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End-of-life LCA allocation methods: open loop recycling impacts on robustness of material selection decisions

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End-of-life LCA allocation methods: open loop recycling impacts on robustness of material selection decisions

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Abstract— **Materials selection decisions exhibit great influence on the environmental performance of firms through their impact 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 (EOL). While lifecycle assessment (LCA) methods provide quantitative input to a product designer's materials selection decision, LCA implementations are evolving and disparate. This work explores several analytical variations of LCA related to the allocation of recycling impacts at product EOL and the implications of these variants across a range of contexts. Stylized analyses across a range of materials are presented, focusing on materials with varying primary and secondary materials production burdens. This work illustrates that a) the application of distinct EOL allocation methods give different values of cumulative environmental impact for the same material, b) these impacts change at differing rates between the various methods, and c) these disparities can result in different rank ordering of materials preference. Characterizing this behavior over a range of parameters illustrates the potential trends in allocation method bias for or against particular materials classes.**

Index Terms— **end-of-life, life cycle assessment, materials selection, recycling**

I. INTRODUCTION

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-

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minded products [1]. As these concerns filter down to an operational level, they challenge industries to conduct business in ways that are sustainable, or minimize impact on the natural environment and human health while improving societal interests. Materials selection decisions provide one important lever to improve the environmental performance of firms because of the impact of a material choice over a product's entire lifecycle. A product's constituent materials drive its environmental profile because of the burden associated with extraction and processing from material to product, product performance during use, and end-of-life (EOL) disposal. 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). LCA requires the analyst to characterize each stage of a product or process, presenting a particular challenge for materials selection decisions occurring early in product development cycles, when options are ample, but data is scarce. As a result, a critical question emerges concerning the effectiveness of LCA to support materials selection decisions: Can LCA results resolve the environmental performance of materials alternatives given the level of uncertainty endemic to materials selection?

One frequently discussed challenge in LCA methodology is the allocation or partitioning of environmental burdens between various coproducts or processes with multiple inflows or outflows. For example, when calculating the disposal burden of a particular municipal solid waste stream, landfill emissions, such as carbon dioxide and methane, must be allocated among the host of materials within a landfill. This work considers the allocation challenge brought by partitioning the benefits or "credits" and burdens at product EOL in the case of open loop recycling. Currently, LCA ISO 14040 standards do not explicitly address the issue of EOL accounting in open loop recycling [2] and a diverse set of methods exist to address this challenge [3]. Another LCA standard, focused on quantifying greenhouse gas emissions is the Publically Available Specification (PAS 2050) developed in the United Kingdom, which describes seven allocation strategies and leaves the burden of open loop recycling calculations to the life cycle analyst [4]. 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 [5]. For metals that can be reused many times, boundary expansion can introduce large sources of uncertainty or lead to a costly and time consuming effort. A recent publication by Frees [6] suggests an allocation approach for aluminum based on determining the price elasticity of primary and recycled aluminum for various products, building on the work of Ekvall and others [7-9]. A conceptually robust method, developed by Franklin Associates, requires the analyst to assume recovery rates and predict the number of times recycling will occur, given the incarnation of future products [10]. While EOL allocation methods have been evaluated for specific products such as waste wood [11], this work 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.

The work presented here builds on previous efforts to explore the implications of various EOL allocation schemes on the elected materials selection decision [12]. Specifically, questions of whether EOL allocation methods can lead to different materials selection decisions are investigated and how these allocation methods differentially favor certain material classes.

II. EOL ALLOCATION METHODS

A. Method description

This paper describes how materials selection decisions might be impacted by using five different EOL allocation methods to determine cumulative environmental impact. Table I outlines the different allocation methods analyzed in this work in relation to the life cycle cascade characterized by Ekvall and Tillman represented in Fig. 1 [13]. Each of the methods described below derive from different perspectives on what is considered reasonable or fair in terms of burden allocation. This equations in Table I do not include a use phase burden.
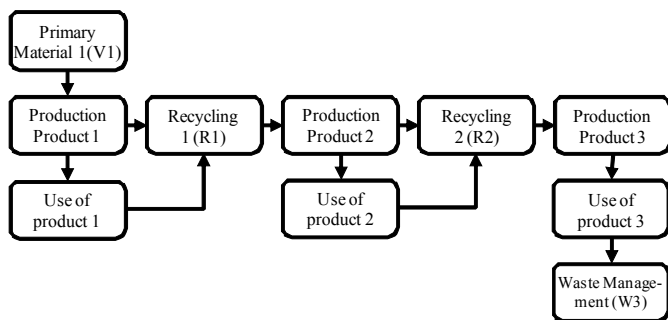

Fig. 1. Life cycle cascade of product material flows and processes involving open loop recycling for 3 life cycles [13].

