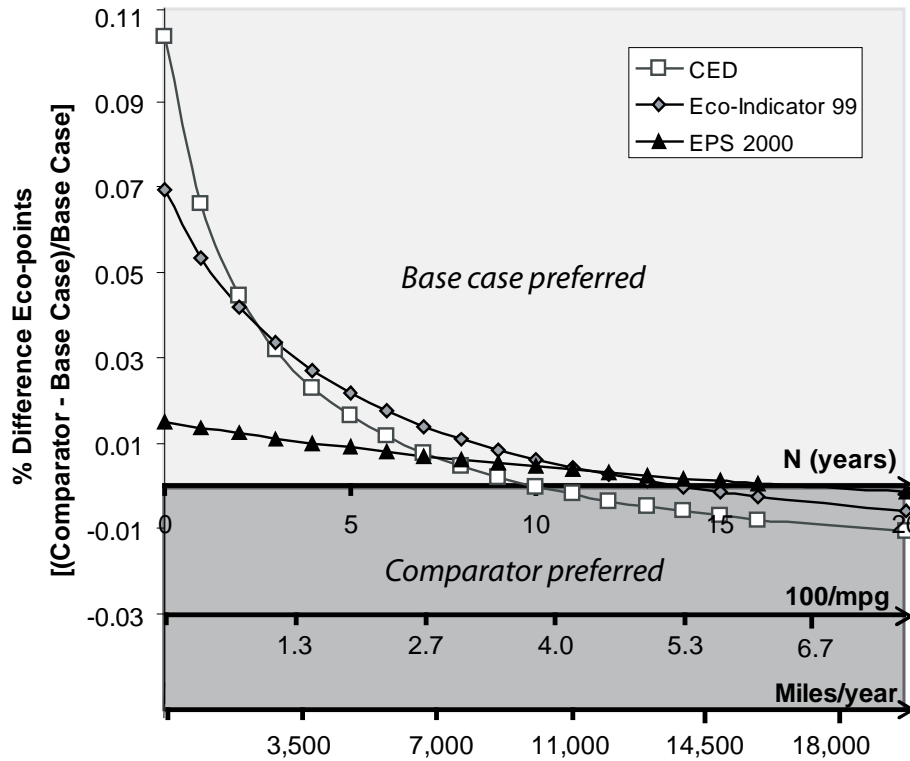
Figure 17: Comparison of Comparator and Base Case vehicles using Eco-Indicator, EPS, and CED varied across intensity of use (i.e. measured in terms of vehicle life, fuel consumption, and miles/year) – includes production, use, and maintenance (excludes end-of-life)

In the end, although excluding any benefit for end-of-life recovery has a strong effect on the absolute magnitude of the total material related impacts (cf. the y-intercepts of Figure 16 and Figure 17), ultimately the robustness of the results is only slightly changed. The CED and Eco-Indicator results show continued preference for operating conditions much less intense than the baseline and current prevailing trends. Similarly, the EPS 2000 result provides less resolution both in terms of the size of the benefit for intense use applications and the small change in relative result across the range of inquiry.

4   Case Study II: Robustness of End-of-life Allocation Methods

Whereas Chapter 3 explores questions of variation in impact assessment, uncertainty in product specification and uncertainty in product use, this chapter explores the uncertainty of end-of-life allocation and how it affects material decision making when using the LCA methodology. Specifically, the question of whether end-of-life allocation methods can lead to different materials selection decisions in early stage product development cycles is investigated and how these allocation methods differentially favor certain material classes. This chapter will further explore the analytical differences examined in the first case study around end-of-life allocation when applied to a vehicle. The chapter then moves beyond the realm of specific products into a more conceptual space that explores the sensitivity of EOL allocation methods when applied to hypothetical material types.

4.1 End-of-life Allocation Methods

As discussed in Chapter 2, ISO 14040 standards currently 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 [75]. 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 [76]. This chapter explores the implications of various EOL allocation schemes on the elected materials selection decision. Table 4 outlines the specific allocation methods analyzed herein in relation to the life cycle cascade in Figure 8, as presented and discussed in Chapter 2. Each of the methods outlined in this table are based on fundamental subjective evaluations of what is considered reasonable or fair in terms of burden allocation.

Cut-off Method

The Cut-off method simply argues that each product should only be assigned environmental impacts directly caused by that product; hence the virgin material production burden is assigned to the life cycle burden (L1) for Product 1. This follows the reasoning that had Product 1 never come into existence, no virgin material would be associated with its creation. Similarly, the recycling burden associated with Product 1 is ascribed to Product 2 (L2). The recycling burden of Product 2 is assigned to Product 3 (L3), which is also accountable for any burden associated with final waste treatment.

Loss of Quality Method

The loss of quality methods are based on the perspective that materials are valuable resources, and virgin material production and final waste treatment are necessary steps for their provision. As a material is recycled, the original material suffers a loss in quality which makes a certain level of upgrading necessary to achieve the same material function. These methods therefore make use of some sort of material quality metric, which ascribes environmental burden to each product life cycle based on its value in the product cascade. For this study, material pricing data for primary and secondary sources was used as a proxy for material value and quality.

Waste Treatment Method

The Waste treatment method is much like the Cut-off method, but assumes that final waste disposal is an ultimate consequence of raw material extraction and processing. Therefore the burden of final waste treatment is allocated to Product 1 as opposed to Product 3. This method is discussed by Östermark and Rydberg and promotes the use of recycled material, assuming that the impacts of recycling are less than the combined impacts of virgin material production and final waste treatment [63]. However, this method provides no direct incentive to developing recyclable products.

Burden on Last Product Method

This method assigns the burden of primary material production and final waste treatment to the last product in the product cascade, Product 3. This is because once disposed of, the lost material embodied in Product 3 must be replaced through virgin material production. This method promotes the development and production of recyclable materials when the combined impact of primary material production and waste treatment are less than the environmental burdens associated with recycling. Like the Waste Treatment method provides no incentive to use recycled material. This method is also discussed in Rydberg, 1995, as cited in [42].

Closed Loop Method

This method assumes that each product is equally responsible for the environmental impacts associated with virgin material production, recycling, and final waste treatment. The burden is therefore an average impact, apportioned equally among products depending on the number of times recycling occurs in the product cascade.

50/50 Method

The 50/50 method ascribes the burden of virgin material production and waste treatment to the first and last products in equal proportions. This method of end-of-life allocation promotes an underlying rationale that supply and demand for recycled material are both necessary to enable recycling. According to the impact formula, the use of recycled material and the production of recyclable products are preferable when the environmental impacts of recycling are less than the combined impacts of virgin material production and final waste treatment [77].

Substitution Method

According to ISO 14041, allocation procedures for recycling can be addressed as follows:

> "a Closed Loop allocation procedure can apply to open-loop product systems
> …where no changes occur in the inherent properties of the recycled material. In
> such cases, the need for allocation is avoided since the use of secondary material
> displaces the use of virgin (primary) materials." [18] as cited in [66]

In this case, the environmental burden of each product life cycle in the cascade are equal (L1=L2=L3), and corresponds to the burden of producing the virgin material which is required to offset the material "lost" to environmental degradation each time the product is recycled. Additionally, the burden of recycling operations must be charged to the product system under

study. Typically, this method is applies to certain metals, such as aluminum and steel, which maintain their inherent properties when recycled.

Table 4: Allocation methods for addressing EOL treatment in LCA

Method	Description	Formula
Cut-off method	Loads directly caused by product are assigned to that product [42].	$L1 = V1, L2 = R1, L3 = R2 + W3$
Loss of quality method[4] (1)	Assigns load to products in relation to their relative loss of quality in each step; virgin material production, final waste management and recycling are included for each product [42].	$L_i = \dfrac{Q_i}{\sum\limits_{i=1}^{3} Q_i} \times (V1+R1+R2+W3)$
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 included in all but last product, which includes virgin material production and final waste management [42, 78].	$L1 = \dfrac{Q1-Q2}{Q1} \times (V1+R1)$ $L2 = \dfrac{Q2-Q3}{Q1} \times (V1+R2)$ $L3 = \dfrac{Q3}{Q1} \times (V1+W3)$
Waste treatment method	Waste treatment is an unavoidable consequence of raw material extraction and processing [42, 79].	$L1 = V1 + W3$, $L2 = R1$ $L3 = R2$
Burden on last product method	Material lost through waste treatment must be replaced through virgin material production [42, 79].	$L1 = R1$ $L2 = R2$ $L3 = V1 + W3$
Closed loop approximation method	Applicable to materials such as metals that do not experience significant losses in quality when recycled [80].	$L1 = L2 = L3 = \dfrac{V1 + (R1+R2) + W3}{3}$
50/50 method	Virgin material production and waste treatment are allocated to the first and last products in equal proportions [42, 77].	$L1 = \dfrac{V1+R1+W3}{2}$, $L2 = \dfrac{R1+R2}{2}$ $L3 = \dfrac{V1+R2+W3}{2}$
Substitution method	Recycled material substitutes primary material; accounts for the load of producing (e.g. X% = 10%) "lost" virgin material and recycling burdens [66].	$L1 = (100\%-X\%) \times (R1) + X\% \times (V1+W3)$

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[4] Q_i is the quality of material in P_i. Quality ratios were computed using market pricing data for primary and scrap materials. Q1 assumes all primary material, hence no material degradation, and is equal to one.

4.2 End-of-life Allocation Methods Applied to Case I

Case I presents an upper and lower bound on how EOL assumptions can affect crossover point, or the elapsed lifetime at which the environmental burden associated with material production and use of the comparator material equals that of the baseline. Referring back to Figure 16 and Figure 17, the crossover time was as high as 10-15 years when excluding EOL consideration, and as low as 2-3 years when assuming EOL credits for recycled material.

To continue this exploration, this section applies five of the EOL allocation methods described above to evaluate how the selected method affects crossover point. Figure 18 illustrates how choice of choice of EOL allocation method can affect the difference in CED eco-points between the Comparator and Base Case vehicles. A dashed line is shown for reference purposes because the substitution method is the most widely applied method in the literature.

Table 5 then shows how these energy values translate into crossover point in years, using the assumptions in Table 2. When no credit is given for material recycling at the vehicle end-of-life, the CED method indicates that the crossover point would occur at 10 years. This crossover time is reduced across each of the five EOL allocation methods from 5.8 years for the Cut-off method. to as little as 0.7 years for the Substitution.
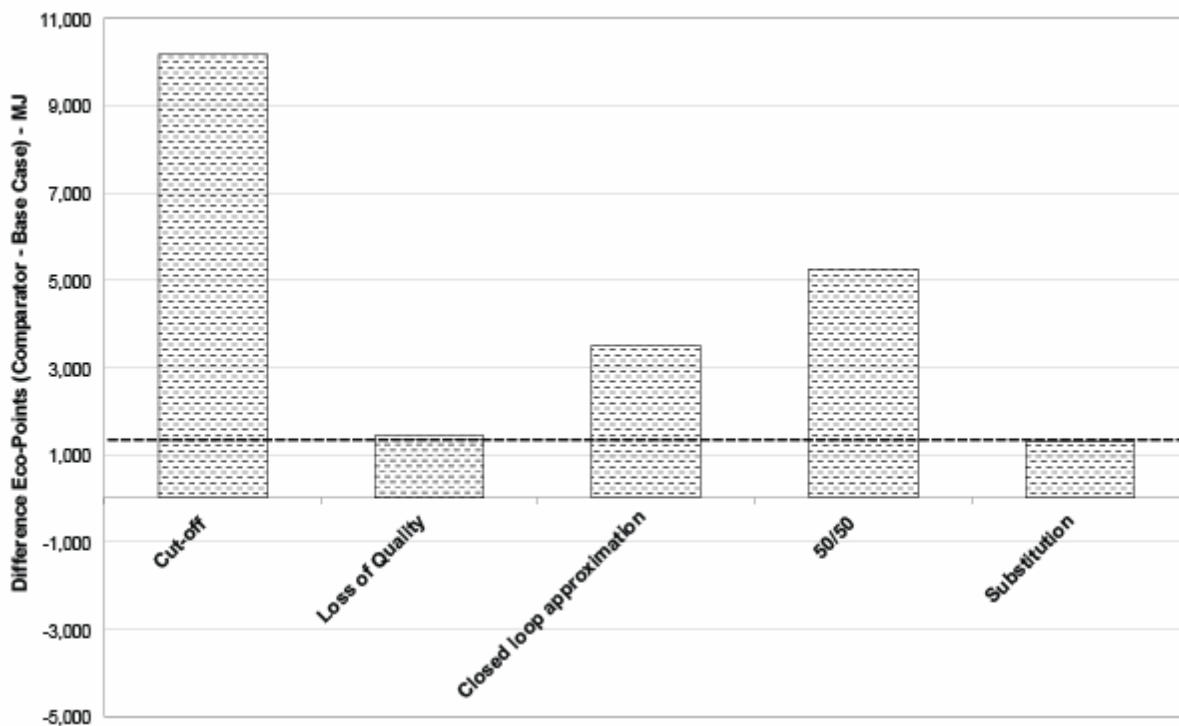
Figure *18: *Comparison of Base Case and Comparator vehicles using CED varied by EOL allocation method*

End-of-Life Method	Crossover point (Years)
No EOL allocation	10.0
Cut-off	5.8
Loss of quality	0.8
Closed loop approximation	2.0
50/50	3.0
Substitution	0.7

Clearly, EOL allocation methods can significantly affect results. It is probably not surprising that the methods lead to different values, but this raises two important questions: Do these methods systematically "favor" certain materials? Furthermore, can we isolate the characteristics of those materials?

4.3 Base Case and Alternative Materials Comparator Selection

To understand the implications of various EOL assumptions, a more conceptual materials selection case study was developed and analyzed. The case involved comparing one kg of Material B with one kg of a several Comparator materials, or Materials A. Each of these comparator materials exhibits a wide range of environmental performance due to material degradation and processing differences between primary and secondary applications. To isolate the effects of the EOL allocation method, this analysis does not take into consideration the use phase associated with these materials. As such, the subsequent results are not useful in identifying the preferred material for any given application. However, these analyses do demonstrate the effects of EOL allocation method in establishing the production phase burden of a particular product. Furthermore, differences in the evaluation of these phases would directly translate into the necessary difference in use phase performance to identify a preferred material.

Before moving into a fully parameterized case, it is useful to explore the impact of EOL allocation in a limited stepwise fashion. Consider the set of materials listed in
 which comprises Material B and a set of Materials A, each of which has the same energy burden

	Material B	Material A Recycling burden = 20% of virgin production energy	Material A Recycling burden = x% of virgin production energy	…	Material A Recycling burden = 100% of virgin production energy
Primary energy burden	50	25	25		25
Recycling energy burden	15	5	$25 \times x$		25

for primary production but difference and increasing burden associated with recycling. **Figure 19:**Figure 19 plots the total burden associated with L1 for each of the materials when using the Substitution method. Compared to Material B, when A has a recycling burden of 20%, it has a much lower burden when evaluated using the Substitution method. This difference is shown more clearly in Figure 20 that plots the difference between Material A and B (A-B). As shown clearly in Figure 20, as the recycling burden of Material A increases, the advantage of A

declines. Somewhere between a recycling burden of 0.6 and 0.75, A and B have the same total burden. If A has a recycling burden beyond 0.8, then the total burden of B is assessed to be less than A. Figure 21 and Figure 22 show how these relationships are changed by shifting to the Closed Loop allocation method. Not surprisingly, Material has a total burden much less than B when using the Closed Loop method and this burden advantage decreases as the recycling burden of A increases. Interestingly, however, Material A only begins to reach an equivalent total burden of B when its recycling burden approaches 1.1 (a level of burden actually higher than that for the primary production of A). Ultimately, the absolute magnitudes of the points 0.8 and 1.1 are not directly meaningful because this assessment excludes any burden associated with product use. Figure 20 and Figure 22 include lines that indicate how these points of burden parity shift if A provides a use phase burden advantage (black line) or a use phase burden disadvantage (dashed line). For the questions here, the most pertinent information is how these two methods are differentially effected by changes in characteristics of the materials being compared (here the recycling burden of A). Figure 23 provides an effective way to examine this question. Specifically, Figure 23 plots the difference in burden between A and B (A-B) for the two methods being explored. As is clear from Figure 23, the Substitution method is much more sensitive to the recycling burden of Material A, increasing the total burden assessed to A at a more rapid rate as recycling burden grows. To explore this more broadly, the next sections develop fully parameterized expressions of the EOL allocation methods being explored herein and then uses these to quantitatively explore the differential sensitivity of these methods.

Table 6: Primary and recycling energy burdens for Material A and B

	Material B	*Material A* Recycling burden = 20% of virgin production energy	*Material A* Recycling burden = x% of virgin production energy	...	*Material A* Recycling burden = 100% of virgin production energy
Primary energy burden	50	25	25		25
Recycling energy burden	15	5	$25 \times x$		25

Figure 19: Substitution method for Material B and Material A across different recycling burdens
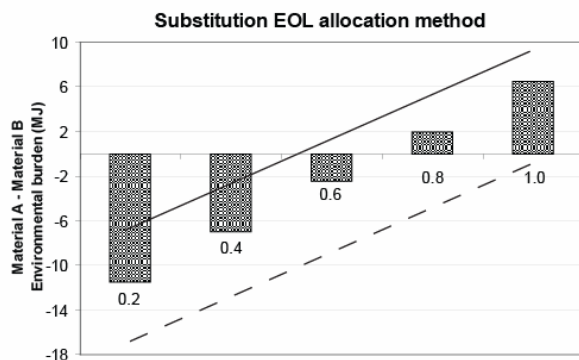
Figure 20: Substitution method for Material A – Material B across different recycling burdens
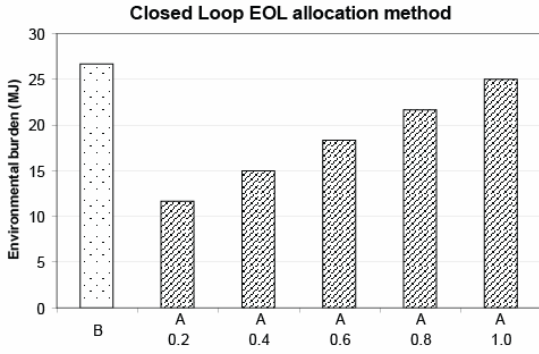
Figure 21: Closed Loop method for Material B and Material A across different recycling burdens
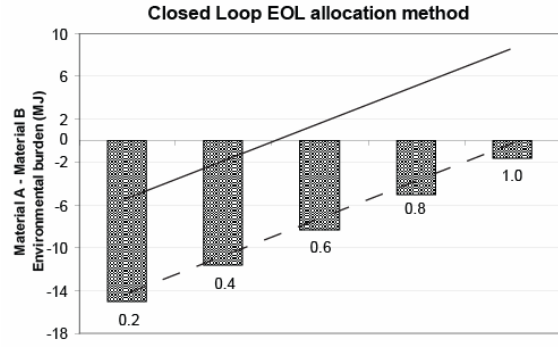
Figure 22: Closed Loop method for Material A – Material B across different recycling burdens
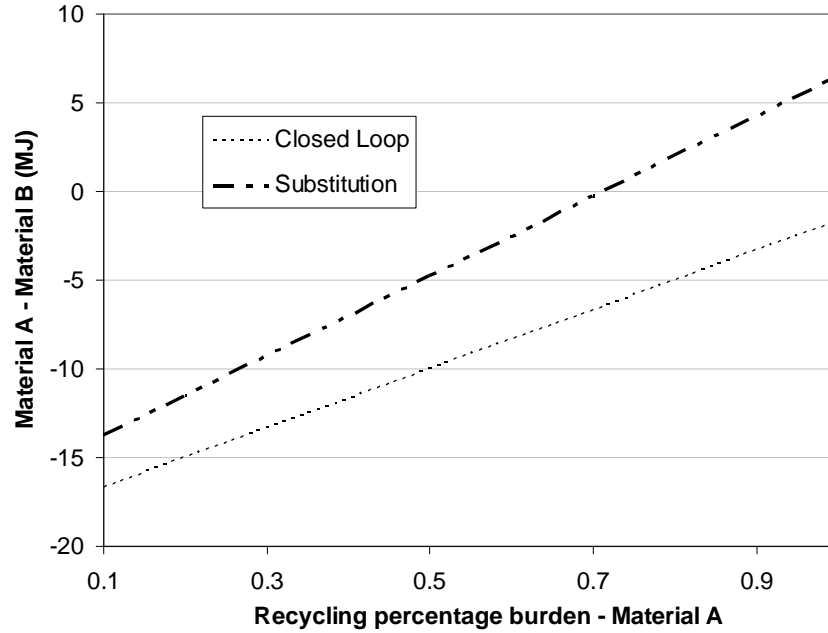
Figure 23: Material A – Material B for Closed Loop and Substitution methods across different recycling burdens

To develop appropriately parameterized versions of the EOL allocation methods, it is first necessary to develop some nomenclature to define the relative performance of Materials A and B. First let the ratio between the primary energies associated with producing one kg of Comparator Material A in proportion to the Baseline Material B, V_A/V_B, be defined herein as the parameter m. In subsequent analyses, values for m between 0.1 and 1.1 were explored. These ratios represent a set of cases ranging from ones where the materials being compared exhibit a high discrepancy between primary production energy ($m=0.1$) to those that have very similar primary energy ($m=1.1$). Similarly, dimensionless parameters k and q were also defined to represent specific material properties; k corresponds to the ratio of secondary production energy to primary production energy (R_A/V_A or R_B/V_B) and q is a measure of material degradation through recycled generations calculated using market pricing data for primary and scrap materials. For a case where there are three product generations, q is defined as:

$$q = \frac{Q1}{Q1+Q2+Q3} = \frac{1}{1 + \dfrac{Price_{scrap}}{Price_{primary}} + \dfrac{Price_{scrap}}{Price_{primary}}} \quad (4)$$

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Other assumed parameters defined in the subsequent formulations include r, used in the Substitution method to indicate the amount of primary material needed in secondary material production to account for lost material in the recycling process and n, the number of generations a material can be used before it is discarded. For all subsequent analyses, $n=3$ unless specified otherwise. Table 7 illustrates the parameters $V_{A\ or\ B}$, m, k and q in terms of commonly known materials for reference purposes.