The **Cut-off method** argues that each product should only be assigned environmental impacts directly caused by that product; hence the primary material burden (V1) is assigned to the life cycle burden (L1) for Product 1. This assumes that had Product 1 never come into existence, no virgin material would be associated with its creation. Similarly, the recycling or secondary material burden (R1) associated with Product 1 is ascribed to Product 2 (L2). The recycling burden (R2) of Product 2 is assigned to Product 3 (L3), which is also accountable for any burden associated with final waste treatment (W3).

Losses of quality methods are based on the perspective that virgin material production and final waste treatment are necessary steps for the 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 make use of a material quality metric, which ascribes environmental burden to each product life cycle based on its value in the product cascade. Material pricing data for primary and secondary sources can be used as a proxy for material quality.

The **Closed loop 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.

TABLE I. DESCRIPTIONS AND FORMULAS FOR DIFFERENT EOL ALLOCATION METHODS, VARIABLES AS DESCRIBED IN FIG. 1 AND DEFINED BELOW.

Method	Description	Formula
Cut-off method	Loads directly caused by product are assigned to that product [13].	$L1 = V1, L2 = R1, L3 = R2 + W3$
Loss of quality method	Assigns load to products in relation to their relative loss of quality in each step [13].	$L_i = \dfrac{Q_i}{\sum_{i=1}^{n} Q_i} \times (V1+R1+R2+W3)$
Closed loop method	Applicable to materials that do not experience significant losses in quality when recycled [14].	$L1 = L2 = L3 = \dfrac{V1 + (R1+R2) + W3}{n}$
50/50 method	Virgin material production and waste treatment are allocated to the first and last products in equal proportions [13, 15].	$L1 = \dfrac{V1+R1+W3}{n-1}$, $L2 = \dfrac{R1+R2}{n-1}$ $L3 = \dfrac{V1+R2+W3}{n-1}$
Substitution method	Recycled material substitutes primary; accounts for lost material and recycling burdens [16].	$L1 = (100\%-r\%) \times (R1) + r\% \times (V1+W3)$
Qi is the quality of material (quality ratios can be computed using market pricing data for primary and scrap materials), *n* is the number of life cycles, and *r* is the amount of primary material needed in secondary material production to account for lost material in the recycling process.		

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 EOL 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 [15].

In the **Substitution** method, the environmental burden of

each product life cycle in the cascade is 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 applied to certain metals, such as aluminum and steel, which maintain their inherent properties when recycled.

B. Example analysis

The differences in the equations in Table I imply that calculating total environmental burden for a particular material would result in different values depending on the allocation method used. A small example illustrates this point by determining the environmental burden of L1 for one kilogram each of three materials: uncoated copy paper (A), corrugated unbleached cardboard (B), and steel (C) where n, the number of product life cycles, is assumed to be identical for all three materials and $r = 0.1$. Data for primary material burden (V1) and secondary material burden (R1) were taken from the Environmental Defense Fund Paper Calculator [17] and the ecoinvent v2.0 database (with the analysis performed using the Cumulative Energy Demand environmental impact assessment methodology [18]); cumulative environmental impacts were calculated according to the equations in Table I. The material with the minimum environmental impact is the *preferred material*. It should be noted that this analysis does not include a use phase burden as these materials are not associated with a particular product. The waste burden (W3 above) is considered small in magnitude compared to the primary and secondary burdens and therefore is omitted from the calculations. This analysis is not intended to suggest that these materials would be substitutes for each other; actual data for materials was used simply for illustrative purposes.

Fig. 2, the result of this small analysis, shows that the environmental impact in terms of Cumulative Energy Demand (CED) of L1 is different for these materials between just three representative EOL allocation methods: Cut-off, Closed loop, and Substitution. The rank order for preferred material (in order of most to least preferred material) is [A, B, C] for the Cut-off method, [A, C, B] for the Closed loop method, and [C, A, B] for the Substitution method.
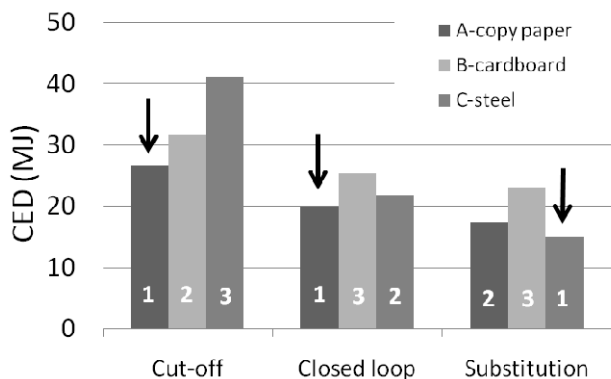

Fig. 2. Environmental impact in CED of L1 for unbleached copy paper (A), corrugated unbleached cardboard (B), and steel (C). Arrows indicate minimum impact or *preferred material* and numbers 1-3 indicate order of most to least preferred material.

This example clearly illustrates that 1) cumulative environmental impact results differ according to EOL allocation method, 2) results change across methods at a different rate for different materials, and 3) results differ in a way that can change the order of materials preference or rank order. If changes in EOL recycling allocation methods can significantly affect results, a potential question that arises from this analysis is: Do these methods systematically "favor" certain materials and what are the characteristics of those materials that drive this favor? In order to begin to answer this question, results are presented for an analysis that varies a series of parameters to determine the nature of a potential EOL allocation method's bias for or against certain materials characteristics.

III. APPROACH

A. Assumptions and parameter definitions

In order to test the robustness of materials selection decisions when using different LCA EOL allocation methods, a case was developed comparing a Baseline Material with an equivalent amount of various Comparator Materials. To isolate the effects of the EOL allocation method, this analysis does not consider the use phase associated with these materials; therefore, the subsequent results do not identify the preferred material for any given application where use phase drives, or represents a significant fraction of, environmental performance. However, differences in the evaluation of these phases would directly translate into the necessary difference in use phase performance to identify a preferred material.

To develop appropriately parameterized versions of the five EOL allocation methods described above, some nomenclature is defined. For the purposes of this analysis, environmental impact is measured in MJ, and the primary and secondary burdens can be thought of as the *energy* for primary and secondary materials production. Let m represent the ratio between the primary energies associated with producing one kg of Comparator Material A to producing one kg of the Baseline Material B, V_A/V_B. Parameter 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. Other assumed parameters include r, used 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 reused before it is discarded.

B. Hybrid life cycle framing

Most products are not easily classified as L1, L2, or L3, but rather represent some blend of all three due to the impossibility of knowing the fate or history of materials in products. Therefore, let L_n define a "hybrid" product life cycle burden for each EOL allocation method as a *weighted average* of the various L1, L2, and L3 burdens calculated using the equations found in Table I. This section describes the method

for calculating the weighted averages to be applied to L1, L2 and L3 for the development of the hybrid life cycle.

Table II shows the percentage contribution of the L1, L2 and L3 burdens towards a hybrid life cycle burden. Each of the rows in Table II corresponds to a path (dashed line) in Fig. 3 illustrating the calculation of the weightings for each L within the hybrid life cycle. These paths are explained in more detail below.

TABLE II. PERCENTAGE CONTRIBUTION OF PATHWAYS FOUND IN FIG. 3.