Table 7: V1, m, k and q values for various materials

Material	$V_{A\ or\ B}$ (MJ)	m (V_A/V_B)	k $(R_A/V_A$ or $R_B/V_B)$	q $(Q_i/\Sigma Q_i)$
Aluminum	160.3	5.2	0.16	0.36
Polypropylene	74.8	2.5	0.51	0.72
Paper	26.6	0.9	0.61	0.87
Steel	30.5	-	0.31	0.57

Table 8 outlines the formulas for the allocation methods studied, both in their traditional LCA format and the format using the parameters defined above for this study.

Table 8: Allocation formulas of Product 1 (L1) using parameters in Table 8

Method	Traditional Formula (Life cycle of P1 (L1))	Formula based on study-defined parameters (Life cycle of P1 (L1))
Cut-off	V1	$V_B \times m$
Loss of quality	$\dfrac{Q_i}{\sum\limits_{i=1}^{3} Q_i} \times (V1+R1+R2+W3)$	$V_B \times m \times \left[q(1+k(n-1))\right]$
Closed loop	$\dfrac{V1 + (R1+R2) + W3}{3}$	$V_B \times m \times \dfrac{1+k(n-1)}{n}$
50/50	$\dfrac{V1+R1+W3}{2}$	$V_B \times m \times \dfrac{1+k}{n-1}$
Substitution	$(100\%\text{-}X\%) \times (R1) + X\% \times (V1+W3)$	$V_B \times m \times \left[k(1-r)+r\right]$

4.4 Results

While the example used in the first case study focuses on a use-phase dominated product, the vehicle, this section seeks to understand on a more fundamental level how end-of-life assumptions affect the environmental profile of the material itself, outside the context of a material's application, or product use. This section will show how each end-of-life allocation method is differentially sensitive across the parameters defined in the previous section.

Specifically, consideration is given to understanding how *m, k, n, q,* and *r* affect preferred material. In this context, the preferred material is defined as the material with less cumulative environmental impact associated with virgin material extraction, recycling, and final waste treatment than its comparator. To this end, these results are not helpful in making proclamations about ultimate preferred material outside the scope of this study. This case study uses the Cumulative Energy Demand LCA methodology, discussed more in-depth in case study I. The evaluation metric is megajoules (MJ), and the preferred material is defined as having a lower environmental impact in MJ.

4.4.1 Sensitivity of material choice to parameter *k*

This section describes sensitivity of the preferred material result to the value of parameter *k* (the ratio of recycling production energy to primary production energy) for each of the five end-of-life allocation methods described previously. Here the Comparator material (Material A) is evaluated against the Base case (Material B) material, for several values of *m* (the ratio of the primary production energies). The figures in this section show both how Material A compares with Material B in absolute space for two values of k_A, then for a "delta" space, in which the difference in MJ between Material A and Material B. In these delta plots, negative values indicate a preference for Material A while positive values indicate preference for Material B. The concept of method rank order is also explored in these delta plots, which considers how the methods change in their relative preference for a certain material across the varied parameter.

Figure 24 compares the results between the Base case and Comparator materials using the EOL methods outlined in Table 8 for k_A and k_B values of 0.1 and 0.9 using an initial value of *m*=0.1. Although the EOL methods clearly effect the absolute magnitude of the evaluation, the preference for Material A is unaffected across these cases. Irrespective of EOL allocation, Material A is assessed at a significantly lower total burden than Material B. Nevertheless, the disparity between Materials A and B can vary significantly from 3 to 40 MJ. Figure 25 shows a plot of the delta space between Material A and Material B for a $k_B = 0.1$ across each of the five end-of-life methods. As seen in this plot, the methods do not change in their relative rank order across the parameter k_A, with all methods preferring Material A, but increasing in their preference starting with Substitution, Closed Loop, 50/50, Loss of Quality, to the Cut-off method, which reveals the highest preference. Figure 26 again shows a plot of the same delta space for a $k_B = 0.9$. The rank order remains the same from the plot in Figure 25, with the exception of the Loss of Quality and Cut-off methods which switch in relative rank order. These delta plots reveal that at low values of *m*, end-of-life allocation methods maintain that Material A is the environmentally preferred and that this preferences is relatively insensitive to changes in parameter k_A, indicating Material A is the environmentally preferred material. For example, when considering the Closed Loop method in Figure 25, the energy burden is -11.0 MJ on the left side of the plot when k_A =0.1, and when $k_A = 0.9$ on the right, is -9.4 MJ. This means that for comparatively large discrepancies between primary energy values of Material A compared to Material B, the choice of method does not change the preferred material, and methods maintain consistent rank order across the parameter k_A. A higher value of k_B in Figure 26 serves to mute the difference between all methods except for Loss of Quality, and pronounces the environmental preference for Material A by shifting the y-intercept downwards.

Lifecycle 1: m=0.1

Figure 24: Environmental impact by EOL allocation method for Material A and Material B for m=0.1, kA=0.1, and kA=0.9

Figure 25: Delta Environmental impact by EOL allocation method for Material A - Material B varied across choice of parameter kA, m=0.1, kB=0.1
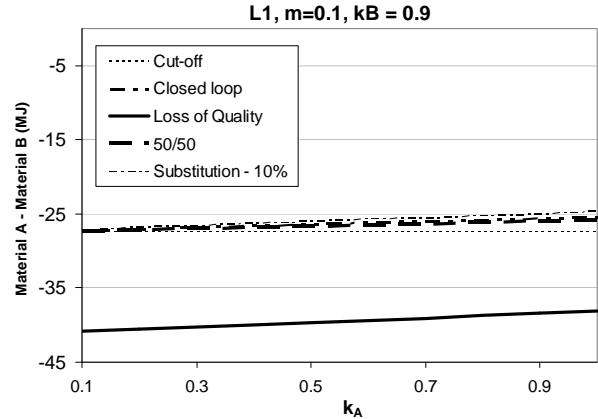
Figure 26: Delta Environmental impact by EOL allocation method for Material A - Material B varied across choice of parameter kA, m=0.1, kB=0.9

Figure 27 considers a mid-range value of *m*=0.5, corresponding with a Material A primary production energy that is half of Material B. At this *m*-value, excluding any consideration of use phase benefits, Material A remains the preferred material in Figure 27 for the Cut-off and 50/50 EOL allocation methods, regardless of parameters k_A and k_B. Figure 27 also shows that material preference for Closed loop, Loss of Quality and Substitution methods depends on choice of parameters k_A and k_B. While Material A is the preferred material for these three methods at low k_A values, Material B becomes the preferred material when k_A becomes large enough for the method to pass over the x-axis, as seen in Figure 28. These methods are all differentially sensitive to k_A, as demonstrated by the markedly differing slopes across the methods. Highlighting this difference in slope are several crossover points, occurring when the Loss of Quality method intersects the Closed Loop and 50/50 methods.

Figure 29 explores the result when parameter k_B is 0.9. Similar to the result when *m*=0.1, a higher k_B value shifts all methods' y-intercepts downwards, pronouncing their preference for

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Material A. In this case, Material A remains the preferred material choice across all k_A values. The Closed loop, 50/50 and Substitution methods do exhibit a crossover point at around k_A =0.8, after which point the methods change in rank order and relative preference for Material A.
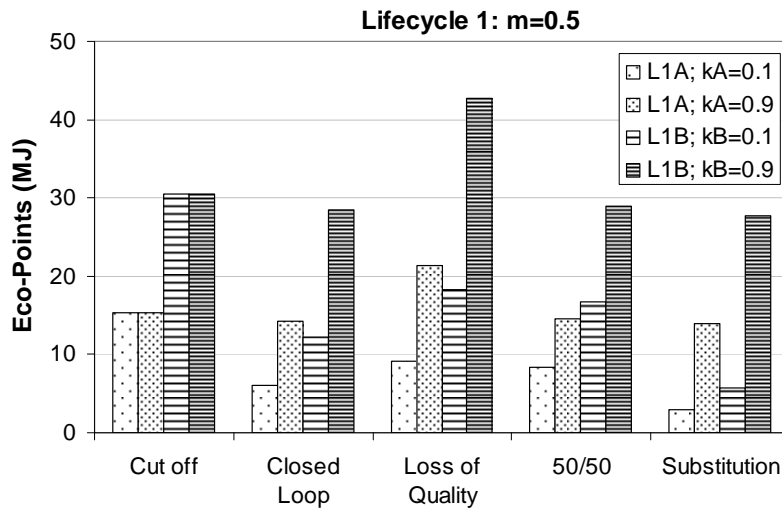
Figure 27: Environmental impact by EOL allocation method for Material A and Material B for m=0.5, k_A=0.1, and k_A=0.9
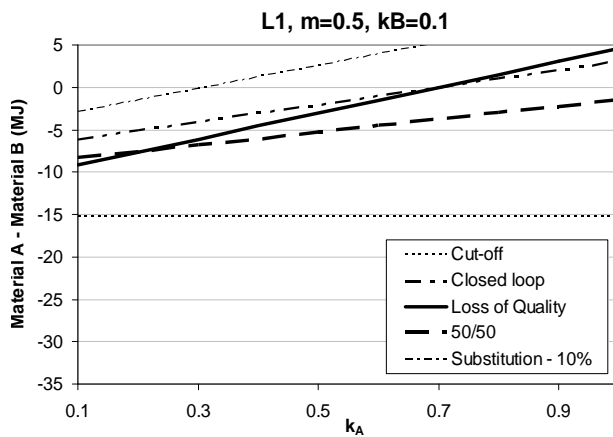
Figure 28: Delta Environmental impact by EOL allocation method for Material A - Material B varied across choice of parameter k_A, m=0.5, k_B=0.1
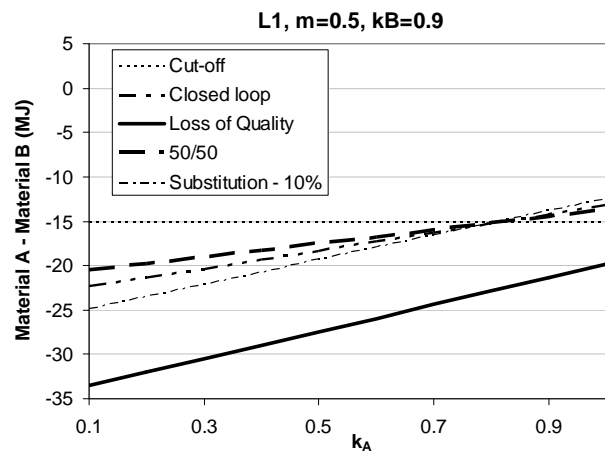
Figure 29: Delta Environmental impact by EOL allocation method for Material A - Material B varied across choice of parameter k_A, m=0.5, k_B=0.9

Figure 30 through Figure 32 present a Material A and Material B with *m*=0.9. Figure 30 indicates that Material A is the environmentally preferred material for all methods when k_A is 0.1, regardless of choice of k_B. When k_A = 0.9 and k_B =0.1, Material B is the environmentally preferred material by a large magnitude. Examining the delta space plot for k_B =0.1 in Figure 31 shows that while extremely low k_A values initially favor Material A for all methods, shortly after k_A>0.1 all methods but the Cut-off method switch to prefer Material B. As k_A continues to grow, the difference between the methods becomes more pronounced. Conversely, in Figure 32, increasing values of k_A cause the methods to converge at approximately k_A = 0.9, the crossover point, after which all methods but the Loss of Quality switch in rank order. In this plot, which considers k_B =0.9, Material A is the preferred material across all values of k_A. In both delta plots, differences between method slope is visible and illustrates the differential sensitivity to the parameter kA. Listed in order of increasing slope, and therefore increasing sensitivity to kA, are the Cut-off, 50/50, Closed Loop, Substitution, and Loss of Quality methods.

Lifecycle 1: m=0.9
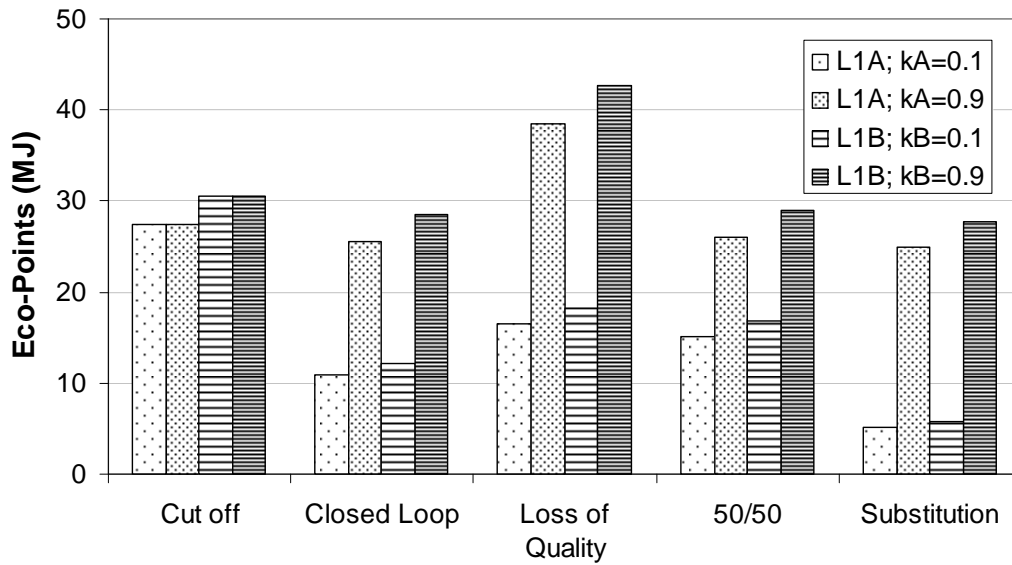
Figure 30: Environmental impact by EOL allocation method for Material A and Material B for m=0.9, kA=0.1, and kA=0.9
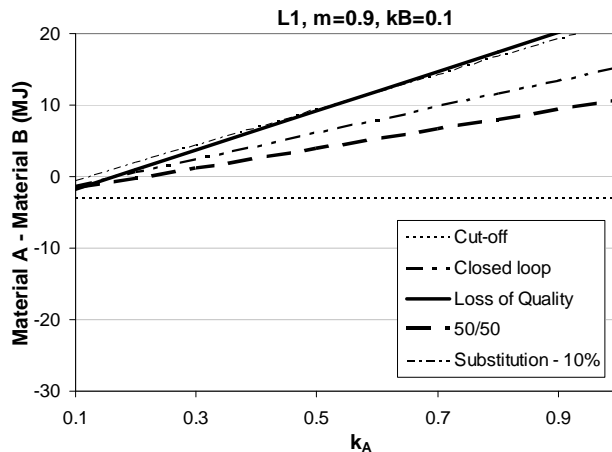
Figure 31: Delta Environmental impact by EOL allocation method for Material A - Material B varied across choice of parameter k_A, m=0.9, k_B=0.1
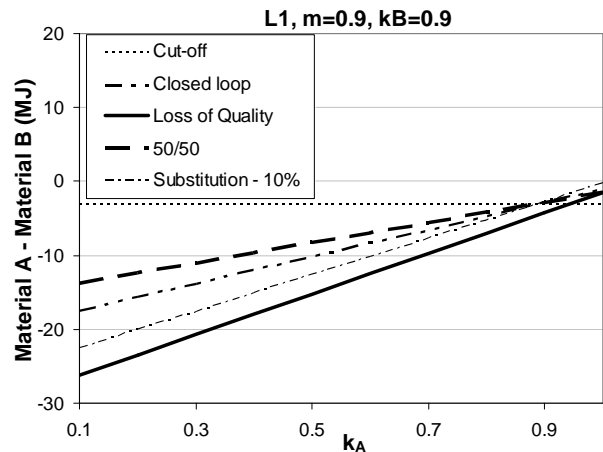
Figure 32: Delta Environmental impact by EOL allocation method for Material A - Material B varied across choice of parameter k_A, m=0.9, k_B=0.9

Figure 33 shows that at high values of *m*, or where there is a similar primary energy burden between Material A and B, material preference depends highly on the parameter *k*. For low values of k_B, Material B is the preferred material candidate across all EOL allocation methods. The delta plot in Figure 34 reveals that when k_B is low, all methods prefer Material B at low k_A values and as k_A grows, so does the relative magnitude of their preference for Material B. However, in Figure 35, low k_A values indicate method preference for Material A up to a approximately k_A=0.7-0.8, at which Material B becomes the environmentally preferable material for all methods. Additionally, there is a crossover point at ∼ k_A = 0.85, at which all methods demonstrate a switching in relative rank order.
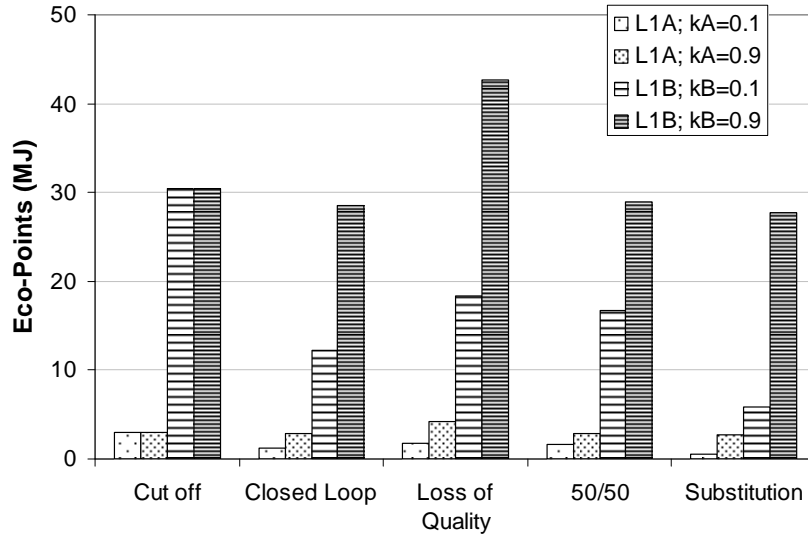
46
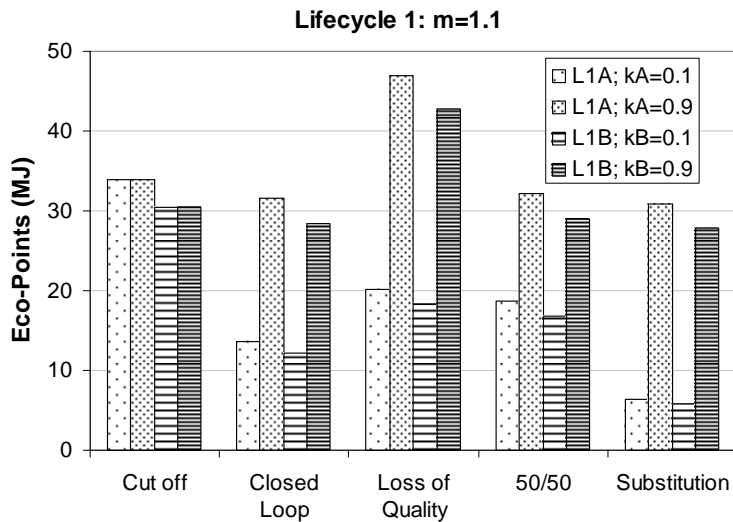
Figure 33: Environmental impact by EOL allocation method for Material A and Material B for m=1.1, kA=0.1, and kA=0.9
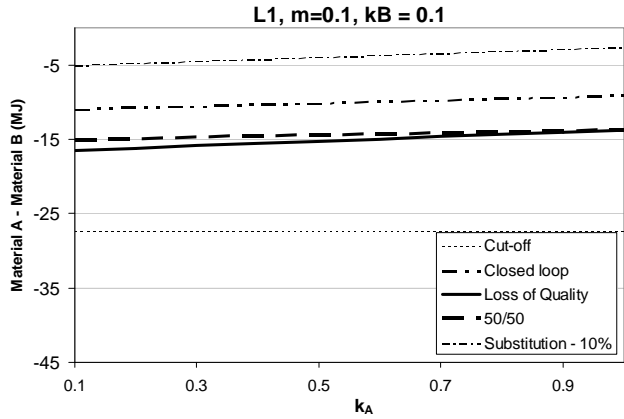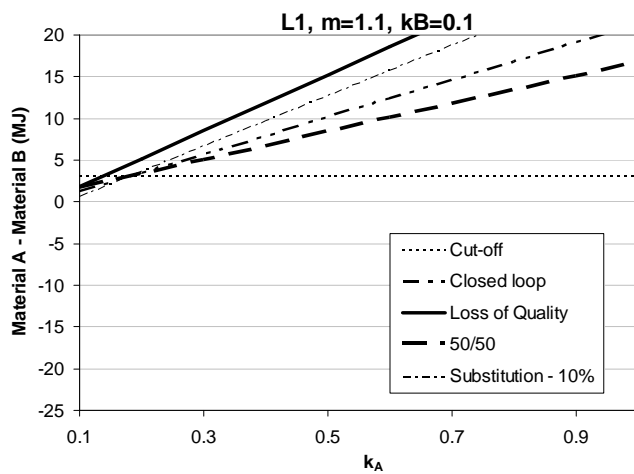

Figure 34: Delta Environmental impact by EOL allocation method for Material A - Material B varied across choice of parameter k_A, m=1.1, k_B=0.1
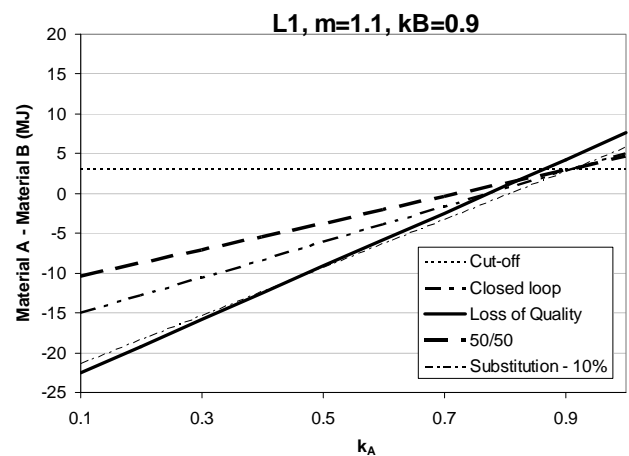
Figure 35: Delta Environmental impact by EOL allocation method for Material A - Material B varied across choice of parameter k_A, m=1.1, k_B=0.9

When considering materials with very different primary energy burdens (low m), end-of-life allocation method does not change the elected material regardless of the parameters k_A and k_B. However, when materials have similar primary energy burdens, as seen in Figure 33 through Figure 35, preferred material is highly dependent on k_A and k_B.