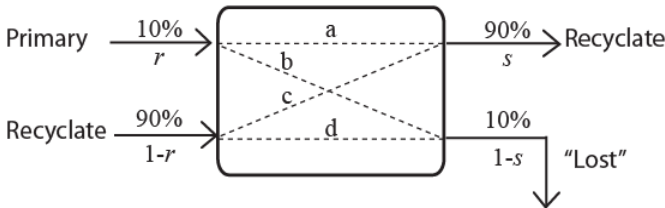| Path	Maps to	Example Percentage Burden	Theoretical Percentage Burden
a	L1	$0.1 \times 0.9 = 0.09$	$r \times s$
b	V1+W3	$0.1 \times 0.1 = 0.01$	$r \times (1-s)$
c	L2	$0.9 \times 0.9 = 0.81$	$(1-r) \times s$
d	L3	$0.9 \times 0.1 = 0.09$	$(1-r) \times (1-s)$

Fig. 3. Schematic diagram for environmental burden hybrid pathway

For this example hybrid life cycle, 10% primary material (r) and 90% recycled material (i.e. $1-r$) enter the product stream. The dashed lines a, b, c, and d represent the fraction of the environmental burden associated with L1, L2, and L3. 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, $r = 1 - s$, a condition necessary for the system to not experience any accumulation or loss. This material path is traced by the dashed line "a" in Fig. 3. 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 ($1-s$) due to processing, use, disposal, degradation, etc. 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), and in this case is calculated by multiplying the percentage primary material by the percentage lost material.

After multiplying L1, L2 and L3 by their fractional burden, the hybrid burden, shown in Eqs. 2 and 3 below, is simply the sum of each of these.

Therefore for the example described above:

$$L_n = (0.09 \times L1) + (0.01 \times (V1+W3)) + (0.81 \times L2) + (0.09 \times L3) \quad (1)$$

More generally, this equation would be given by:

$$L1 \times (r \times s) + (V1+W3) \times (r \times (1-s)) + L2 \times ((1-r) \times s) + L3((1-r) \times (1-s)) \quad (2)$$

Due to the small fractional burden associated with the lost material in V1+W3, the contribution of this impact is ignored in this analysis.

Fig. 4 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 $r_A=r_B=0.1$. The Closed loop and Substitution methods maintain a relatively consistent result across the L1, L2, L3, and the hybrid life cycle burden, as these EOL 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 less than the burden associated with L1. This hybrid life cycle, the weighted average of L1, L2, and L3 will be used for the remainder of the analysis.
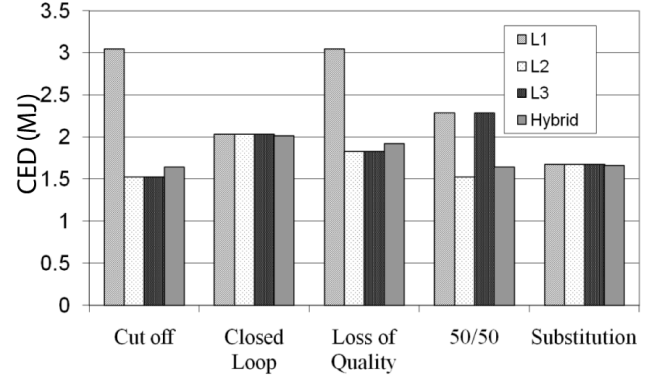

Fig. 4. Comparison of hybrid and conventional life cycle calculation methods for $m=0.1$, $k_A=k_B=0.5$, $n_A=n_B=3$, $q_A=q_B=0.5$, $r_A=r_B=s_A=s_B=0.1$

IV. RESULTS

The following results describe the sensitivity of the preferred material for each of the five EOL methods to the value of parameter k_A (the ratio of secondary materials production energy to primary materials production energy for the Comparator material). Here the Comparator material (Material A) is evaluated against the Baseline (Material B) material for the hybrid life cycle burden. Two values for m were explored. First, $m = 0.1$, where the Comparator and Baseline materials exhibit a high discrepancy between primary energies, and, second, $m = 1.1$, where the materials have very similar primary energies. In addition, two values of k_B were explored, the ratio of secondary production energy to primary production energy for the Baseline material. The figures below show how the cumulative environmental impact of Material A compares with Material B in terms of the difference in energy between Material A and Material B. In these 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. To restate, Fig. 5 - Fig. 8 examine the hybrid life cycle burden for $m = 0.1$, and 1.1 and $k_B = 0.1$ and 0.9 as a function of k_A. All other variables are as stated in Fig. 4.

A. Large primary production energy difference

Fig. 5 plots the difference between the environmental burdens of Material A and Material B and illustrates the sensitivity of environmental burden with k_A at low values of m (0.1) and low k_B (0.1) across each of the five EOL methods. This describes a case when the magnitude of the primary

energy for Comparator materials is much less than that of the Baseline material (V_A<<V_B) and the secondary production energy is considerably lower than the primary energy for the Baseline material. As seen in this plot, the methods do not significantly change in their relative rank order across the parameter k_A, with all methods preferring Material A. Irrespective of EOL allocation, Material A is assessed at a significantly lower total burden than Material B. The consistent flattened slope of all 5 methods in Fig. 5 demonstrates that all methods are equally and weakly sensitive to k_A, with a slight increase in favor for Material B as the secondary production energy for Material A, k_A, grows. For this case, the five allocation methods essentially converge to two lines in the burden difference plot in Fig. 5, 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 higher trend.
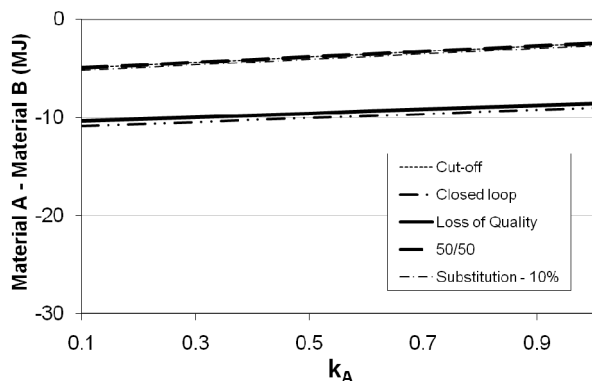

Fig. 5. Material A-Material B for the hybrid life cycle burden, m=0.1, k_B=0.1

Fig. 6 depicts the same sensitivity with k_A at m = 0.1, however, here the recycling burden of Material B is higher, with k_B=0.9. Consistent with the previous plot, this graph reveals that for comparatively large discrepancies between primary energy values of Material A compared to Material B (low values of m), EOL allocation methods maintain that Material A is the environmentally preferred, relatively insensitive to changes in parameter k_A. The Cut-off, Closed loop and 50/50 methods exhibit slightly stronger sensitivity to k_A than the other methods, and the higher value of k_B serves to mute the difference between the methods. The choice of method does not change the preferred material, and methods maintain consistent rank order across the parameter k_A.
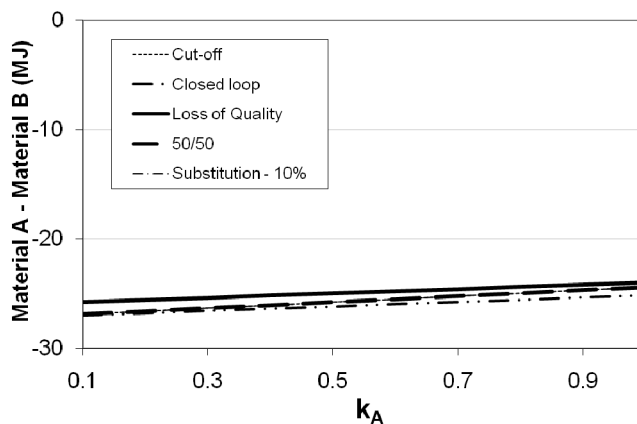