Overall, the differences in EOL allocation method slope, resulting from the parameter *m*, cause a differential sensitivity to the parameter k_A. The Loss of Quality method demonstrates the strongest sensitivity to k_A, followed by the Substitution, Closed Loop, 50/50 and Cut-off methods. A high sensitivity to k_A implies that a method incentivizes the use of materials with low recycling burden compared to other methods. For example, when the primary energy difference between Materials A and B is similar (*m*=1.1), and the recycling energy for B is low, the Loss of Quality method incentives the use Material B. When the recycling energy for B is high, the Loss of Quality method then incentivizes the use of Material A up to a crossover value of k_A, after which Material B is preferred.

4.4.2 Sensitivity of material choice to parameter *n*

This section describes sensitivity of the preferred material result to the parameter *n*, the number of recycling generations assumed for a product. Again, each of the five end-of-life allocation methods described previously are explored. As no definitive baseline number of recycling generations exists for any particular material, these results examine how different choices regarding the number of times a material is recycled can affect choice of the environmentally preferred material.

Figure 36 through Figure 47 explore the results between the Base case and Comparator materials again using the EOL methods outlined in Table 4, when varying *n*, the number of recycling generations before a material is discarded. In these plots, the parameter *k* is held constant and it is assumed that $k_A = k_B = 0.5$. Although only three methods, 50/50, Loss of Quality, and Closed Loop, are affected by varying the parameter *n*, the Cut off and Substitution methods are shown here for comparative purposes. All results shown are for L1, the first product life cycle stage in the product cascade in Figure 8.

Figure 36 shows how Materials A and B compare given a ratio of primary energies of *m*=0.1. The first graph shows a comparison between the two materials when it is assumed that Material A and B will be recycled for both two and seven generations. In this former case, Material A is always the environmentally preferable material, for both an assumed low (2) and high (7) number of recycling generations. However, this discrepancy between materials becomes less pronounced for the Closed Loop method and even more so for the 50/50 method as seen when seven recycling generation is assumed for Material B. Conversely, the Loss of Quality method indicates a higher environmental burden for Material B as the number of recycling generations increases.

Figure 37 and Figure 38 show the delta space plots between Material A and Material B for the graph in Figure 36. For $n_B = 2$, the methods maintain relatively equal sensitivity to material preference across the parameter n_A. The Loss of Quality method has a steeper slope than the other methods, contributing to a switch in rank order at ~n_A= 2 and 9. It is interesting to note the switching in rank order between the methods in the delta plots n_B=2 and n_B =7. At n_B,=2 the 50/50 method shows highest rank order preference for Material B; however, at n_B =7, the method switches and shows lowest preference for Material B. Similar findings are apparent for the Loss of Quality method, which shifts to a much stronger preference for Material B when considering higher recycling generations for B. These results show that Material A remains the environmentally preferred material regardless of choice of n_A or n_B for this combination of material characteristics. Nevertheless, both the 50/50 and Loss of Quality methods are very, and conversely, sensitive to n (in this base n_B).

m = 0.1
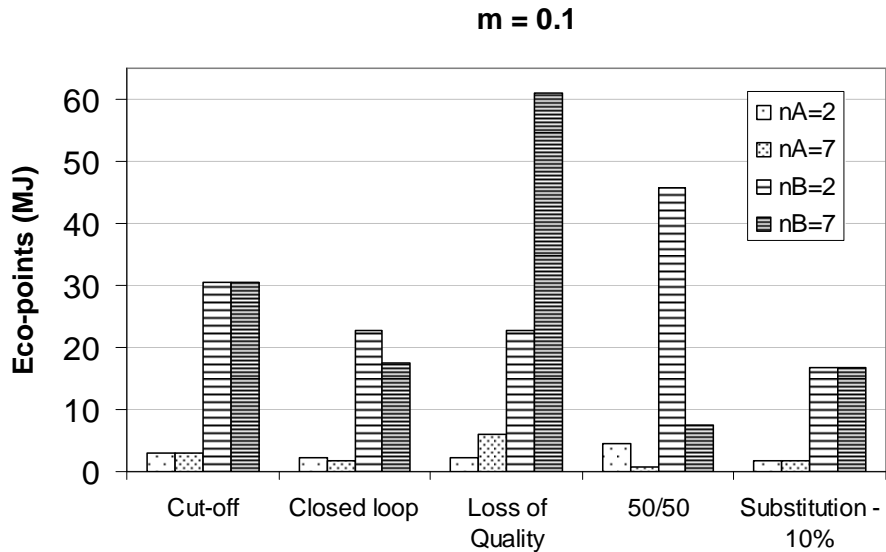
Figure 36: *Environmental impact by EOL allocation method for Material A and Material B, assuming n = 2 and 7 generations of recycling. kA = kB = 0.5, m=0.1*
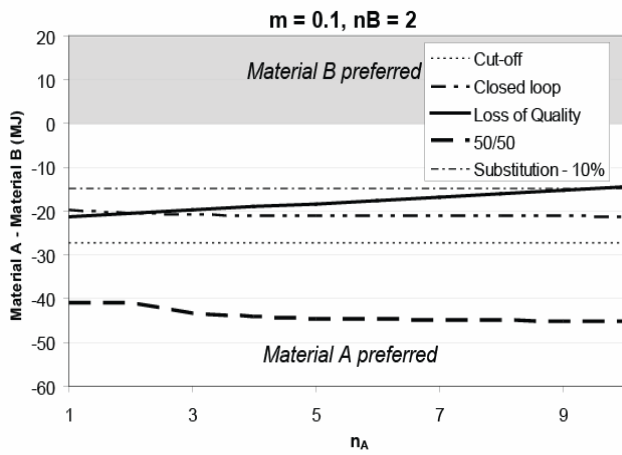
Figure 37: *Delta environmental impact by EOL allocation method for Material A - Material B in MJ across nA, assuming nB = 2 generations of recycling. kA = kB = 0.5, m=0.1*
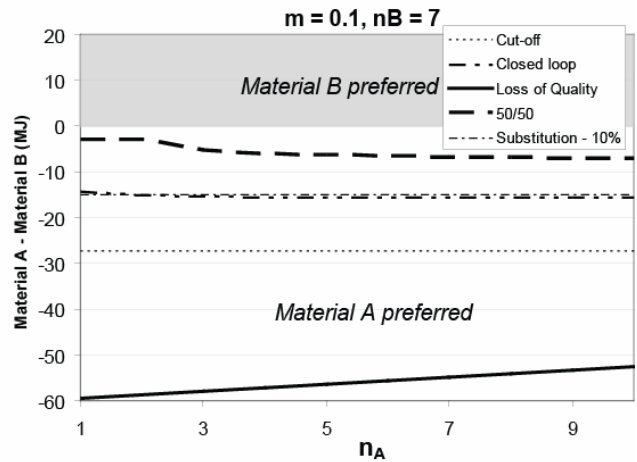
Figure 38: *Delta environmental impact by EOL allocation method for Material A - Material B in MJ across nA, assuming nB = 7 generations of recycling. kA = kB = 0.5, m=0.1*

Figure 39 considers the behavior of the methods across the parameter *n* a higher *m* value of 0.5. Immediately apparent in Figure 39 is that Material A at n_A =2 and n_B =7 is the preferred material choice for all allocation methods except Loss of Quality, when n_A =7.   Once again, it is interesting to look at plots of the delta space between Material A and Material B, as seen in Figure 40 and Figure 41.   When considering a low number of recycled generations for Material B (Figure 40), the relative performance of A is most strongly effected in the Loss of Quality method. In fact, excluding any use phase benefit, Material B actually becomes the preferred material at or above $n_A \approx 5$. The 50/50 method also demonstrates strong sensitivity to nA, increasingly favoring Material A as n_A grows.

When considering a high n_B for Material B, the preferred material choice switches for the 50/50 method as n_A grows; at low n_A, the 50/50 method prefers Material B but then switches at ~ n_A =4 to prefer Material A. This sensitivity behavior is also consistent with that for low n_B. Also, the preference switch seems consistent with that sensitivity as well. The Closed Loop method also

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reveals some sensitivity to n, although not as pronounced as the 50/50 and Loss of Quality methods.

m = 0.5
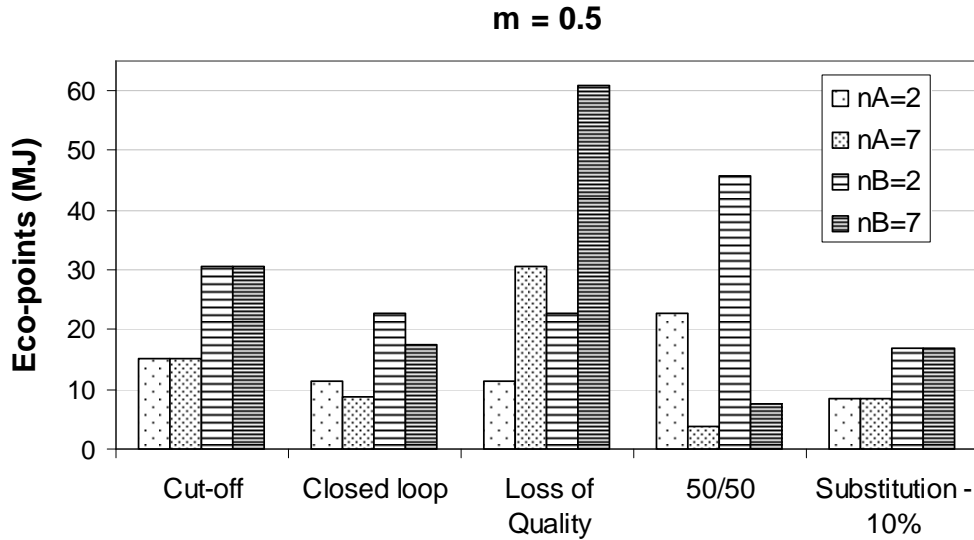
Figure 39: *Environmental impact by EOL allocation method for Material A and Material B, assuming n = 2 and 7 generations of recycling. kA = kB = 0.5, m=0.5*
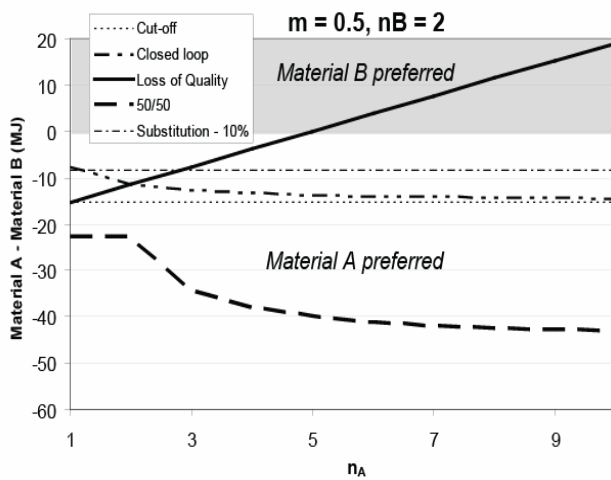
Figure 40: *Delta environmental impact by EOL allocation method for Material A - Material B in MJ across nA, assuming nB = 2 generations of recycling. kA = kB = 0.5, m=0.5*
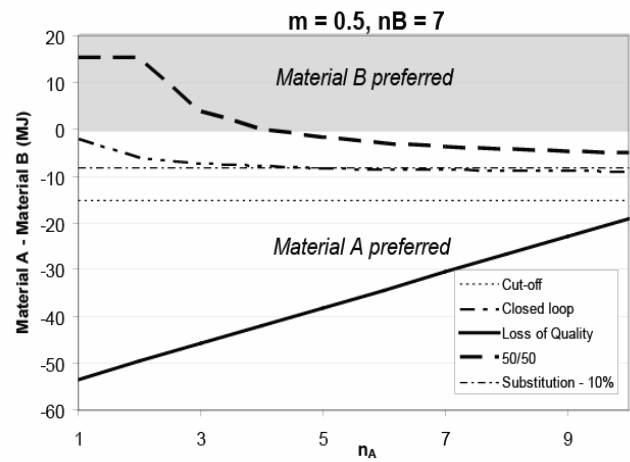
Figure 41: *Delta environmental impact by EOL allocation method for Material A - Material B in MJ across nA, assuming nB = 7 generations of recycling. kA = kB = 0.5, m=0.5*
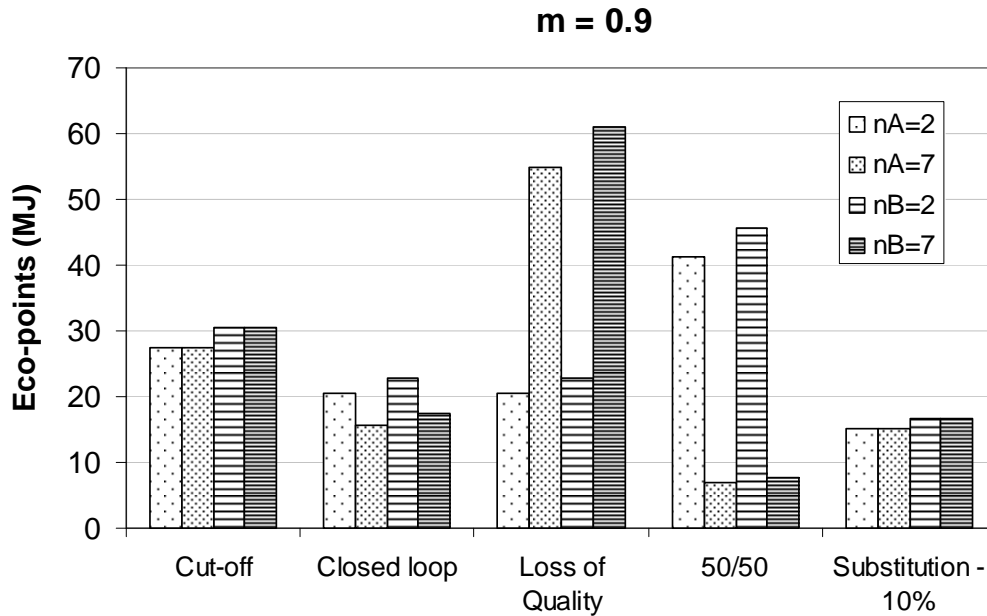
Figure 42: *Environmental impact by EOL allocation method for Material A and Material B, assuming nB = 2 and 7 generations of recycling. kA = kB = 0.5, m=0.9*
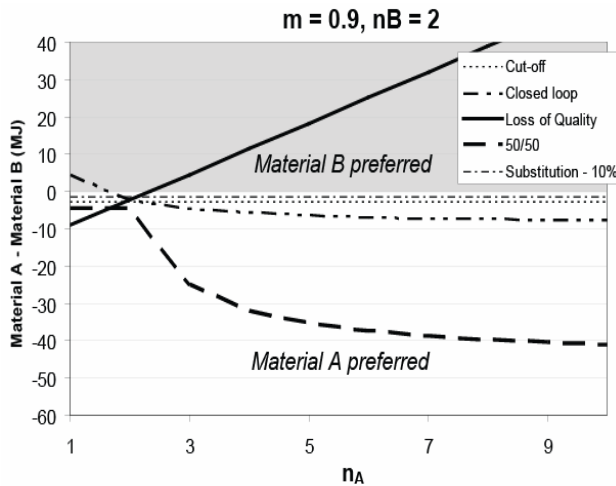
Figure 43: *Delta environmental impact by EOL allocation method for Material A - Material B in MJ across nA, assuming nB = 2 generations of recycling. kA = kB = 0.5, m=0.9*
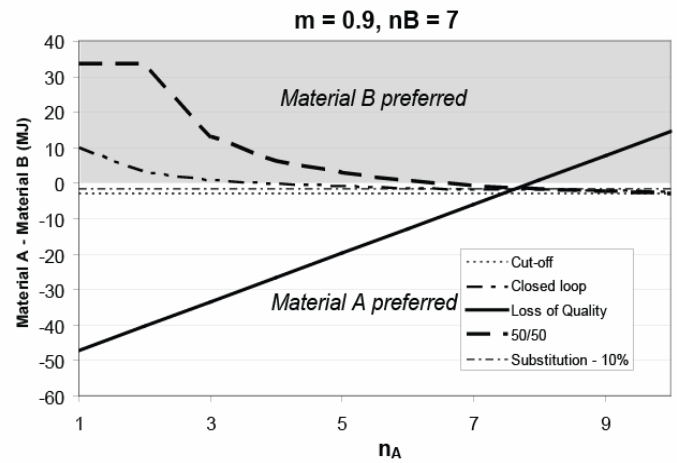
Figure 44: *Delta environmental impact by EOL allocation method for Material A - Material B in MJ across nA, assuming nB = 7 generations of recycling. kA = kB = 0.5, m=0.9*

The last case investigated considers an *m* of 1.1, corresponding with similar primary production energies for Material A and B. The results from previous explorations are even more pronounced here for the Loss of Quality and 50/50 methods. Whereas with lower *m*'s, material A is the preferred material choice for the Closed Loop, Loss of Quality, and 50/50 methods when $n_A = n_B = 2$, an *m* of 1.1 causes Material B to be the environmentally preferred material for these methods (Figure 45). This figure also reveals that Material A is the preferred material choice for Closed Loop and 50/50 when a higher value of $n_A = 7$ is considered. This switches when considering a higher n_B for Material B; Material B becomes the preferred material for Closed Loop and 50/50 when compared to a Material A of $n_A = 7$. Similarly, Figure 45 shows that a high

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n_A and low n_B combination results in a preferred Material B for the Loss of Quality Method, which does not change when considering a high n_B.

m = 1.1
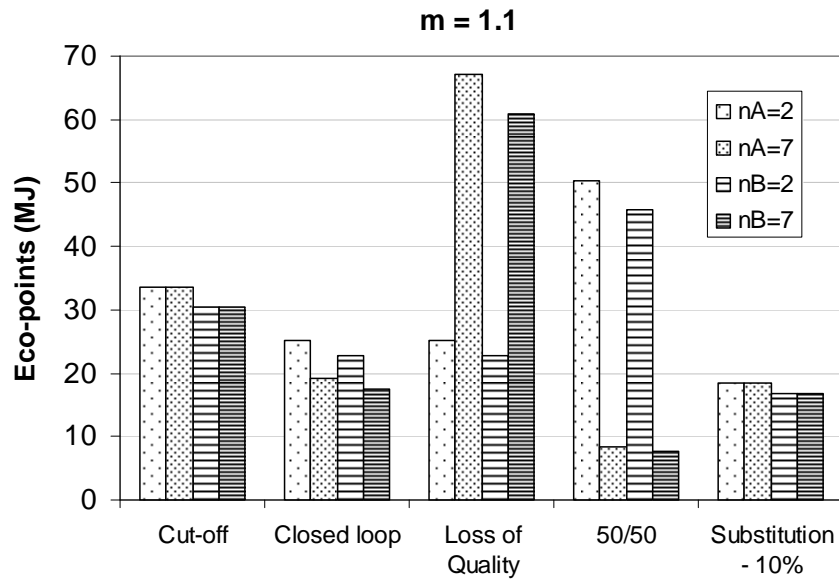
Figure 45: *Environmental impact by EOL allocation method for Material A and Material B, assuming $n_B = 2$ and 7 generations of recycling. $kA = kB = 0.5$, $m=1.1$*
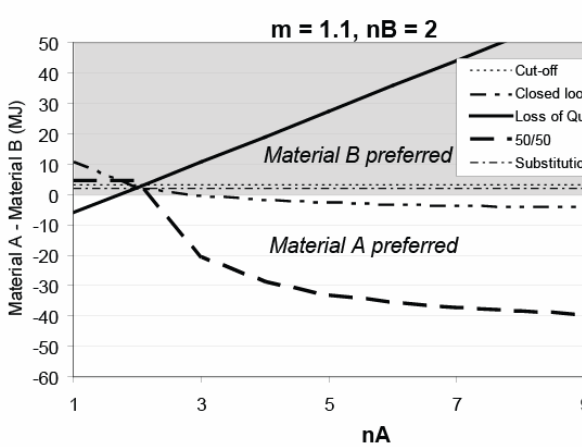
Figure 46: *Delta environmental impact by EOL allocation method for Material A - Material B in MJ across nA, assuming $n_B = 2$ generations of recycling. $kA = kB = 0.5$, $m=1.1$*
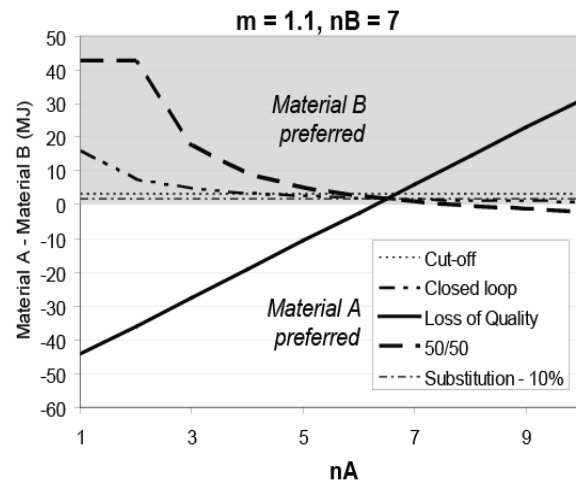
Figure 47: *Delta environmental impact by EOL allocation method for Material A - Material B in MJ across nA, assuming $n_B = 7$ generations of recycling. $kA = kB = 0.5$, $m=1.1$*

Assumptions about number of recycling generations can have significant effect on the preferred material, especially when considering the 50/50 and Loss of Quality methods, and to a lesser extent the Closed Loop method. When both n_A and n_B are low, the Loss of Quality method indicates preference for Material B and the 50/50 method reveals preference for Material A. This relative preference becomes more pronounced for each method as n_A grows. However, when assuming a higher number of recycling generations for Material B ($n_B =7$), the results switch at low values for n_A; the 50/50 method preferentially favors Material B while the Loss of Quality method favors Material A. When considering higher recycling generations for Material

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A when n_B =7, the results switch again, depending on the relative primary energies of Materials A and B. When the materials are close in primary energy production, the 50/50 and Loss of Quality methods switch in relative preference at an earlier number of recycling generations. To explore why the Loss of Quality and 50/50 methods go in opposite directions, it is worth revisiting the EOL allocation method formulas. Specifically, the Loss of Quality formula is:

$$V_B \times m \times \left[q(1 + k(n-1)) \right]$$

The 50/50 method formula is:

$$V_B \times m \times \frac{1+k}{n-1}$$

Whereas the slope of the Loss of Quality method is governed by $m \times n$, the 50/50 method slope is determined by m/n. This causes the Loss of Quality method slope to steepen as n gets larger, while the 50/50 slope decreases as n grows. A higher value of m serves to pronounce this method sensitivity to the parameter n, seen in the steepening method slopes as m goes to 1.0. Intuitively, this makes sense because as the number of recycling generations grows, the 50/50 method is allocating the total environmental burden across a greater number of product generations, thereby decreasing the impact assigned to any one product in the life cycle cascade. Conversely, the Loss of Quality method ascribes a greater environmental burden to products as n grows.

4.4.3 Sensitivity of material choice to parameter *r*

This section concerns the Substitution method, the only end-of-life allocation method that explicitly considers the amount, or rate, of recycled material impacting the environmental burden of the product life cycle. In this method, the amount of recycled material is expressed as 1-*r*, where *r* represents the percentage of virgin material needed to compensate for losses in material quality each time a material is recycled into a new product.[5] This section explores the sensitivity of the Substitution method to preferred material as the parameter *r* is varied. As in previous sections, the methods are examined at *m* values of 0.1, 0.5, 0.9, and 1.1. Parameters *n*, k_A, and k_B are held constant at *n*=3 and k_A= k_B=0.5. Although the Substitution method is the only method affected by the parameter *r*, the other methods are shown side-by-side for comparison purposes. Specifically, the next set of figures show the sensitivity of the Substitution method across Material A recycling rates r_A from 0.1 to 1.0, compared to Material B baselines with recycling rates r_B of 10% and 90% for each of the four m-values.

Figure 48 shows a plot of the delta space between Material A and Material B for each of the five end-of-life methods using an initial value of *m*=0.1, corresponding with the ratio of primary energy for production between the materials. The four methods other than the Substitution method are shown here for reference purposes, as mentioned previously. Two recycling rates were explored in these graphs; r_B = 0.1 and r_B = 0.9. In each case, Material A is consistently the environmentally preferable material, irrespective of r_A. However, the difference in r_B is enough to cause a change in method rank order, as seen in Figure 48. Not surprisingly, the lower assumed virgin content of 0.1 for Material B causes the Substitution method to preferentially favor Material B when compared to the other EOL methods. Assuming a required virgin content of r_B=0.9 pushes the Substitution method result to more closely match the Cut-off and Loss of Quality result. At low values of *m*, the Substitution method maintains relative low sensitivity across the parameter r_A, indicating Material A is the environmentally preferred material. This

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[5] Refer to Table 8 for original method formula.

means that for comparatively large discrepancies between primary energy values of Material A compared to Material B, the EOL allocation method does not change the preferred material, and methods maintain consistent rank order across the parameter r_A.

Figure 49 considers the behavior of the Substitution method across the parameter r_A at a higher m value of 0.5. A switch in method rank order is apparent for the Substitution method when assuming a high virgin content needed for recycling Material B ($r_B = 0.9$). In this case, at an r_A value of ~0.8, the Substitution method changes in rank order with the Cut-off and Loss of Quality methods. Overall, the choice of r_A does not affects the preferred material choice for the Substitution method, although it is worth noting is the method increasingly favors Material B as r_A grows.

Figure 50 present a Material A and Material B with $m=0.9$. In this plot, Figure 50, low r_A values once again favor Material A, but here we again see evidence of a crossover point at which the Substitution method switches in relative rank order with the other methods. At a r_A value of ~0.9, the Substitution method with $r_B = 0.1$ switches in its relative preference for Material A with the Closed Loop, 50/50, Loss of Quality, and Cut-off methods. However, at a higher value for $r_B=0.9$, Material A always remains the preferred material candidate, regardless of choice of parameter r_A.

Figure 51 show the Substitution method at an m value of 1.1, representing a Material A and B that have very similar primary production energies. This plot shows two crossover points between the Substitution method (at both values of r_B) and the other EOL methods. This plot reiterates that Material B is the preferred material across the parameter r_A when r_B is low (0.1). A crossover point is evident at a low value for r_A when r_B is 10%. At approximately $r_A = 0.15$, the Substitution method switches in relative rank order with the other four EOL methods, although Material B remains the preferred material. Unlike a low value, when r_B is high (0.9), Material A is the preferred material at r_A values up to 0.7. After this point, the Substitution method switches in rank order with the other EOL methods at approximately $r_A =0.9$.

Figure 48: Delta environmental impact by EOL allocation method for Material A - Material B for m=0.1 varied across choice of parameter r_A

Figure 49: Delta environmental impact by EOL allocation method for Material A - Material B for m=0.5 varied across choice of parameter r_A

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Figure 50: Delta environmental impact by EOL allocation method for Material A - Material B for m=0.9 varied across choice of parameter r_A

Figure 51: Delta environmental impact by EOL allocation method for Material A - Material B for m=1.1 varied across choice of parameter r_A

4.4.4 Sensitivity of material choice to parameter q

This section concerns the Loss of Quality method, the end-of-life allocation method that explicitly accounts for material degradation in the recycling process as a product is recycled into new products. Here, material degradation is represented by q, a material quality metric which ascribes environmental burden to each product life cycle based on its value in the product cascade.[6] In this section, hypothetical values for q are explored but q could actually be represented, for example, using material pricing data for primary and secondary sources as a proxy for material value and quality. For example, if a virgin material is priced on the open market at $1.00/kg and its recyclate is priced at $0.90/kg, the secondary material would retain 90% of the value of the virgin and q = 0.9. To revisit the Loss of Quality method formula, $V_B \times m \times [q(1+k(n-1))]$, q has substantial impact on y-intercept, which, when coupled when m, can have significant influence on preferred material.

This section explores the sensitivity of the Loss of Quality method to preferred material as the parameter q is varied. As in previous sections, the methods are examined at m values of 0.1, 0.5, 0.9, and 1.1. Parameters n, k_A, and k_B are held constant at n=3 and k_A= k_B=0.5. The Substitution method assumes constant r_A and r_B values of 0.1. Although the Loss of Quality method is the only method affected by the parameter q, the other methods are shown side-by-side for comparison purposes. Specifically, the following figures explore the sensitivity of the Loss of Quality method for Material A at retained secondary q-values of 0.1, 0.4, and 0.9, compared to Material B baselines with q = 0.1 and 0.9 for each of the four m-values.

The primary questions addressed in this section are what parameters make the evaluation sensitive to q, and what impact do parameters k_A and k_B have? Also, because the Loss of Quality method was one of the more sensitive methods to k and n in previous sections, what changes in q increase or decrease that sensitivity?

Figure 52 is a plot of the delta space between Material A and Material B for each of the five EOL methods using an initial value of m=0.1. This plot reveals that at low values of m, the Loss of Quality method maintains relative low sensitivity across the parameter q_A, indicating Material A

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[6] Refer to Table 8 for original method formula.

is the environmentally preferred material. However, as q_A goes to 1, the Loss of Quality method preferentially favors Material B, almost causing a change in material preference when $q_B = 0.1$ by approaching the x-axis. This is surprising and a bit counter-intuitive, because when q_B is small and q_A is large, there is much more economic incentive to recycle Material A over Material B. However, because q is a proxy of environmental burden, a higher q is associated with a higher environmental burden. It is interesting to note that the Loss of Quality methods provide a considerable upper and lower bound for both values of q_B when compared with the other four EOL methods.

Figure 53 considers the behavior of the Loss of Quality method across the parameter q_A at a higher m value of 0.5. When exploring the delta space between the two materials in Figure 53, the result is similar to the case for $m=0.1$. However, this time we see for the case of $q_B = 0.1$ a shift in material preference for Material B at around for $q_A = 0.15$. In the case of for $q_B = 0.9$, Material A remains the preferred material candidate across the range of for q_A values. There is also no switching in method rank order. Overall, the choice of q_A only affects the preferred material choice for the Loss of Quality method, when the for q_B for the baseline Material B is low.

Figure 54 presents a Material A and Material B with $m=0.9$. In this plot, Material B is favored for most q_A values when $q_B = 0.1$, although there is evidence of a crossover point at a very low q_A, below which Material A is the preferred material candidate. In the case where $q_B = 0.9$, the Loss of Quality method switches in relative rank order preference for Material A with the other EOL methods at a q_A value of ~0.95. Figure 55 shows the Loss of Quality method at an m value of 1.1, representing a Material A and B that have very similar primary production energies. The plot shows two crossover points between the Loss of Quality method (at both values of q_B) and the other EOL methods, indicating a shift in rank order between methods. This plot reiterates that Material B is the preferred material across the parameter q_A when q_B is low (0.1). At approximately $q_A = 0.12$, the Loss of Quality method switches in relative rank order with the other four EOL methods, although Material B remains the preferred material. When q_B is high (0.9), Material A remains the preferred material for q_A values up to 0.85, after which Material B is the preferred material. Shortly after this point, the Loss of Quality method also switches in rank order with the other EOL methods at approximately $q_A =0.9$.

As m approaches 1, these delta plots show that sensitivity to the parameter q becomes more pronounced. Also, as was the case for the parameters k and n, higher values of q cause the Loss of Quality method to grow in sensitivity to m and tend to favor materials that with a low q, i.e., materials that have a higher retained value for when recycled.
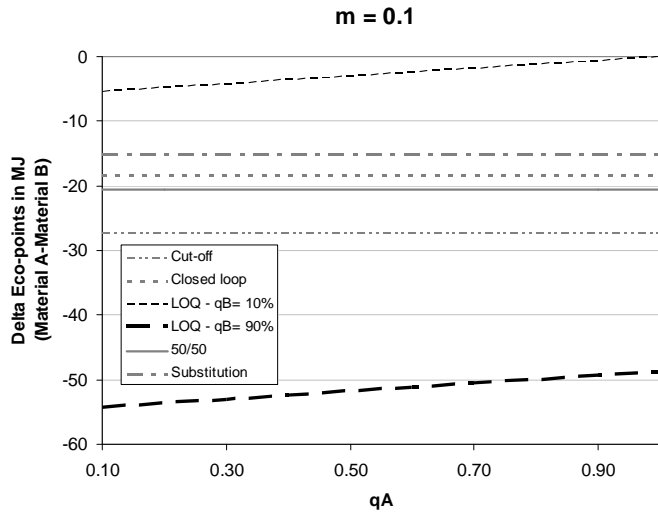
Figure 52: Delta environmental impact by EOL allocation method for Material A - Material B for m=0.1 varied across choice of parameter q_A
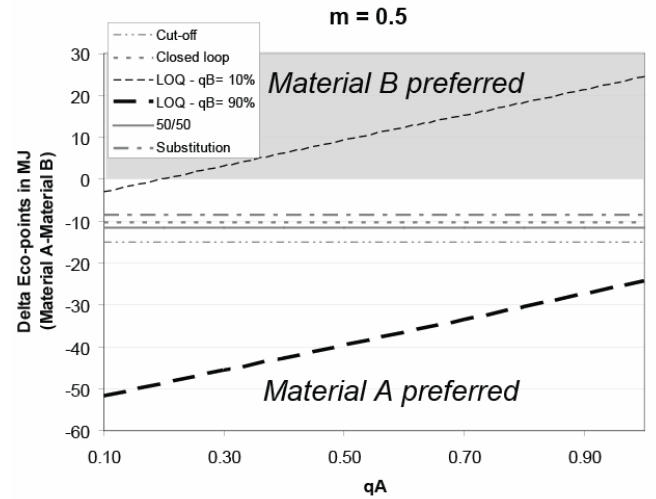
Figure 53: Delta environmental impact by EOL allocation method for Material A - Material B for m=0.5 varied across choice of parameter q_A
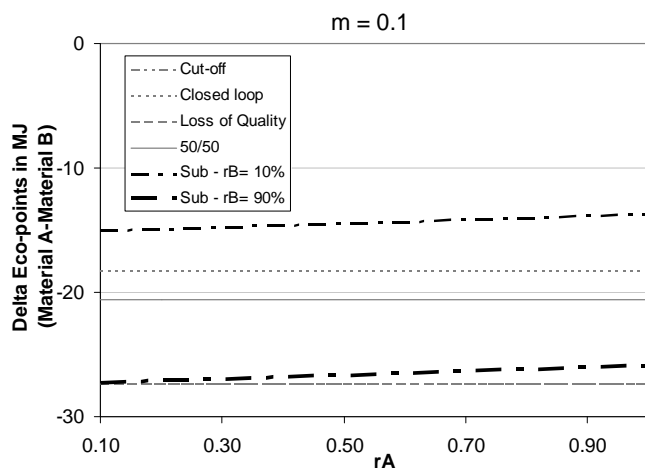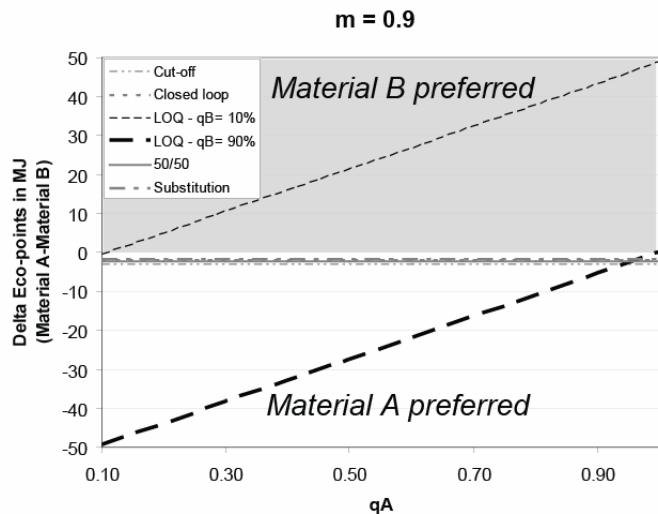

Figure 54: Delta environmental impact by EOL allocation method for Material A - Material B for m=0.9 varied across choice of parameter q_A
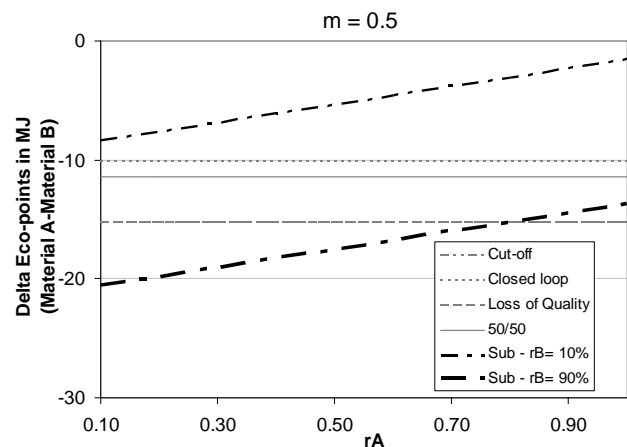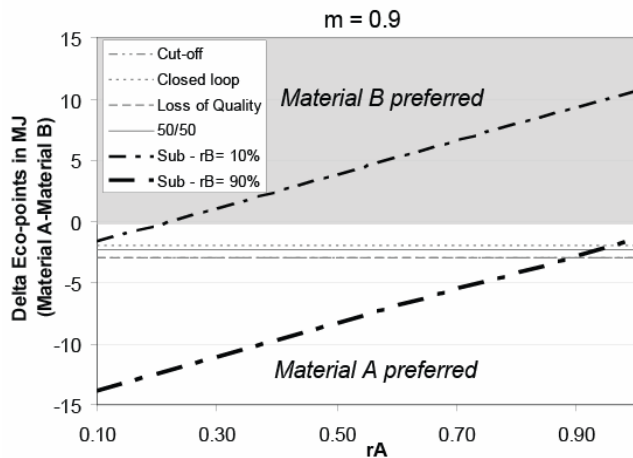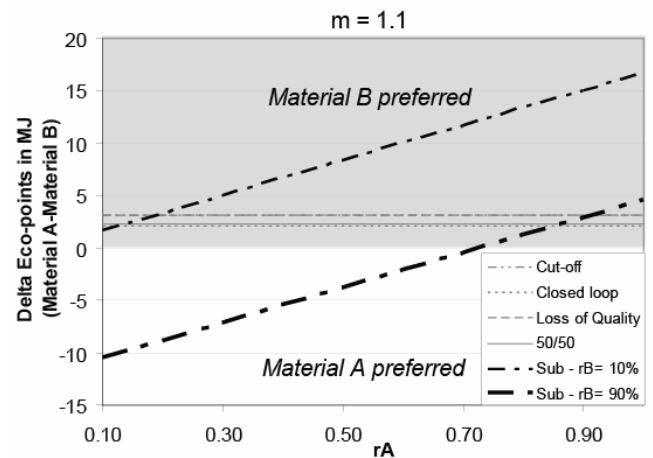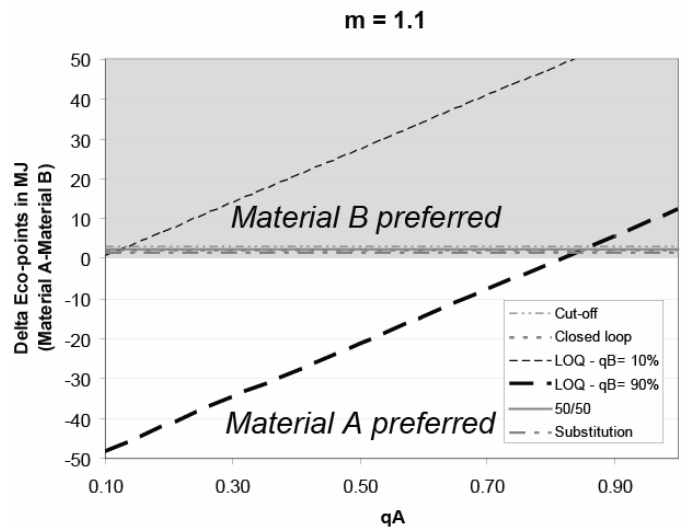

Figure 55: Delta environmental impact by EOL allocation method for Material A - Material B for m=1.1 varied across choice of parameter q_A

4.4.5 Sensitivity of material choice to additional life cycle phases

The previous sections of this thesis consider the environmental burden of the first product in a life cycle cascade, represented in Figure 8 as L1. As these analyses essentially characterize the burden of one product in the life cycle, it is worth exploring how the result changes when considering future products in the product recycling cascade; L2, L3, and hypothetically L_n. This section defines a "hybrid" product life cycle burden, taken to be a weighted average of L1, L2, and L3 and explores how its result compares with the result for L1. Most products are not easily classified as L1, L2, or L3, but rather represent some blend of the three due to the impossibility of knowing the fate or history of materials in products.