Fig. 6. Material A-Material B for the hybrid life cycle burden, m=0.1, k_B=0.9

B. *Small primary production energy difference*

Fig. 7 plots the difference between the environmental burden of Material A and Material B at high values of m (1.1) and low k_B (0.1) across each of the five EOL methods. This describes a case when the magnitude of the primary energy for Comparator materials is similar to that of the Baseline material ($V_A \cong V_B$) and the secondary production energy is considerably lower than the primary energy for the Baseline material. The strong positive slope exhibited by all methods indicates that material preference depends on the parameter k_A and this dependence is stronger for Cut-off, 50/50, and Substitution methods. The plot reveals that when k_B, or the recycling energy of the Baseline material 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. The two sets of trend lines are again evident. There is a shift in rank order between these methods at low Comparator material recycling energy, k_A.
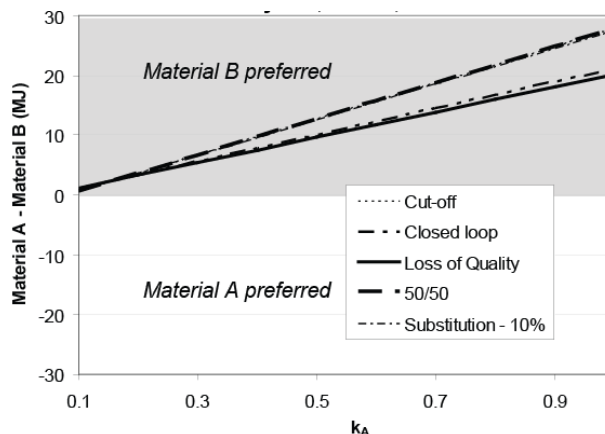

Fig. 7. Material A-Material B for the hybrid life cycle burden, m=1.1, k_B=0.1, grey region indicates when Material B is preferred

For the case of m =1.1 at higher k_B, as shown in Fig. 8, there is a method preference for Material A at low k_A values up to an 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 methods demonstrate a switching in relative rank order. In Fig. 8 this is seen when the lines associated with the 50/50, Substitution, and Cut-off methods, with increased sensitivity

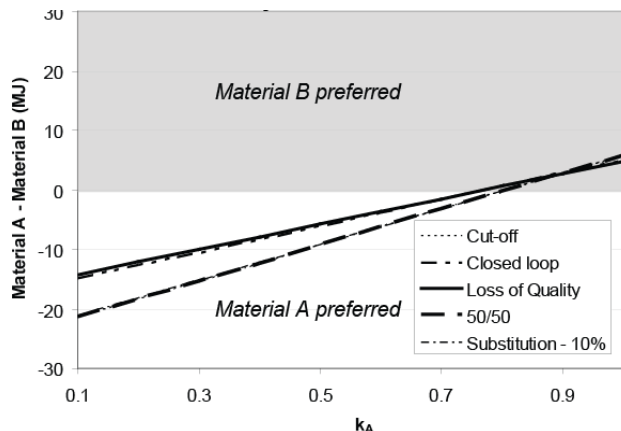to k_A, shift above the other trend lines (Closed loop and Loss of quality).

Fig. 8. Material A-Material B for the hybrid life cycle burden, m=1.1, k_B=0.9, grey region indicates when Material B is preferred

In general, at higher m, or smaller differences between the primary energies of materials, the materials preference sensitivity to k_A increases. Consideration of the hybrid life cycle indicates the various EOL methods converge to approximately two trend lines. 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_A.

V. CONCLUSION

The results of this work indicate that the choice of EOL allocation method can have a significant impact on materials selection decisions. Specifically, this paper has demonstrated that 1) cumulative environmental impact results differ according to EOL allocation method, 2) the results change across methods at a different rate for different materials, and 3) they differ in a way that can change the order of materials preference or rank order.

When the primary energy of one material is much less than the alternative (i.e., $V_A << V_B$), the preferred material remains the same regardless of EOL allocation method; all methods incentivize the use of Material A regardless of the energy associated with recycling either material.

However, when materials have similar primary energy burdens, material preference will change depending on the EOL allocation method. Notably, methods show differential preference for materials with larger disparity between the impact of primary and secondary production, k. Specifically, the trend line including the 50/50, Substitution, and Cut-off methods show a much stronger bias against materials with high recycling burden compared to the methods Closed loop and Loss of quality. This differential preference leads to a change in rank order between Materials A and B depending on the method selected. The results of this analysis demonstrate that as m (V_A/V_B) approaches 1, the difference in the relative sensitivity of the EOL allocation methods becomes apparent.

Future work will explore alternate LCA impact assessment methodologies such as Eco-indicator 99 [19] where the value of W, the disposal burden, becomes large, and therefore cannot be eliminated, to more fully characterize how different EOL allocation methods impact materials selection decisions. Variations in the other parameters such as r, q, and n as well as the impact of a use phase will be explored.

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