Figure 56 is helpful to consider when discussing the calculation of a hybrid life cycle impact. In this scenario, 10% virgin material (also noted as *r*) and 90% recycled material (i.e. 1-*r*) enter the

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product stream, although these percentages depend on the material and recycling scenario. The dashed lines a, b, c, and d are used to represent the fraction of the environmental burden associated with L1, L2, and L3. In this case, the fractional burden associated with the first life cycle stage, or L1, is the percentage primary content multiplied by the percentage recyclate that emerges post-life cycle stage (also noted as s). In this case, $r = s$, a condition necessary for the system to not experience any accumulation or loss. This material path is traced by the dashed line "a" in Figure 56. Similarly, the fractional burden associated with L2 is the percentage recycled content multiplied by the percentage recyclate on the right side of the life cycle stage, traced by the dashed line "c". The dashed line "d" traces the fractional burden associated with L3 and accounts for material that is essentially lost in the life cycle due to processing, use, disposal, degradation, etc (i.e. 1-s). Similarly, the dashed line "b" represents the fractional environmental burden of the lost material that can be attributed to primary material processing and final waste disposal (V1 and W3, respectively, in Figure 8), and in this case is calculated by multiplying the percentage primary material by the percentage lost material.
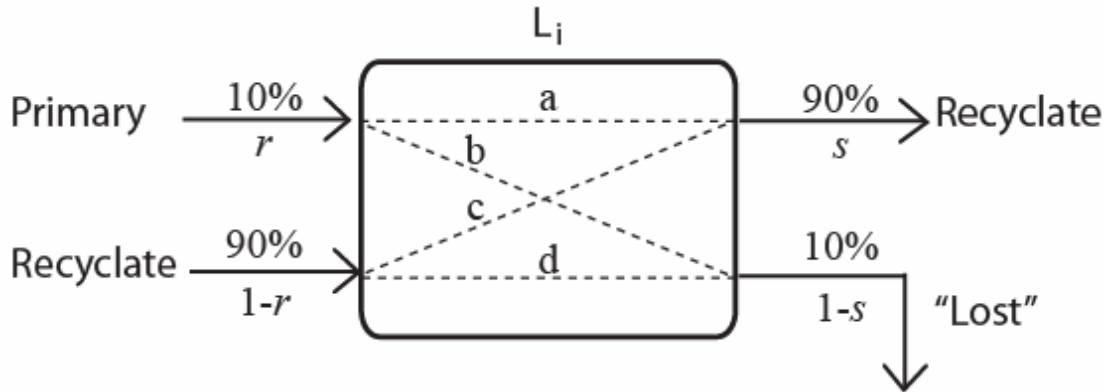
Figure 56: Schematic diagram for environmental burden of life cycle L_i

Table 9: Calculation of fractional burden of L1, L2, and L3 towards hybrid

Path	Maps to	Example Percentage Burden	Theoretical Percentage Burden
a	L1	$0.1 \times 0.9 = 0.09$	$r \times s$
b	V1+W3	$0.1 \times 0.1 = 0.01$	$r \times (1-s)$
c	L2	$0.9 \times 0.9 = 0.81$	$(1-r) \times s$
d	L3	$0.9 \times 0.1 = 0.09$	$(1-r) \times (1-s)$

Table 9 shows the percentage contribution of the L1, L2 and L3 burdens towards a hybrid life cycle burden. After multiplying L1, L2 and L3 by their fractional burden, the hybrid burden is calculated in Equation 6 by their simple addition; in the example given:

$$(0.09 \times L1) + (0.01 \times (V1+W3)) + (0.81 \times L2) + (0.09 \times L3) \tag{5}$$

More generally, this equation would be given by:

$$L1 \times (r \times s) + (V1+W3) \times (r \times (1-s)) + L2 \times ((1-r) \times s) + L3((1-r) \times (1-s)) \tag{6}$$

Due to the small fractional burden associated with the lost material in V1+W3, the contribution of this impact is not included in this analysis. Specifically, the fractional burden of V1+W3 can be thought of the material losses incurred in Figure 57, a simplified version of Figure 8:
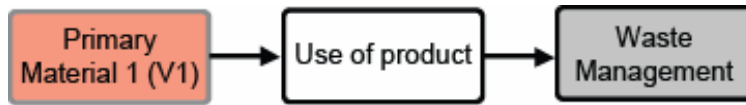
Figure 57: Fractional burden of material loss associated with L1/L3

Figure 58 shows a comparison between the hybrid environmental burden calculation method and L1, L2 and L3. In this example, m is 0.1, $k_A=k_B=0.5$, $n_A=n_B=3$, $q_A=q_B=0.5$, and $r_A=r_B=s_A=s_B=0.1$. Not surprisingly, the Closed Loop and Substitution methods maintain a relatively consistent result across the L1, L2, L3 and the hybrid life cycle burden, as these end-of-life allocation methods average the burden between the life cycles. For the remaining three methods, Cut-off, Loss of Quality and 50/50, the hybrid life cycle burden is substantially less than the burden associated with L1. Figures Figure 59-Figure 74 explore how the result changes in terms of preferred material when comparing the hybrid life cycle calculation with that of L1, the life cycle burden explored in other sections of this chapter.
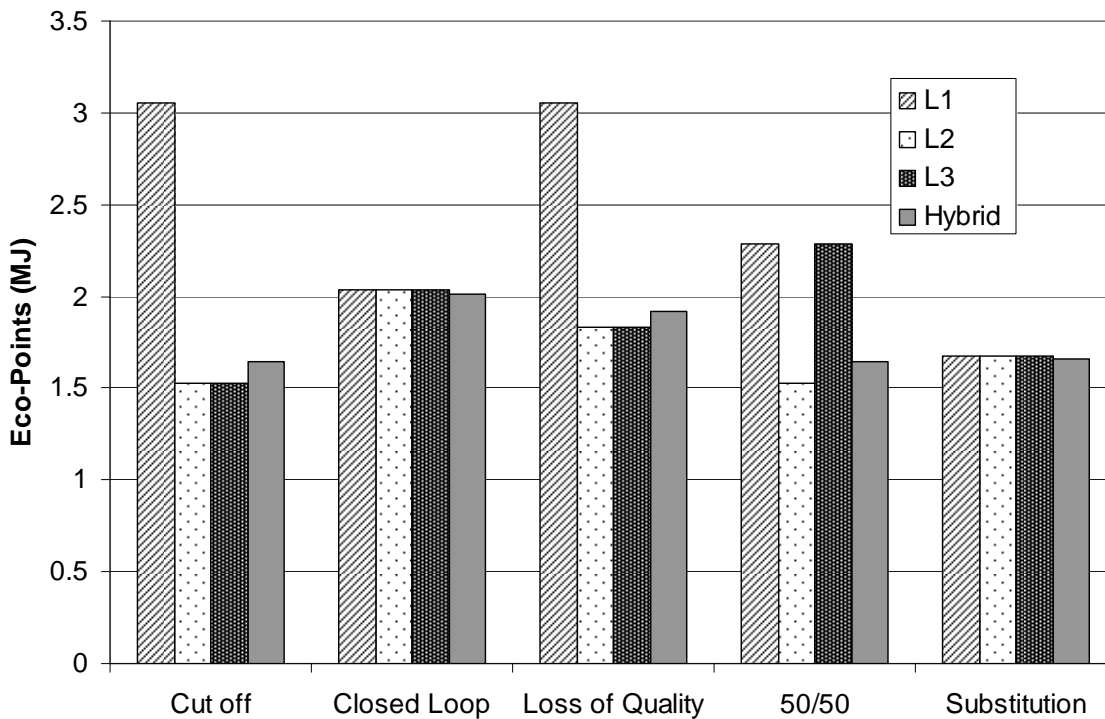
Figure 58: Comparison of hybrid and conventional life cycle calculation methods for
$m=0.1$, $k_A=k_B=0.5$, $n_A=n_B=3$, $q_A=q_B=0.5$, $r_A=r_B=s_A=s_B=0.1$

Figure 59-Figure 74 compare the hybrid life cycle burden with that of L1 for four m-values: 0.1, 0.5, 0.9, and 1.1. All other variables are as stated in Figure 58, with the exception of k_A and k_B. When comparing Figure 60 with Figure 59, it is apparent how hybrid method effects method sensitivity to the parameter kA. It appears that all methods are equally and weakly sensitive to kA. We see that the hybrid allocation method causes the y-intercept to shift upwards for the Cut-off, Loss of Quality and 50/50 methods, causing a shift in method rank order. It is interesting to note that the five allocation methods essentially converge to two lines in the delta space plot in Figure 60, serving as an upper and lower bound on the degree of 'preference' for Material A. Specifically, the Closed loop and Loss of Quality methods trend together, and the Cut-off, 50/50 and Substitution methods converge in a second trend. Like the result for L1, when considering the hybrid burden for the five methods, the methods increasingly favor Material B as k_A grows. Figure 61 and Figure 62 compare the L1 and hybrid result when k_B=0.9. Once again, the y-intercept for the Loss of Quality method shifts upwards, and the higher value for k_B causes very little differentiation between allocation methods.
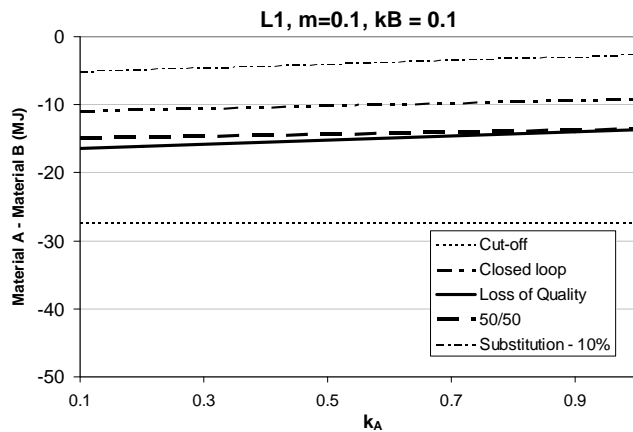
Figure 59: Delta space (Material A-Material B) for life cycle burden L1, m=0.1, k_B=0.1
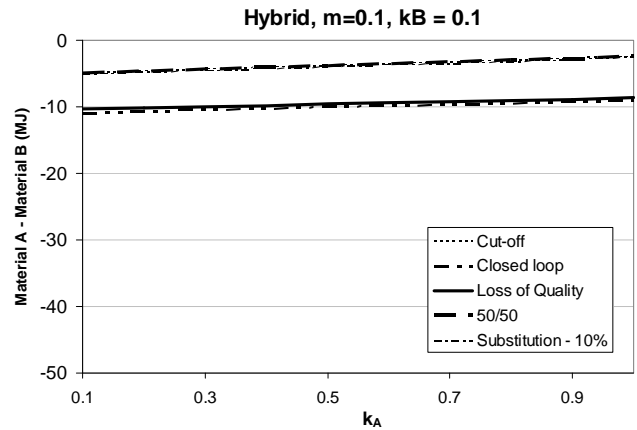
Figure 60: Delta space (Material A-Material B) for hybrid life cycle burden, m=0.1, k_B=0.1
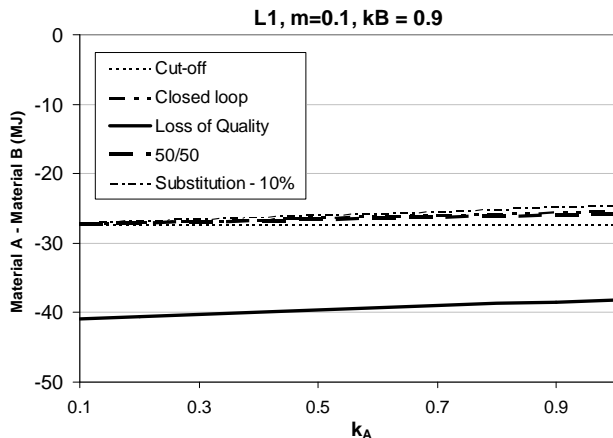
Figure 61: Delta space (Material A-Material B) for life cycle burden L1, m=0.1, k_B=0.9
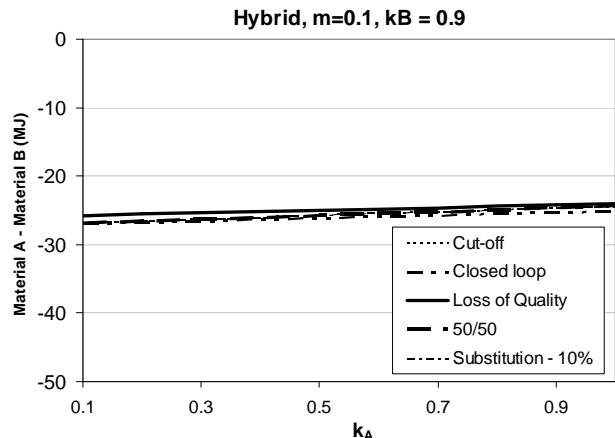
Figure 62: Delta space (Material A-Material B) for hybrid life cycle burden, m=0.1, k_B=0.9

The next set of plots considers the life cycle burden for L1 and the hybrid calculation method when m=0.5. Again, Figure 64 shows the muted effects of environmental burden when applying the allocation methods using the hybrid life cycle as compared to Figure 63. However, in this case, the effect is pronounced enough to cause Material B to become the preferred material for

the Cut-off and 50/50 methods when k_A=0.9 and k_B=0.1. Once again, in Figure 64 we see that the hybrid allocation method causes the y-intercept to shift upwards for the Cut-off, Loss of Quality and 50/50 methods, resulting in a change in method rank order. The hybrid delta plot also reveals that the point of crossover between Material A and Material B for the Cut-off and 50/50 methods occurs at a k_A=~0.3. Also, as was the case when m=0.1, the two trends of convergence are evident in Figure 64 for a low k_B value. Figure 66, which shows the hybrid delta plot at a k_B value of 0.9 shows that y-intercept shifts again shifts upwards for the Loss of Quality method but this time downwards for the Cut-off method. Out of the two trend lines seen in Figure 64 and Figure 66, there is one group of methods that demonstrates consistently higher y-intercept than the other, showing a greater preference for Material B. The lower of these trend lines is somewhat more sensitive to the parameter k_A.
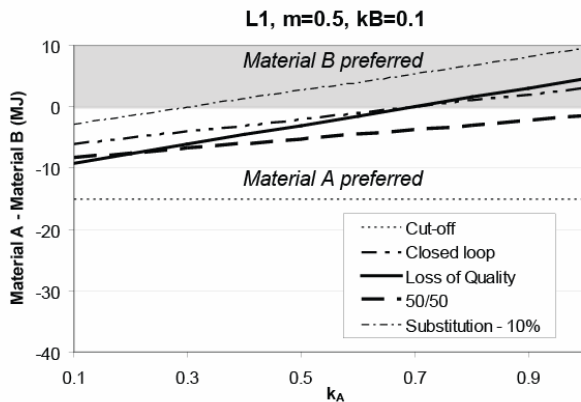
Figure 63: Delta space (Material A-Material B) for life cycle burden L1, m=0.5, k_B=0.1
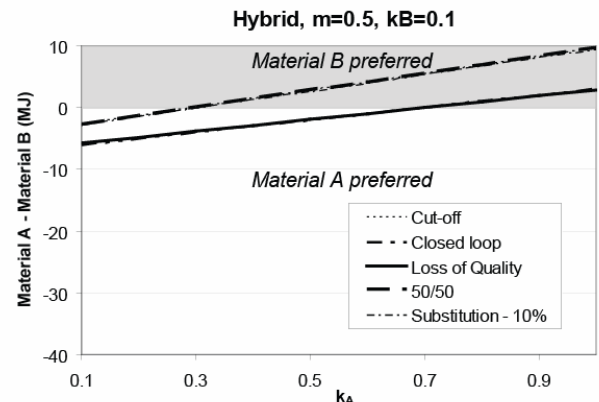
Figure 64: Delta space (Material A-Material B) for hybrid life cycle burden, m=0.5, k_B=0.1
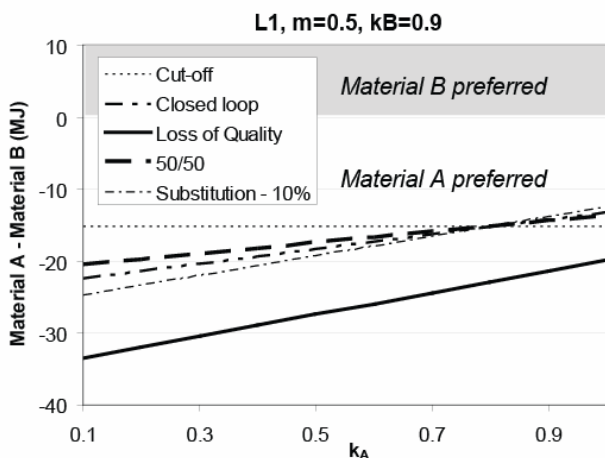
Figure 65: Delta space (Material A-Material B) for life cycle burden L1, m=0.5, k_B=0.9
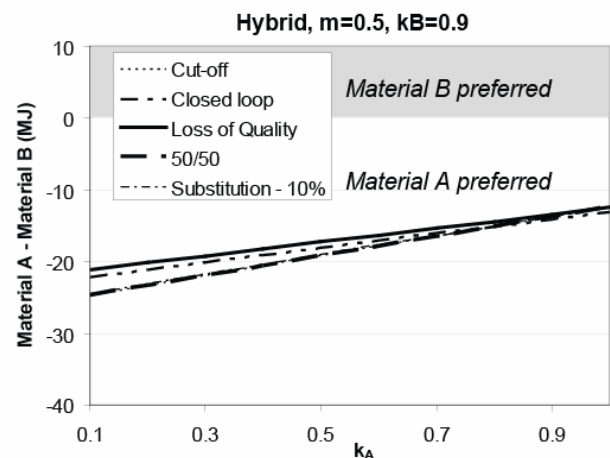
Figure 66: Delta space (Material A-Material B) for hybrid life cycle burden, m=0.5, k_B=0.9

Figure 67-Figure 70 show the result for L1 and the hybrid calculation method when m=0.9. At this higher m-value, the hybrid result more closely resembles the result for the L1 life cycle. Figure 68 shows a change in slope from Figure 67 for the Loss of Quality, 50/50, and Cut-off method, including a significant upwards shift in y-intercept for the Cut-off method. The most pronounced effect between the hybrid and L1 delta plots is therefore a switch in rank order between the 50/50 and Loss of Quality methods, and causing the Cut-off method to prefer Material B. The hybrid delta plot in Figure 70 reveals that at a higher k_B value, the y-intercept

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for the Cut-off method shifts downward when compared to Figure 69, again causing a shift in method rank order. Also, as was the case when m=0.1 and 0.5, the two trends of convergence are evident in Figure 68 and Figure 70. One set of these trend lines is clearly more sensitive to k. When comparing Figure 68 and Figure 70 this is seen because the trend line 50/50, Substitution, and Cut-off methods shifts above the other trend line (Closed Loop and Loss of Quality). Once again, the evaluation using the hybrid life cycle demonstrates that sensitivity to k increases with the parameter m. In this set of plots, the difference in sensitivity to k is definitely more pronounced than in the previous figures that considered m values of 0.1 and 0.5.
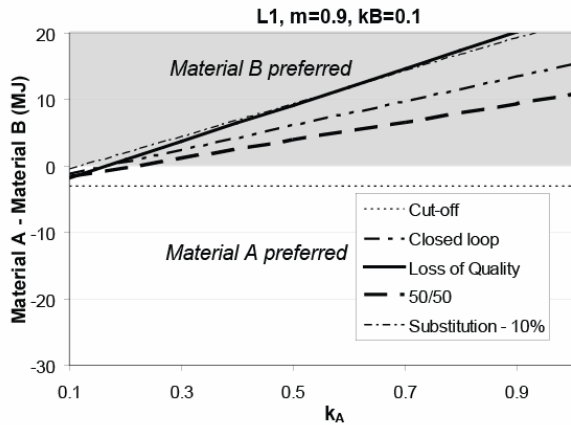
Figure 67: Delta space (Material A-Material B) for life cycle burden L1, m=0.9, k_B=0.1
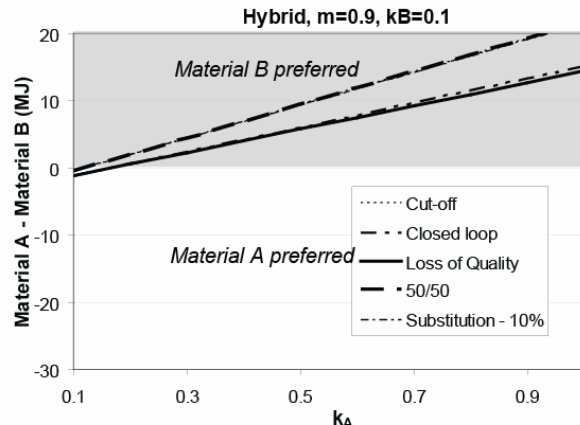
Figure 68: Delta space (Material A-Material B) for hybrid life cycle burden, m=0.9, k_B=0.1
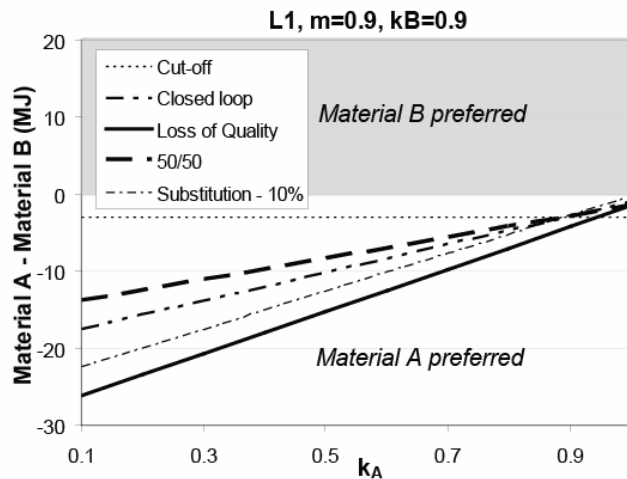
Figure 69: Delta space (Material A-Material B) for life cycle burden L1, m=0.9, k_B=0.9
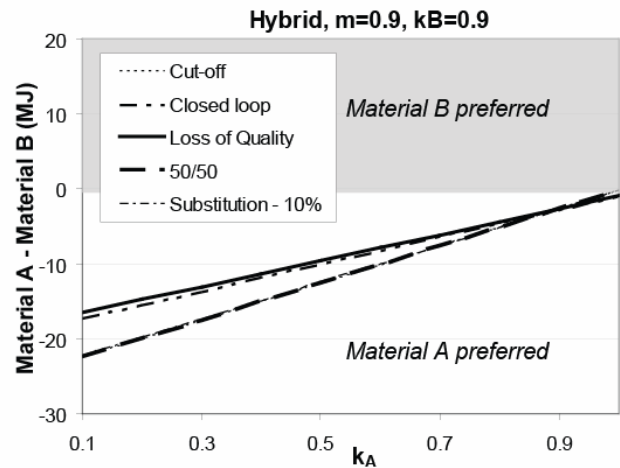
Figure 70: Delta space (Material A-Material B) for hybrid life cycle burden, m=0.9, k_B=0.9

Figure 71-Figure 74 show the result for L1 and the hybrid calculation method when m=1.1. Again, the delta plot in Figure 72 shows a shift in method slope that results in a change in method rank order between the L1 and hybrid methods. When considering the hybrid life cycle, the slope for the Loss of Quality method shifts upward, indicating an increased preference for Material B. The slope for the 50/50 method shifts down, indicating an increased preference for Material A. The Cut-off method also demonstrates a downwards shift in y-intercept yet increase in slope and coincides with the result for the 50/50 method. The hybrid delta plot in Figure 74 for the higher k_B value of 0.9 shows that the y-intercept for the Cut-off method shifts downwards. This is different from the L1 life cycle, where the Cut-off method prefers Material B regardless of choice of parameter k_A in Figure 73. As was the case for the hybrid life cycle for m=0.9, the two trends of convergence are evident in Figure 72 and Figure 74. Again, one set of these trend

lines is more sensitive to k. When comparing Figure 72 and Figure 74 this is seen because the trend line 50/50, Substitution, and Cut-off methods shifts above the other trend line (Closed Loop and Loss of Quality). Once again, the evaluation using the hybrid life cycle demonstrates that sensitivity to k increases with the parameter m. In this set of plots, the difference in sensitivity to k is even more pronounced than all previous figures that considered lower m values.

L1, m=1.1, kB=0.1

Material B preferred

Material A preferred

- Cut-off
- Closed loop
- Loss of Quality
- 50/50
- Substitution - 10%
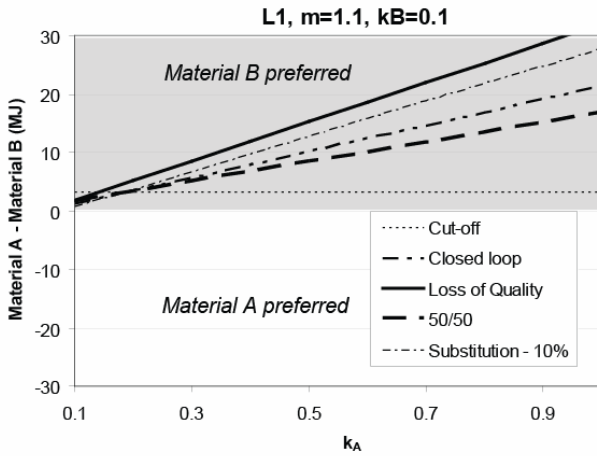
Figure 71: Delta space (Material A-Material B) for life cycle burden L1, m=1.1, k_B=0. 1

Hybrid, m=1.1, kB=0.1

Material B preferred

Material A preferred

- Cut-off
- Closed loop
- Loss of Quality
- 50/50
- Substitution - 10%
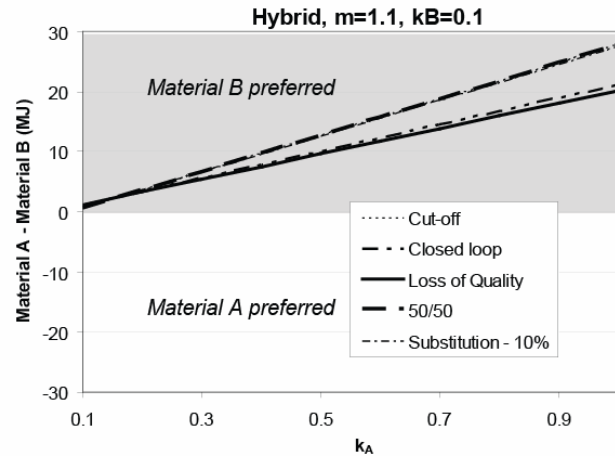
Figure 72: Delta space (Material A-Material B) for hybrid life cycle burden, m=1.1, k_B=0.1

L1, m=1.1, kB=0.9

Material B preferred

Material A preferred

- Cut-off
- Closed loop
- Loss of Quality
- 50/50
- Substitution - 10%
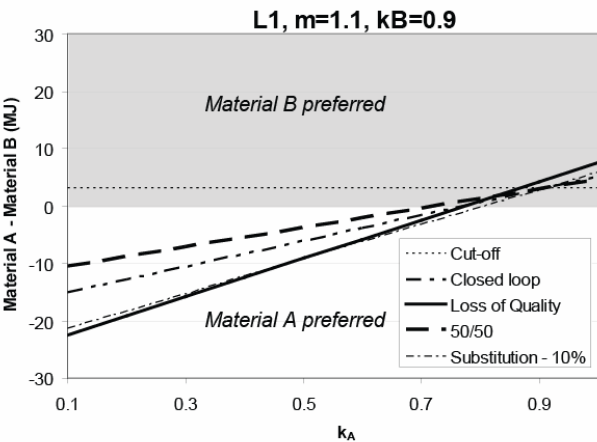
Figure 73: Delta space (Material A-Material B) for life cycle burden L1, m=1.1, k_B=0. 9

Hybrid, m=1.1, kB=0.9

Material B preferred

Material A preferred

- Cut-off
- Closed loop
- Loss of Quality
- 50/50
- Substitution - 10%
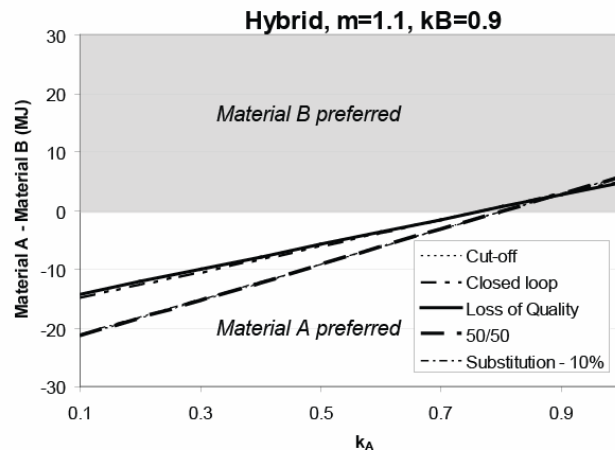
Figure 74: Delta space (Material A-Material B) for hybrid life cycle burden, m=1.1, k_B=0.9

In general, consideration of the hybrid lifecycle compared to L1 causes an increased preference for Material B at low values of m. As m grows, the hybrid life cycle sensitivity to k increases. Consideration of the hybrid life cycle causes the methods to converge to two trend lines, each trend represented by an EOL allocation method that remains unchanged between consideration of the L1 and hybrid life cycle – the Closed loop and Substitution methods. At higher values of m, the 50/50 and Loss of Quality methods switch in rank order between the L1 and hybrid lifecycle, although overall material preference trends are consistent. Perhaps the most significant effect is on the Cut-off method, which changes from a horizontal line for the L1 case to having a positive slope when considering the hybrid case. For low values of m, the hybrid life cycle causes an increased preference for Material B when considering the Cut-off method. However, at higher values of m, this preference switches to favor Material A, causing a complete change in

material preference when $m=1.1$ between L1 and the hybrid method. At high values of m, one trend line (50/50, Substitution, and Cut-off methods) shifts above the other trend line (Closed Loop and Loss of Quality), depending on parameter k. Overall, the evaluation using the hybrid life cycle demonstrates that sensitivity to k increases with the parameter m.

5   Discussion

Table 10 summarizes the results from the previous section and explains under which conditions certain end-of-life allocation methods encourage the application Material A versus Material B from an environmental burden standpoint. For the different values of m (ratio of primary production energies V_A/V_B) evaluated in case II, this table explores method sensitivity to the parameters k (ratio of recycling production energy to primary production energy), n (number of assumed recycling generations in product cascade), r (percentage primary needed to offset losses in Substitution method), q (percentage of material degradation between product generations in Loss of Quality method), as well as the hybrid life-cycle when compared to L1. Additionally, method rank order is summarized in terms of which methods indicate a stronger preference for Material A (listed in order from greatest to least preference).

Figure 75 explores the boundary between environmentally preferred material for each EOL allocation method given m values of 0.1, 0.5, and 1.1. Specifically, sensitivity to the parameter k is explored in these plots, with k_B on the x-axis and k_A on the y-axis. As it is difficult to see the slope differences that are very apparent in figures from case II, the first row includes plots revealing method slope sensitivity. Sample materials such as aluminum and steel are plotted for each of the methods to provide a context for where actual materials might appear in this space relative to the material boundary. For example, when looking at the Substitution method for m=0.5, the point that represents polypropylene and aluminum lies very close to the boundary that determines preferred material. This highlights the fact a) to first order, choice of method can have significant impact on the preferred material, and b) material choice is heavily dependent on parameter k when comparing two materials.

Figure 76 similarly explores the boundary between preferred material for each EOL allocation method across the same three m values, but examines sensitivity to the parameter n, with n_B on the x-axis and n_A on the y-axis. As there exists no definitive baseline number of recycling generations for any particular material, these plots serve to examine how different assumptions regarding the number of times a material is recycled can affect choice of the environmentally preferred material. Although there is not a consensus method for estimating number of recycling generations, several papers attempt to approximate this [76], [81] .

Table 10: Summary of end-of-life allocation method sensitivity to defined parameters

Parameter	High primary energy difference (low m – 0.1)	Medium primary energy difference (mid m – 0.5)	Low primary energy difference (high m – 1.1)

k (Recycling energy as percentage of primary energy)
 	
Methods that are *italicized and bold* indicate methods that change in rank order as k_A grows.
	Material preference shows little sensitivity to parameter k;
	Preference for Material A (low k_B):
	  Cut-off
	  Loss of Quality
	  50/50
	  Closed Loop
	  Substitution
	Preference for Material A (high k_B):
	  Loss of Quality
	  Cut-off
	  50/50
	  Closed Loop
	  Substitution
		Material preference shows moderate sensitivity to parameter k;
		Preference for Material A (low k_B):
		  Cut-off
		  Loss of Quality
		  50/50
		  Closed Loop
		  Substitution
		Preference for Material A (high k_B):
		  Loss of Quality
		  Substitution
		  Closed Loop
		  50/50
		  Cut-off
			Material preference shows high sensitivity to parameter k;
			Preference for Material A (low k_B):
			  Cut-off
			  50/50
			  Closed Loop
			  Substitution
			  Loss of Quality
			Preference for Material A (high k_B):
			  Loss of Quality
			  Substitution
			  Closed Loop
			  50/50
			  Cut-off

n (number of assumed recycling generations in product cascade)
 	
Methods that are ***italicized and bold*** indicate methods that change in rank order as n_A grows.
	Material preference shows slight sensitivity to parameter n;
	Preference for Material A (low n_B):
	    50/50
	    Cut-off
	    Loss of Quality
	    Closed Loop
	    Substitution
	Preference for Material A (high n_B):
	    50/50
	    Cut-off
	    Closed Loop
	    Substitution
	    Loss of Quality
		Material preference shows moderate sensitivity to parameter n;
		Preference for Material A (low n_B):
		    50/50
		    Cut-off
		    Loss of Quality
		    Substitution
		    Closed Loop
		Preference for Material A (high n_B):
		    Loss of Quality
		    Cut-off
		    Substitution
		    Closed Loop
		    50/50
			Material preference shows high sensitivity to parameter n;
			Preference for Material A (low n_B):
			    Loss of Quality
			    Substitution
			    Cut-off
			    50/50
			    Closed Loop
			Preference for Material A (high k_B):
			    Loss of Quality
			    Substitution
			    Cut-off
			    Closed Loop
			    50/50

r (percentage primary needed to offset losses in Substitution method)
 	
When the Substitution method is ***italicized and bold***, this indicates a switch in rank order as r_A grows.
	Material preference shows little sensitivity to parameter *r*;
	Higher values of r_B favor Material A; Lower values of r_A favor Material A (low r_B):
	    Loss of Quality
	    Cut-off
	    50/50
	    Closed Loop
	    Substitution
	(high r_B):
	    Substitution
	    Loss of Quality
	    Cut-off
	    50/50
	    Closed Loop
		Material preference shows moderate sensitivity to parameter *r*;
		Higher values of r_B favor Material A; Lower values of r_A favor Material A (low r_B):
		    Loss of Quality
		    Cut-off
		    50/50
		    Closed Loop
		    Substitution
		(high r_B):
		    Substitution
		    Loss of Quality
		    Cut-off
		    50/50
		    Closed Loop
			Material preference shows high sensitivity to parameter *r*;
			Higher values of r_B favor Material A; Lower values of r_A favor Material A (low r_B):
			    Substitution
			    Closed Loop
			    50/50
			    Loss of Quality
			    Cut-off
			(high r_B):
			    Substitution
			    Loss of Quality
			    Cut-off
			    50/50
			    Closed Loop

q (percentage of material degradation between product generations in Loss of Quality method)
 	
When the Loss of Quality method is ***italicized and bold***, this indicates a switch in rank order as q_A grows.
	Material preference shows little sensitivity to parameter *q*;
	Higher values of q_B favor Material A; Lower values of q_A favor Material A (low q_B):
	    Cut-off
	    50/50
	    Closed Loop
	    Substitution
	    Loss of Quality
	(high q_B):
	    Loss of Quality
	    Cut-off
	    50/50
	    Closed Loop
	    Substitution
		Material preference shows moderate sensitivity to parameter *q*;
		Higher values of q_B favor Material A; Lower values of q_A favor Material A (low q_B):
		    Cut-off
		    50/50
		    Closed Loop
		    Substitution
		    Loss of Quality
		(high q_B):
		    Loss of Quality
		    Cut-off
		    50/50
		    Closed Loop
		    Substitution
			Material preference shows high sensitivity to parameter *q*;
			Higher values of q_B favor Material A; Lower values of q_A favor Material A (low q_B):
			    Loss of Quality
			    Cut-off
			    50/50
			    Closed Loop
			    Substitution
			(high q_B):
			    Loss of Quality
			    Cut-off
			    50/50
			    Closed Loop
			    Substitution

Hybrid life cycle: Substitution and Closed loop methods remain unaffected. Methods that are *italicized and bold* indicate methods that change in rank order as k_A grows.	Material preference shows little sensitivity to hybrid life cycle; (low k_B): Closed Loop Loss of Quality Substitution Cut-off 50/50 (high k_B): Closed Loop Substitution Cut-off 50/50 Loss of Quality	Material preference shows moderate sensitivity to hybrid life cycle; (low k_B): Closed Loop *Loss of Quality* Substitution Cut-off 50/50 (high k_B): *Cut-off* *50/50* Substitution Closed Loop Loss of Quality	Material preference shows high sensitivity to hybrid life cycle; (low k_B): *Cut-off* *50/50* Substitution Closed Loop *Loss of Quality* (high k_B): *Cut-off* *50/50* Substitution Closed Loop *Loss of Quality*

EOL Allocation Method Implications on Recycling

When considering the EOL allocation methods in the context of incentivizing the use of recycled material, it is useful to refer back to Table 10. When the primary energy of $V_A \ll V_B$, all methods incentivize the use of Material A regardless of the energy associated with recycling either material. Of the methods explored in this thesis, the Cut-off consistently prefers Materials A (the material with lower primary burden). Among the other methods, Loss of Quality prefers A, with this preference growing rapidly as the recycling burden of B grows.

When the primary energy of $V_A < V_B$, the Cut-off method consistently provides a strong incentive for Material A (material with low primary). In general, at low values for k_B (recycling burden of Material B), the 50/50 method consistently favors A (low primary burden) over B more than most other methods. At low values of k_A (recycling burden of A) the Loss of Quality method indicates strong preference for A, but this method is the most sensitive to k_A. As such, for high values of k_A it provides one of the strongest disincentives for Material A. To a slightly lesser than the Loss of Quality method, the Closed Loop method reveals similar sensitivity to k_A. The Substitution seems to provide the lowest incentive for A (lower primary burden) and is strongly sensitive to recycling energy. The sensitivity of the Substitution and Loss of Quality methods to recycling energy is supported by the amount of movement in the high k_B plot, with both methods shifting to strongly disincentivize B.

As A approaches a similar primary energy of B ($V_A = V_B$), the Cut-off and 50/50 methods favor Material A when the recycling energy of B is low (followed in order by the Closed Loop, Substitution, and Loss of Quality methods). As the recycling energy of A grows, this serves to increase the sensitivity all methods but the Cut-off and pronounces their relative difference. When considering a higher recycling energy for Material B, the methods order in reverse. In this case, at low recycling energies for A, the Loss of Quality and Substitution methods show strongest preference for Material A, followed in order of preference by the Closed Loop, 50/50 and Cut-off methods as the energy to recycle Material B grows.

Perhaps the last example, when $V_A = V_B$, best indicates how the methods incentivize recycling. In this example, B can simply be thought of as A′. When the energy associated with recycling A is high (as k approaches 1.0), it is the equivalent of using A′, or primary material. When the energy of recycling A is low, we can see which methods prefer Material A vs. A′, indicating a preference for recycled content over primary. Ultimately, the Loss of Quality and Substitution methods most highly favor the use of recycled content, followed by the Closed Loop, 50/50 and Cut-off methods.

Overall, the Cut-off EOL allocation method is insensitive to the material recycling energy while the Loss of Quality is most sensitive, followed in decreasing order by the Substitution, 50/50, and Closed Loop methods.

Table 11: EOL allocation method sustainability characteristics (format taken from [82])

	Cut-off	*Closed Loop*	*Loss of Quality*	*50/50*	*Substitution*
Future utility	Uncertain	Uncertain	Uncertain	Uncertain	Yes
Sustainability concept	Strong	Weak	Weak	Weak	Weak
Environmental grants from future generations	No	Yes	Yes	Yes	Yes
Shifts burdens into future?	No	Partially	Partially	Partially	Partially
Risk perception	Risk averse	Risk seeking	Risk seeking	Risk seeking	Risk seeking

The quantitative analyses of the previous sections can be extended to infer broader implications of these EOL allocation methods in terms of sustainability. Table 11 outlines EOL method characteristics in terms of sustainability concept served (strong versus weak), assumptions that support this sustainability concept, and risk perception involved. Characterizing the methods in these terms draws from the discussion presented in Section 4.1 and uses the framework offered by Frischknecht [82].

In the debate about sustainable development, there is a key question as to whether natural capital can be substituted by man-made capital. Proponents of weak sustainability maintain that man-made and natural capital are substitutable in the long term while followers of strong sustainability believe they are not. In terms of the methods explored in this thesis, all but one represent the weak sustainability philosophy.

For most of the allocation methods (Closed Loop, Loss of Quality, 50/50 and Substitution), materials that are recycled in the future are credited today with avoiding primary material production, at least to a certain degree. Crediting this avoided impact to the product that provides the recyclate greatly reduces its environmental impact, and one can make the argument that this supports the weak sustainability concept in that these credits are therefore substitutable for man-man capital (primary material).

The Cut-off method embodies the strong sustainability concept in that it assigns all of the burden of primary material to the first product in a life cycle cascade. No credits, or reductions in material environmental burden, are assigned to this product even when it can be recycled in the future. If this product is in fact recycled, secondary materials do not bear any environmental load from the primary materials production activities. The rationale behind this method is very much aligned with the strong sustainability philosophy, where natural capital (primary material) is not replaceable by man-made capital (for example, carbon credits).

Risk perception is a notion related to market conditions and the length of time between the production of a product or material and when it will be recycled. Because the Closed Loop, Loss of Quality, 50/50 and Substitution methods assume that the original materials will still have market demand when product is eventually recycled, in a sense these methods borrow "an environmental loan…from future generations [82]." Thus, these methods take a risk according to the uncertainty associated with lack of knowledge paying back environmental credits in the

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future and can be categorized as risk seeking. The Cut-off method aligns with a risk averse mentality in that it is blind to whether a product will be recycled in the future, and does not take the risk of accepting environmental credits from future generations of recycled products.

Many of the decisions in LCA are value-laden, with the selection end-of-life allocation providing no exception. As Frischknect points out, certain primary material industries may favor methods such as Closed Loop, Loss of Quality, 50/50, and Substitution that align with the weak sustainability philosophy, as they tend to reduce the overall perceived environmental burden method associated with extracting and processing virgin material. This risk-seeking mentality might be different from those who have longer-term goals of protecting environmental welfare. In this sense, those involved with government policy makers at the local and national levels might be more inclined to select a method that allows for no environmental credits to be assigned to primary materials.

Material	$V_{A\ or\ B}$ (MJ)	m (V_A/V_B)	k (R_A/V_A or R_B/V_B)	q ($Q_i/\Sigma Q_i$)
Aluminum	160.3	5.2	0.16	0.36
Polypropylene	74.8	2.5	0.51	0.72
Paper	26.6	0.9	0.61	0.87
Steel	30.5	-	0.31	0.57

Material A to Material B

- Aluminum to Steel, m = 0.19
- ⬠ PP to Aluminum, m = 0.47
- ✕ Paper to Steel, m = 0.88
- ☐ Paper to Aluminum = 0.17
- ◇ Steel to PP, m = 0.41

70
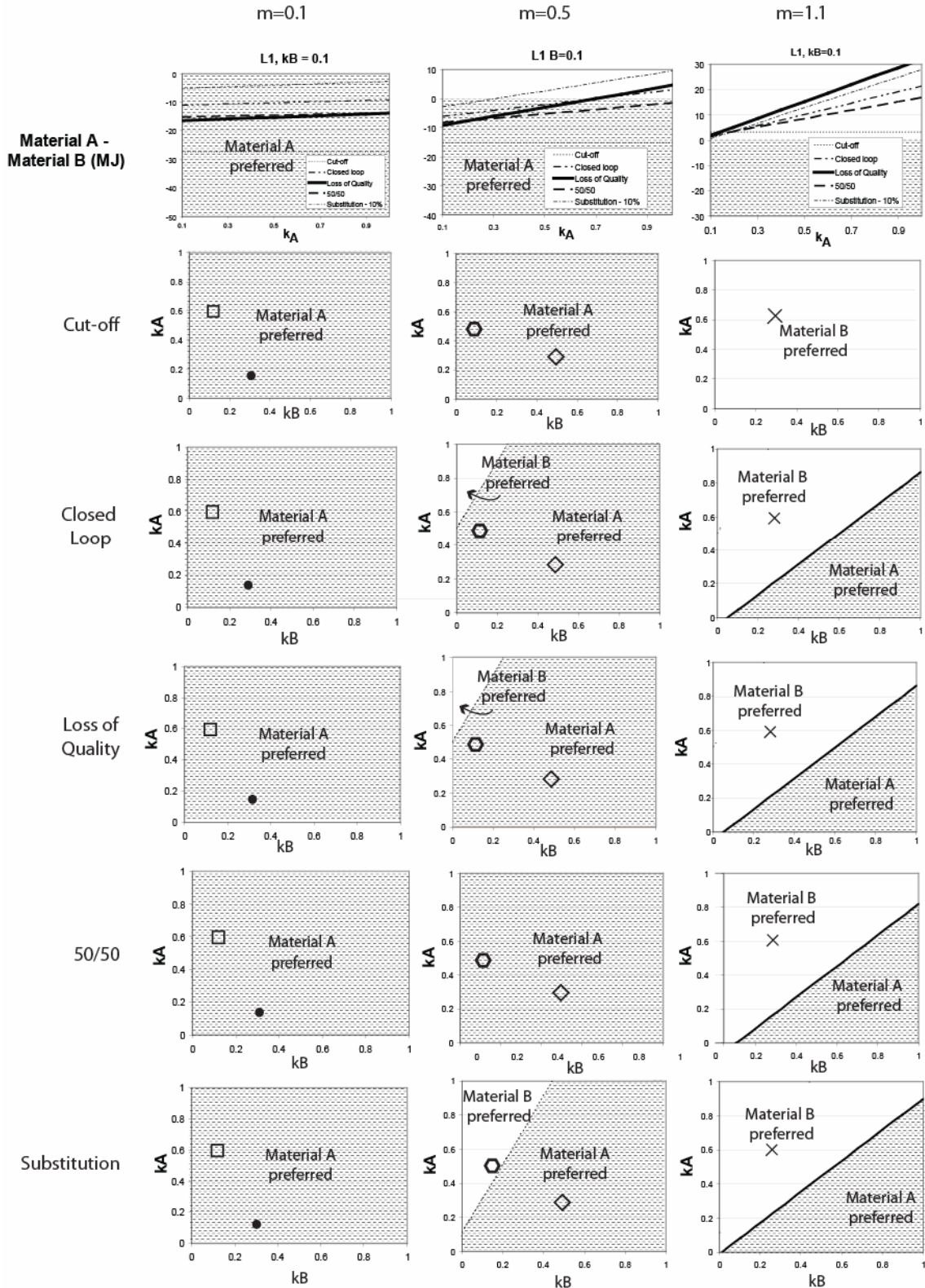
Figure 75: Variation in material preference across *m*, *k_A*, and *k_B* for Cut-off, Closed Loop, Loss of Quality, 50/50 and Substitution EOL allocation methods
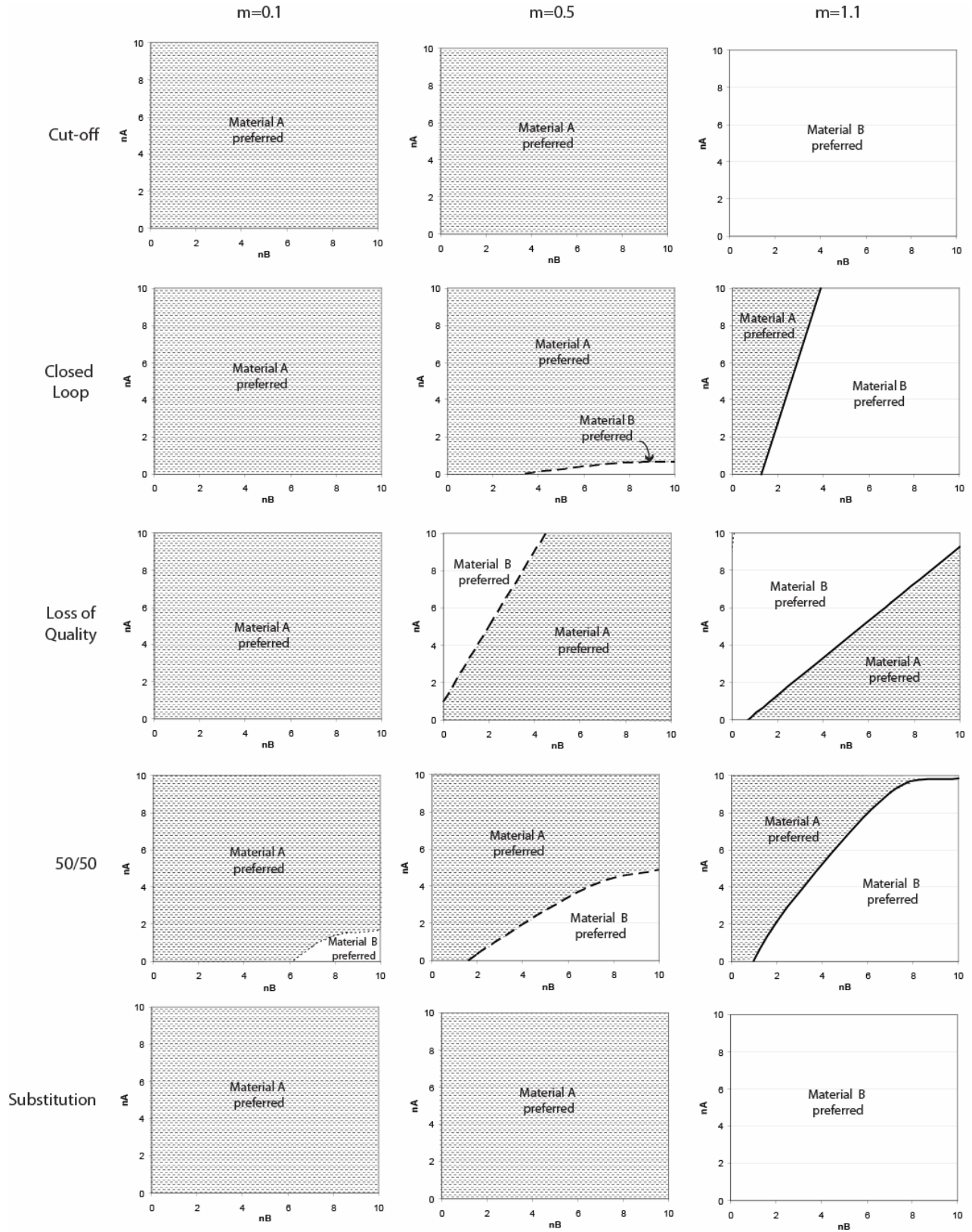
Figure 76: Variation in material preference across *m*, n_A, and n_B for Cut-off, Closed Loop, Loss of Quality, 50/50 and Substitution EOL allocation methods

6 Conclusions

Creating products with substantially lower environmental burden will be one of the key engineering challenges of the 21st century. Any fundamental solution to this challenge will require careful selection of materials and the processes used to fashion material into product. LCA 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.

In case I, this thesis provides an exploration into the robustness of the LCA result in response to variation in (1) the method used for evaluating environmental impact, (2) the characteristics of the intensity of vehicle use, (3) the specification of the product in the form of secondary weight savings, and (4) uncertainty in end-of-life processing. This assessment was carried out in the context of a specific materials selection case that would lead to a lighter weight vehicle. For the case presented herein, the EPS 2000 evaluation method provided a significantly different distribution of relative burden for the two alternative designs compared to either the CED or Eco-Indicator methods. Nevertheless, all three methods maintained consistent choice order, with the lighter weight Comparator technology leading to lower environmental impact under baseline conditions. For both of the latter methods, this choice order was not strongly sensitive to assumptions made about vehicle driving life or secondary weight savings for conditions similar to those for most personal vehicles in the US today. The EPS 2000 method showed stronger sensitivity to intensity of use. Nevertheless, across all of these results the intensity of use required to lead to Comparator preference was well below that of the average vehicle life within the United States.

The last section of case I explores the sensitivity of preferred material to different assumptions about product end-of-life, and lays the groundwork for the analysis in case II. In this case, the CED method was used to explore the robustness of the LCA result in response to variation in end-of-life allocation method. For case II presented herein, the CED evaluation method provided significantly different distribution of relative burden for alternative materials when considering different allocation methods. Notably, EOL allocation method rank order (revealing which method gives a stronger preference for particular material) is highly contingent on choice of parameters k (ratio of recycling production energy to primary production energy), n (number of assumed recycling generations in product cascade), r (percentage primary needed to offset losses in Substitution method), q (percentage of material degradation between product generations in Loss of Quality method). Moreover, each of these parameters is differentially sensitive to the parameter m, which establishes the ratio of primary energy burden between the two materials under consideration. Overall, the differences in EOL allocation method slope, resulting from the parameter m, cause a differential sensitivity to the parameter k (the ratio of secondary energy to primary energy). The Loss of Quality method demonstrates the strongest sensitivity to k, followed by the Substitution, Closed Loop, 50/50 and Cut-off methods. A high sensitivity to k implies that a method incentivizes the use of materials with low recycling burden compared to other methods and, conversely, strongly disincentivizes materials with a high recycling burden. Additionally, uncertainty in the number of life-cycles, n, can greatly and differentially affect identification of preferred material across the methods explored, particularly for the 50/50 and Loss of Quality methods, which demonstrated greatest sensitivity. This is especially relevant to the strong versus weak sustainability debate, as using a high number of recycling generations implicitly assumes a future market in which there is sufficient demand for a material to warrant recycling.

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 results presented here indicate that material decision-makers need to be aware of the implications of end-of-life assumptions on choice of material. The value judgments associated with the modeling of recycling using the LCA method make it unlikely that a consensus will ever be found. However, what is needed are clear and transparent reports from public and privately commissioned LCA studies on fundamental leanings with regard to concepts such as weak and strong sustainability concept, as well as their assumptions behind the parameters explored in this thesis.

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8 Appendix – Sloan Industries Report

The information presented in this study explores the role of the LCA method in materials decision-making in the automotive industry.

Environmental decision-making in the automotive industry

One area with significant environmental ramifications is the process of material choice in automotive product development cycles. This research seeks to understand the role of environmental, or sustainable, objectives in materials selection, product design, and production processes. To evaluate current materials and environmental strategies in the context of vehicle structural materials, a series of interviews was conducted with representatives from major automotive manufacturers. These interviews focused upon a consideration of the current bases for the evaluation of materials choice, product costs and environmental performance.

An interview protocol was developed to assess the integration of high-level automaker strategies into the material evaluation process, based upon the MSL's past experience with automaker product development processes. The interview protocol is given in the Appendix. Interviewees from both the automaker and materials communities were surveyed, with particular emphasis upon product engineering and support teams. The interview questionnaire explored topics around (1) environmental priorities and strategies within the larger context of automotive decision-making, (2) drivers and barriers to environmentally motivated decisions, (3) perceptions of lightweight materials, and (4) the methods and metrics used to assess environmental performance in the auto industry. The following sections summarize the key elements of these discussions.

Motivation behind material selection decisions

Table 1 gives the summary statistics for the interview responses to the questions examining the importance of particular vehicle characteristics in making automobile material choices.

Table 12: Categories of influence on vehicle materials selection decisions
(1 is most important, 5 not very important)

	Average Response:
Cost	1.4
Manufacturability	1.6
Performance characteristics	1.9
Environmental Impact - During use	2.4
Maintenance needs	2.6
Environmental Impact - At EOL	2.8
Environmental Impact - From manufacturing	2.9

Unsurprisingly, the issues that dominated discussions of materials selection decisions in the automotive industry were cost and manufacturability. Of these two considerations, cost was credited with a greater influence on materials selection decisions. Interview subjects indicated that individual firms are attempting to increase knowledge and performance in the area of manufacturability, since it bears directly on cost and quality. Interviewees cited the importance of performance characteristics when factored into materials selection decisions, although not to same degree of influence as cost and manufacturability. While subject indicated that cost and manufacturability are expected to retain their importance in influencing material selection decisions five years from now, the importance of performance characteristics is projected to grow slightly.

Interviews showed that product environmental impacts are being considered at three stages in the product life cycle: manufacturing, use, and end-of-life. At the manufacturing stage, energy consumption is an essential business consideration since it translates directly into operating costs. Subjects indicated that environmental impact during use and at end-of-life are also important, but of lesser concern, particularly in the US. Although subjects ranked environmental impacts between somewhat important to important, several indicated that use and end-of-life considerations would become increasingly significant if the US moves to a system like Europe's REACH. Moreover, these stages were expected to increase in their importance with an increase in general awareness of future liabilities, such as retroactive mercury legislation. Overall, the consensus among the interview subjects was that environmental impact from manufacturing, during use, and at product end-of-life will have greater influence on materials selection decisions made five years from now, particularly if regulations change energy efficiency and end-of-life standards.

Lastly, interviewees predicted that vehicle maintenance needs would remain of mild importance to less importance, as extended auto-manufacturing warranties would give customers less reason to worry about vehicle service costs.

Environmental priorities and strategies

After establishing the relative influence of factors that weigh on materials selection decision-making in the previous section, consideration was given to how firms prioritize environmental impact during the life cycle stages of the vehicle. Specifically, emissions and energy consumption from manufacturing and during use, resource depletion, and recycling were all considered as domains of environmental impact.

Table 13: Prioritization of environmental impact during vehicle life cycle
(1 is most important, 5 not very important)

	Average Response:
Energy Consumption - During use	1.3
Emissions - During use	1.7
Energy Consumption - From manufacturing	2.4
Emissions - From manufacturing	2.6
Recycling	2.6
Resource Depletion	2.9

The ranking of importance given to the environmental impact of the components of the vehicle lifecycle is unsurprising, reflecting how the combination of market and regulatory forces largely lead the automakers to focus upon energy consumption and emissions.

Drivers and barriers to environmentally motivated decisions

The next section of the interview explored drivers and barriers to environmentally motivated decisions in the automotive industry. The consensus was that the main drivers of environmentally motivated decisions are government legislation and regulation (including the threat of regulation), which ultimately determine price of environmental technologies in the industry. Government regulation includes emission control laws, CAFE standards, and CO_2 regulations in Europe -- all drivers that directly affect firm success or failure. A second main driver is customer surveys that provide direct feedback on how well environmental decisions bode in the marketplace, for example, recent data shows that more consumers are focusing on fuel economy in their purchasing habits.

Respondents indicated support for environmental choices leading to direct customer benefit, such as implementing oil light monitors or using longer-life coolant. The potential to foster a "green image" can also drive environmentally motivated decisions. Some firms believe that a "green" image will be the next big selling point after quality. According to one interviewee, consumer movement toward the environment is the next rationale for product purchase, while styling and the emotional response it elicits is no longer as highly valued.

Another interviewee indicated that although the environment was of interest five years ago, at that time it did not have a place in the marketplace and was not priceable. However, today it has major impact in the market, in that consumers are expecting green products. It used to be only a matter of social consciousness, but now the environment serves as a business driver.

Most frequently cited as a barrier to environmentally motivated decisions was cost and the complementary notion of customer affordability. One company explained that, even though over 30 environmentally-minded vehicles were introduced in Europe in the last 10 years, none were picked up by consumers because they were too expensive. One firm further cited the uncertainty surrounding environmentally motivated decision-making, stating that "even if we make an environmentally sustainable decision, even if it is cost beneficial, can we really sustain it? Will we have to alter our path again given a future business case?"

Manufacturing-related barriers mentioned include commonality of parts, in addition to designing for fleet goals. Conflicting performance requirements definitely affect decision making in the environmental realm.

Other barriers listed by respondents include "misguided government policies" such as CAFE, as well as confusion in the marketplace over what is truly environmentally advantageous. Another well-intended government policy that ultimately proved to be a barrier was the case of the EV-1, which, according to the interviewee, was shut down by the government due to the elimination of the zero emission vehicle mandate and battery functionality issues. Other, softer barrier issues cited include corporate inertia and a general lack of experience among those in positions who can affect the most change. Special interest groups, particularly the oil industry, were named by some as an additional barrier.

In a later section of the questionnaire, interviewees were asked to rank a list of barriers to adoption of environmentally sustainable practices in terms of their level of significance. Results are seen in Table 14, with lower numbers indicating greater significance as a barrier. An additional barrier mentioned, which was not on the list, was that components are currently not priced correctly to include the cost of environmental impact.

Table 14: Barriers to the adoption of environmentally sustainable practices

	Average Response:
Commercial disadvantage	2.0
Lack of customer demand	2.4
Conflict with functional requirements	3.3
Lack of incentives to designers/decision makers	4.3
Not required by legislation	4.9
Insufficient resources dedicated to analyzing environmental impact	5.6

Perception of lightweight materials

The use of alternative materials to reduce vehicle mass is a tactic often promoted to improve the fuel efficiency and environmental performance of vehicles. However, a growing array of materials candidates confronts today's designer. This section explores the positioning and environmental perception of various lightweight material alternatives (versus mild steel) used in vehicle structural body applications. The following sections will profile the interviewees' opinions on high strength steel, aluminum, magnesium, thermosets and thermoplastics in terms of emissions, energy consumption, resource depletion, and recycling.

Figure 77 shows the average interviewee perception of lightweight material environmental performance in comparison to a baseline of mild steel. Interviewees were asked to rate the material as beneficial, neutral, or detrimental in four environmental categories; emissions, energy consumption, resource depletion, and recycling. A higher score is associated with greater environmental benefits along each axis; a low score is associated with negative environmental effects.
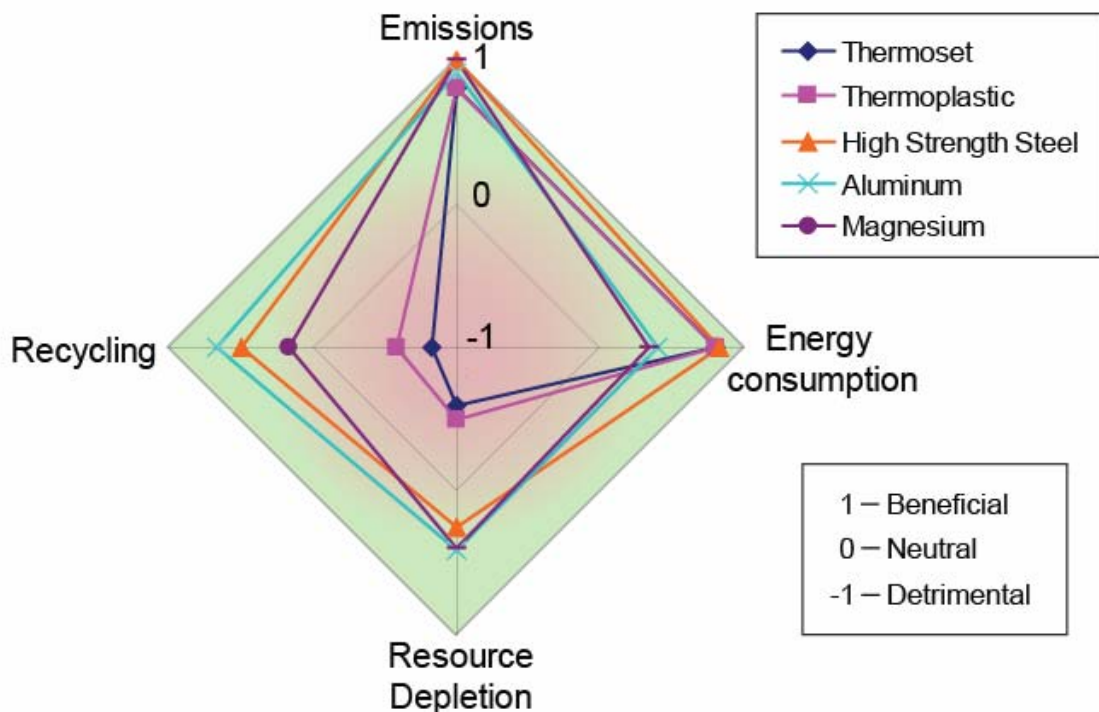
Figure 77: Environmental perception of lightweight materials compared to mild steel when used in vehicle structural applications

One interviewee hastened to point out that a material can only be considered beneficial in terms of emissions when used in the "right way" or when used in a lightweighting application; e.g. thermoplastics when used for lightweighting and not for styling. Similarly, another interviewee stated that all lightweighting materials are beneficial given that all environmental categories can be optimized based on appropriate material selection. In a multi-material vehicle, it depends on where the material is applied, and "the right material used in the right part of the vehicle is always going to be beneficial."

Another interviewee indicated that aluminum use is environmentally detrimental from an energy consumption standpoint when weighing production energy versus the vehicle lifetime. This

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subject also indicated that thermosets and thermoplastics are similarly detrimental from a resource depletion standpoint because of their connection to oil and natural gas, while use of high strength steel is beneficial because there is a great deal of iron ore. Aluminum, magnesium, and thermoplastic are viewed as neutral when it comes to recycling because, unlike steel, the recycling infrastructure either does not exist or is not of the same magnitude.

For lightweight materials in general, interviewees stated that the environmental performance of a material depends on the weight reduction achieved. However, one individual went on to say that all lightweighting materials in question are generally perceived as beneficial compared to mild steel. On the other hand, this is a question that is not possible to answer when one is aware of life cycle considerations. The subject cited, for example, the SF_6 required in magnesium casting process generates "horrible" greenhouse gases. Similarly, aluminum is extremely energy intensive to produce and substantial lightweighting is needed to offset production burdens.

Two interviewees chose not to give specific answers to this question, feeling that they lacked access to the "right" answer. Explanations detailed the sources of uncertainty inherent in the life cycle assessment methodology, such as a dependence on where the material is being sourced (e.g. different thermal processes for magnesium that depends on the country and plant). This individual stated that there are no straightforward answers in terms of ranking materials as beneficial or detrimental, and so responses to these questions are fundamentally not useful.

Based on participant responses, using an environmental platform to position lightweight materials is perhaps a misguided effort, given the way environmental information is incorporated into materials decision-making. While lightweight materials are not necessarily environmentally unfavorable when considering their life-cycles, the fact is that the auto industry maintains a subtle appreciation of the economic and institutional barriers that greatly influence the adoption of more arguably more environmentally preferable materials. However, this begs the question of how does one really know what is better in an environmental sense? Hence, the next section considers the methods and metrics firms use to assess environmental performance of their products and processes.

Methods used to assess environmental performance

Product design considerations

This section of the interviews explored how firms incorporate environmental information into product design decisions affecting the vehicle use phase and vehicle end-of-life. Specifically, the methods used to achieve environmental goals in product design stage and the measurements used to quantitatively assess environmental effects during production are discussed. Finally, this section surveys how firms assess these environmental metrics.

Most participants responded that, as new products are developed, both internal materials and those from suppliers are subject to regular review protocols and GADSLs (Global Automotive Declarative Substances Lists), which provide basic material environmental specifications. While one individual responded that environmental information is assessed during the vehicle design phase in tandem with cost, performance, and other traditional considerations, another stated that environmental effects are assessed "after the fact", or as confirmation that the vehicle allows regulations to be met. One individual communicated that environmental effects are definitely *not* driving materials selection decisions in this regard.

Contributing to this conflicted mentality is perhaps a certain level of organizational or institutional fragmentation when it comes to consideration of environmental issues. While there may exist corporate processes that deliver action bulletins to engineering in terms of what to investigate and implement in products, much environmental research is done through agencies that have little overlap with those involved in product design decisions.

For global firms, some internal environmental assessment procedures vary by region, as in the development of product sustainability indices in Europe by one firm. According to this firm, there is a movement to employ these sustainability metrics in the US. These indices involve multi-panel charts with listed enviromental targets as well as "green, yellow, and red" thresholds developed by the Program Office and Product Development teams. These teams are responsible for developing environmental performance "road maps" with subject matter experts, and these considerations are included from the very beginning of the product design stage and communicated to various development teams and suppliers. At the end of the development process, values are verified against dismantling reports. The use of this particular indexing system gives this firm a sense of ownership for environmental issues.

Overall, many interviewees indicated that sustainability as a concept is gradually diffusing across the company down to the plant level.

In terms of specific methods, Life Cycle Analysis (LCA) software is used to conduct studies around energy and emissions. However, one respondant indicated that although LCA is used, it is not used as extensively as it should be. Generally LCA is used for product comparisons as opposed to absolute product assessments.

Specifically, firms analyze the fuel life cycle using Argonne's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. This tool is used for well-to-tank analyses and then a proprietary model is used for tank-to-wheel analyses and used to compare conventional, hybrid, electric, and fuel-cell vehicles.

In terms of vehicle end-of-life, the consensus among interviewees is that, for the moment, regulation adequately addresses these issues. Several firms are members of the Vehicle Recycling Partnership, which seeks to promote an integrated and sustainable approach to improving the technical and economic feasibility of vehicle recycling in North America.

Increasingly, the vehicle use phase is being influenced by designs that pay specific attention to achieving improvements in fuel economy and emissions. Preference is given to materials that offer favorable recycling performance. However, recyclability will lose out when other engineering factors such as performance, cost, and durability favor a less recyclable material. In particular, material alternatives that optimize vehicle fuel economy are the initial environmental focus of product designers.

Influential positions in product design process

Four categories of positions were cited as having particular influence upon environmentally motivated decisions in the product design processare: (1) firm executives/senior management, (2) energy and environment departments, (3) materials/platform/ component engineering, and (4) purchasing.

Several interviewees at different firms indicated that those with the most influence on environmentally motivated decisions are those at the highest level of the company. At one particular firm, the group of executives affiliated with these decisions is the Energy and Environmental Strategy Board, comprising global vice presidents and senior management from public policy, engineering, marketing, and legal that meet once a month. The board bases its product design decisions on presentations given to it on critical engineering and environmental issues by the appropriate departments. Similarly, another subject suggested that the Chief Technology Officer has most influence the product design cycle, due to her position over research and advanced engineering.

In contrast, another firm/interviewee indicated that the materials engineering department, followed by the purchasing department, have the most influence on environmentally motivated decisions. While senior management may guide the overall thought process, senior management definitely is not directly making the decisions, only supporting them. Interviewees from other firms echoed this sentiment by describing component engineers, chief program engineers, chief platform engineers, product strategists, and product designers as having a significant role in decisions that affect the environment.

One individual noted that despite the fact that the decisions that actually lead to environmental change are made by product design and engineering staff and management, a real commitment from senior management is required – something that is only possible in companies that have a long term commitment to an environmental strategy. Subjects from another firm stated that vehicle line executives have the most influence by giving directions and making trade-offs based on the metrics provided them from the senior management vehicle product council, which are formulated based on specifications around factors such as target demographic, fuel economy, and cargo space.

Subjects from another firm responded that influence is systemic throughout the organization and involves everyone, starting with the top. Much depends on whether upper management has communicated an environmental strategy; assuming they have, the rest is up to middle management to implement. Given the carbon dioxide (global warming) debate, a job exists for everyone regardless of position, from powertrain design to marketing. There is a "shepherding" mentality within the company that everyone is responsible for environmental decision making.

Manufacturing/Production considerations

This section of the interview explored how environmental information is incorporated into vehicle production and manufacturing decisions –the methods used to achieve environmental goals during the manufacturing stage and the measurements used to quantitatively assess environmental effects during production. This section summarizes what the survey subjects had to say about how firms assess these environmental metrics.

Most interviewees indicated that the environmental effects of production are decided and tracked in the product design phase, and are grounded in cost considerations and government regulation. In addition to industrial hygiene compliance, achieving environmental goals during the production stage is strictly a consequence of cost analyses (e.g. reducing water consumed, reducing oven temperatures, etc.). Measurements used to assess environmental effects include waste (heat, solid waste, water, etc.) and cost. Since energy consumption in production is directly related to cost, groups within the firm are tasked with continually seeking ways to save money and improve emissions during the manufacturing phase; for example, exploring ways to

produce energy from volatile organic compounds. One firm indicated that the the environmental drivers in the manufacturing process are simply a reflection of the cost to landfill.

Economic analysis and Life Cycle Analysis are used as methods to achieve environmental goals during the production stage. According to subjects from one firm, LCA tools are being used more intensively in plants – a reflection of a more general policy that if something is measurable, it is measured.   In terms of assessing environmental effects, no specific pre-established measurement levels were cited; rather, environmental effects are a consequence of the need to achieve performance characteristics at cost. Hence, everything is, in one interviewee's words, "blended together."

Most decisions for new material applications are determined by consideration of issues such as sludge treatment options, scrap handling, maximizing recyclate value, and acid bath disposal. Because so many of these criteria are dependent upon context, such decisions are location specific. Plant managers have targets for cost, efficiency, and spills, and the materials handling employees working on the plant floors are the ones who carry out these methods.

There are also benchmarks among plants for energy consumption and other metrics. Similar to the product sustainability index, one subject cited the use of a manufacturing sustainability index that tracks roughly eight plant-level indicators involving energy, materials and emissions, with waste elimination as an ultimate goal. Most firms have set up a special group of plant and regulatory people that share best practices and more. Depending on the specific emissions regulations in the area of production, firms want to lower their exposure to fluctuations in practice that might arise from expected changes in regulation. Initiatives such as windmills and photovoltaic sources at plants, referred to by one as "greening strategies," are also ways firms are seeking to demonstrate an environmental conscience.

Influential positions in production processes

Like product design, four job categories were cited as having the most influence on environmentally motivated decisions in production processes: (1) firm executives/senior management, (2) energy and environment departments, (3) facilities groups, and (4) manufacturing engineering.

Positions of influence cited at the level of senior management include positions such as the Vice President of Sustainability and Environmental Operations. As in the product design section, the Energy and Environmental Strategy Board was mentioned again, which is composed of vice presidents and senior management.

Roles cited as falling under the environmental category within manufacturing include Environmental and Safety Engineering.   One firm's subjects indicated that this group tries to set consistent environmental and safety standards across the world, so as not to take advantage of countries with more lax regulations, but there are still circumstances when standards vary by country.

At the manufacturing level, facilities management groups pursue environmental solutions on their own; for example, taking advantage of state rebates in California to place solar arrays on a warehouse rooftop. Another subject named the executive position of plant manager as having the most influence on manufacturing decisions affecting the environment. For example, it is the plant manager who decides when to install a $1B state of the art scrubber on a paint shop, and he or she faces expensive ramifications when anything goes wrong.

Lastly, those involved in manufacturing engineering, as well as production processing and process engineering, were characterized as bearing direct influence on decisions affecting the environment.

Sustainability Impact Categories

This section of the interview gave explicit consideration to the role of sustainability impact categories on product development decisions. Impact categories are used in life cycle assessment to determine the environmental impact of all the quantified inputs and outputs contributing to a product life-cycle. Understanding the relative importance ascribed to each of these impact areas is fundamental when interpreting LCA results, and arguably, when using LCA to make materials selection decisions. Figure 78 shows the average importance rating cited by interviewees when considering environmental emissions.
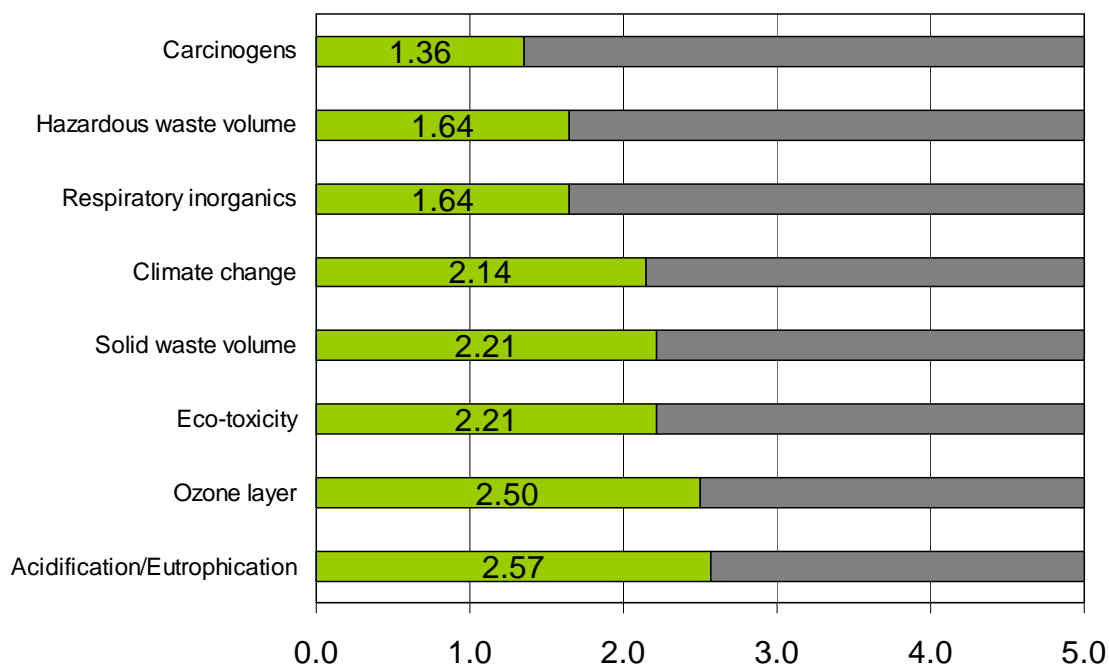

Figure 78: Average rating of impact categories when considering environmental sustainability in product development decisions (1 is the most important, 5 is the least important)

Unsurprisingly, carcinogens were rated as the most important impact category when considering environmental sustainability in product development decisions. As one interviewee stated, "We don't make decisions that we know expose people to carcinogens. When we make product design decisions, we're not looking at tradeoffs between different levels of carcinogens. If these categories were knowingly released into the environment, then they would all be number one. However, it is not possible to completely eliminate risk. Overall, things that impact people's lives and health [are] number one, while things that involve more long-term strategic thinking [are] of less importance, such as climate change."

These sentiments were echoed in another interviewee's response, who indicated that the listed sustainability impact categories are all defined by cost issues and regulatory standards. "Issues that are number one and number two determine whether you can stay in business. Carcinogens, respiratory inorganics, and hazardous waste are possibly the most important considerations. Climate change, ozone layer, eco-toxicity, acidification and eutrophication, solid waste, and

energy consumption are all very important when considering product development decisions, as is land, water, material use, and recycling, but to a lesser degree than the other categories."

It was further noted that the relative importance of specific impacts depends on regional considerations; for example, a plant in Mexico has a complete on-site water recycling system because water is expensive there. One interviewee stated that water is extremely undervalued, especially in the US. In the same vein, another interviewee indicated that in an ideal market, materials that are priced correctly demonstrate a valuing of environmental and sustainability issues.

Figure 79 shows the average rating of resource impact categories by interview subjects when considering environmental sustainability in product development decisions. Energy consumption was identified as the most important concern, followed next by material availability and recycling and last by water and land use.

While interviewees largely discounted the importance of environment in product decisions, the issue of global warming seemed to elicit some different perspectives. For example, one interviewee responded that climate change has shifted from being important to possibly the most important consideration in product decisions. This person went on to say that ozone layer really is not talked about anymore and can be considered "not very important." In fact, one interviewee went so far as to say that categories labelled as "important" are only considered as such because they have previously been addressed and are no longer as much of an issue (e.g. hexavalent chromium and acidification, air conditioning and ozone layer depletion).

Finally, another interviewee indicated that all impact categories are important, and that the weighting of their contribution to environmental sustainability depends on who you are asking, leading to the imperative that environmental decisionmaking should be as transparent as possible. Decision makers need to know what conditions they are basing their decisions on and should be aware of implicit values and boundary conditions. Given the subjective nature of weighting or ranking different impact categories, one interviewee refused to answer this question.
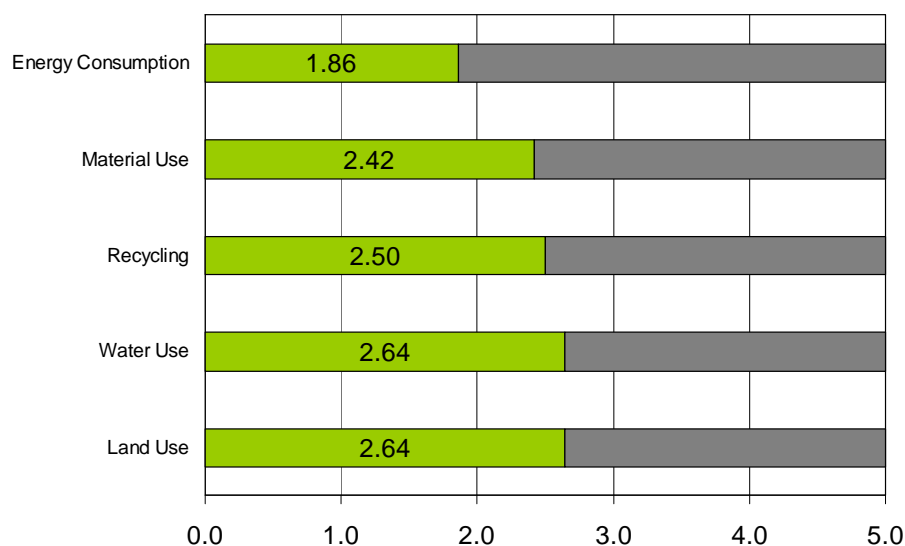

Figure 79: Average rating of resource impact categories when considering environmental sustainability in product development decisions (1 is the most important, 5 is the least important)

Interview Questionnaire

The Materials Systems Laboratory at MIT is interested in learning about factors that influence material selection processes in the automotive product development cycle. We recognize several key areas that drive the need for this research, including the slow commercialization of alternative materials, a poor understanding of materials decision making processes within the automotive industry, and a lack of implementation of materials research advances in products.

### Ongoing research in materials selection

Currently we are conducting a series of interviews with material suppliers and automotive industry experts to determine how technology change, essential material characteristics, lightweighting and cost, and barriers to material use affect novel material adoption. The following trends are of note:

- Technology change includes incentives such as competitiveness, reduced costs, and weight/fuel economy; impediments include conservatism and inertia.
- Cost, manufacturability, corrosion resistance, and fatigue behavior affect selection decisions more often than recyclability, lightweighting, customer perception, vehicle maintenance needs, and environmental impacts during manufacturing.
- Stiffness, strength, and specific gravity are central lightweighting selection metrics.
- Most advantageous to lightweight areas far from vehicle center and unsprung mass.
- New material cost complexity considerations include: piece cost, tooling cost, raw material cost volatility, and impacts on downstream production cost.
- Decisions affecting material selection are made early in the development cycle.
- Adoption barriers more often include technical limitations, inertia, and supplier problems rather than a lack of material awareness, long material approval lead times, or lack of exec. support.

Materials strategy research in environmental sustainability

Industry currently faces numerous environmental pressures to conduct operations in ways that protect the natural environment and human health. Included among these environmental pressures are corporate regulations, resource availability, ethical responsibility, and consumer demand for environmentally-advanced products and services, illustrated by the figure below[7]. One area with vast environmental ramifications is material choice in automotive product development cycles. Consequently, this research seeks to understand the role of environmental, or "sustainable," objectives in materials selection, product design, and production processes. We have organized several questions according to the format below. We hope to arrange phone interviews to discuss these issues and hope this questionnaire can guide our conversation.

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[7] Paquette, J. (2006). The Supply Chain Response to Environmental Pressures. Unpublished Master's Thesis, M.I.T., Cambridge.
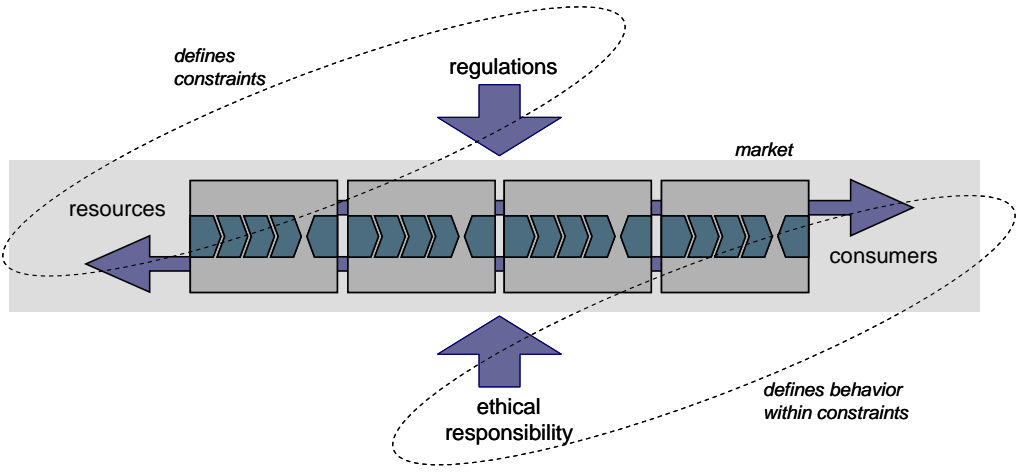
1. Please rate the following in terms of their current influence on vehicle materials selection decisions (Indicate by rating from 1-5 where 1 is the most important and 5 is not very important). Five years from now, do you think these will be of **G**reater, **E**qual, or **L**ess influence?

Category	Current level of influence					Five years from now (G,E,L)
	Most important		⟹		Not very important	
Manufacturability	1	2	3	4	5	
Cost (e.g. piece cost, tooling cost, cost volatility of raw materials, etc.)	1	2	3	4	5	
Environmental impact:						
From manufacturing	1	2	3	4	5	
During use	1	2	3	4	5	
At end-of-life	1	2	3	4	5	
Performance characteristics (above standard warranty thresholds)	1	2	3	4	5	
Vehicle maintenance needs	1	2	3	4	5	

2. How does your firm prioritize environmental impact, or environmental sustainability, in terms of vehicle life cycle? Please use the following scale (1 is the most important environmental life cycle impact, 5 is least important):

Category	Possibly the most important consideration	Very important	Important	Somewhat important	Not very important
Emissions:					
From manufacturing	1	2	3	4	5
During use	1	2	3	4	5
Energy Consumption:					
From manufacturing	1	2	3	4	5
During use	1	2	3	4	5
Resource Depletion	1	2	3	4	5
Recycling	1	2	3	4	5

3. In your opinion, what are the main **drivers** of environmentally motivated decisions in the automobile industry?

4. In your opinion, what are the main **barriers** to environmentally motivated decisions in the automobile industry?

Material Selection Considerations

5. As compared with current practice, which materials (used in vehicle structural applications) are **B**eneficial, **N**eutral, or **D**etrimental to environmental sustainability when considering the following categories:

	High Strength Steel	Aluminum	Magnesium	Thermoset RP/C	Thermoplastic RP/C
Emissions					
Energy consumption					
Resource depletion					

Recycling					

Product Design Considerations

6. How is environmental information incorporated into product design decisions affecting: 1) the vehicle use phase and 2) vehicle end-of-life?

    a. What methods does your firm use to achieve environmental goals in the product design stage?
    b. What measurements does your firm use to assess environmental effects? How does your firm assess these environmental metrics?

7. In the product design process, which job positions at your firm have the most influence on environmental decisions?

Manufacturing/Production Considerations

8. How is environmental information incorporated into production decisions (e.g. prompt scrap use)?

    a. What methods does your firm use to achieve environmental goals in the production stage?
    b. What measurements does your firm use to quantitatively assess environmental effects during production? How does your firm assess these environmental metrics?

9. In the production process, which job positions at your firm have the most influence on environmental decisions?

Sustainability Impact Categories

10. How important are each of the following when considering environmental sustainability in product development decisions? Please use the following scale (1 is the most important environmental concern, 5 is least important):

Category	Possibly the most important consideration	Very important	Important	Somewhat important	Not very important
Emissions:					
Carcinogens	1	2	3	4	5
Respiratory inorganics	1	2	3	4	5
Climate change	1	2	3	4	5
Ozone layer	1	2	3	4	5
Eco-toxicity	1	2	3	4	5
Acidification/Eutrophication*	1	2	3	4	5
Solid waste volume	1	2	3	4	5
Hazardous waste volume	1	2	3	4	5
Resource Depletion:					
Land Use	1	2	3	4	5
Water Use	1	2	3	4	5
Material Use	1	2	3	4	5
Energy Consumption (result from question #2)	1	2	3	4	5

Recycling (result from question #2)	1	2	3	4	5

* Acidification is the contamination of air and water by chemical compounds that either develop acids or deposit metals. Eutrophication is water pollution caused by excessive plant nutrients.

Barriers to Sustainability

11. Please rank the following barriers to the adoption of environmentally sustainable practices in order of their significance (1 is the most significant barrier, 6 is least significant).

Barrier	Rank
Commercial disadvantage (e.g. increased product cost)	
Lack of incentives to designers/decision makers	
Conflict with functional requirements	
Lack of customer demand	
Insufficient resources dedicated to analyzing environmental impact	
Not required by legislation	
Other:	

Biographical Background

12. What is your job title? Please describe your primary professional responsibilities.

13. Have you worked in related positions for other vehicle manufacturers, parts suppliers, or materials suppliers? If so, where?