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6.1 On improving the product sustainability of metallic automotive components by using the total life-cycle approach and the 6R methodology

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Abstract

This paper presents a novel methodology involving the use of total life-cycle approach, including the Life-cycle Assessment (LCA) method, for improving the product sustainability performance of metallic automotive components. This involves consideration of all four life-cycle stages (pre-manufacturing - PM, manufacturing - M, use - U and post-use - PU), and integration of the 6R activities (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture). Various end-of-life (EOL) product scenarios - reuse, remanufacturing, and recycling - are modeled and analyzed within the chosen SimaPro LCA software environment. By using the recently established metrics-based Product Sustainability Index (*ProdSI*) methodology, final aggregated product sustainability scores for different product EOL options are generated. The validated *ProdSI* results provide options for improving the overall product sustainability by using the new evaluation methodology. This work also shows that a closed-loop material flow, and multiple life-cycles can be achieved through the use of this new methodology.

Keywords:

Automotive Products, Product Sustainability Index (*ProdSI*), 6R Methodology, Total Life-cycle Approach, Life-cycle Assessment (LCA)

1 INTRODUCTION

The auto industry, which continues to expand and grow, has in recent times recognized the need for embracing sustainable manufacturing because of the increasing demands, stricter regulations and growing concerns over resource utilization. According to the European Directive 2000/52/CE, the minimum requirement of resource recovery must be at least 95% of the average weight per vehicle and year, while the energy recovery must be a minimum of 10% of the average weight per vehicle and year [1]. Sustainable products, processes and systems constitute sustainable manufacturing, with the need for producing sustainable products forming the basis for sustainable manufacturing. For the purpose of producing more sustainable product generations, all processes involved in designing and manufacturing the products should be included. Consequently, traditional concepts are expanded to include total life-cycle of manufactured products, including pre-manufacturing (PM), manufacturing (M), use (U), and post-use (PU) stages [2]. Life-cycle Assessment (LCA) allows assessing the environmental consequences and potential impacts caused by the products [3]. However, to be able to comprehensively evaluate the products' sustainability behavior and sustainability performance, assessing their environmental impacts alone is insufficient. The other two sustainability components (economy and society) are also required when considering product sustainability. These three major components are also known as the Triple Bottom Line (TBL) [4]. Traditionally, the 3R concept (Reduce, Reuse, and Recycle) was focused on reducing the use of virgin materials and resources, promoting reuse activities with recycling of products at the end of their life. To enable significant improvement of the overall product sustainability, a novel methodology-the 6R methodology, involving Reduce, Reuse, Recover, Redesign, Remanufacture, and Recycle-has been introduced to incorporate multiple life-cycles of a product and a closed-loop material flow [5]. To facilitate effective decision making in developing sustainable products, it is essential to evaluate the sustainability behavior of the proposed products comprehensively. The recent Product Sustainability Index (*ProdSI*) methodology offers such a comprehensive evaluation capability [6]. It is metrics-based and is built on a five-level hierarchical structure. Computing the final *ProdSI* score can be completed via a sequence of steps: data normalization, weighting, and score aggregation.

The previous work by the authors has shown that EOL product recycling contributes towards improving the product sustainability of metallic automotive components [7]. In this paper, a novel method incorporating the total life-cycle approach including the LCA method, the TBL, and the 6R methodology is presented for improving the product sustainability performance of metallic automotive components with multiple end-of-life (EOL) product options. Continuing the previous work [6-7], two additional product EOL scenarios – reuse and remanufacturing, are included in this study to present final product sustainability scores for a total of three different product EOL options – reuse, remanufacturing, and recycling. With the validation of the *ProdSI* results, the overall product sustainability shows improvements at various levels, which verify that using product EOL strategies improve the overall product sustainability. Ultimately, this work contributes towards implementing a near-perpetual material flow with multiple life-cycles.

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2 BACKGROUND

Due to the recent awareness of the significance of manufacturing sustainable products, during the last few years a range of methods for assessing the product sustainability has been developed. A comprehensive review of the most commonly used methodologies for product sustainability assessment was presented by Feng and Joung [8].

Various approaches are used in the auto industry to measure and evaluate the sustainability performance of vehicles. The product sustainability index (PSI) method, developed by Schmidt and Butt [9], was based on LCA impact assessment categories. It includes eight key environmental indictors across three major aspects of the product sustainability. The economic indicators are from Life-cycle Costing (LCC) assessment method. The societal indicators are aimed at evaluating the safety and mobile capability of a product. This methodology was further applied to two of their vehicle models. Based on the sustainability scoring method developed by de Silva et al. [10], Ungureanu et al. [11] developed a new methodology to quantitatively assess the potential benefits of using aluminum alloys for manufacturing of an autobody. This method involves six major elements of the Design for Sustainability (DfS): environmental impact, functionality, manufacturability, recyclability and re-manufacturability, resource utilization/economy and societal impact [2]. Each of these elements was sub-divided into several corresponding sub-elements. Different levels of influencing factors were categorized based on their significance to the product. The level of importance of each sub-element was assigned with high, medium, or low weights. Finally, sustainability scores of two different materials (steel alloy and aluminum alloy) were computed and their levels of sustainability performance were compared. This method can also be used for comparing the same family of different generation of products. A set of initial key performance indicators (KPIs), proposed by Amrina and Yusof [12], was specifically developed for the auto industry to evaluate product sustainability. The new methodology involving total life-cycle cost analysis, proposed by Ungureanu et al. [13], was aimed at developing a new sustainability model to quantitatively evaluate the total direct cost across the entire life-cycle of a vehicle. The environmental impact caused by using a light-weight material, aluminum alloy, for auto body was presented.

Despite technical merits, the above-reviewed methodologies are not efficient enough to provide or even define the product sustainability comprehensively. They do not cover all life-cycle stages of the products, and they mostly focus on M and/or U stages at the design stage. Neither have considered all three major areas of the TBL as they mostly assess economic and/or environmental impacts caused by the products. Also, very limited research has been reported on improving a product's sustainability through enhancing product EOL activities.

The recently developed *ProdSI* methodology provides a comprehensive assessment for product sustainability [6]. The new method proposed in this paper, integrating total life-cycle approach, the TBL, and the 6R methodology, enables significant improvement in the overall product sustainability assessment of metallic automotive components via application of different EOL product options.

3 THE 6R METHODOLOGY

This section presents a novel approach for improving the overall product sustainability performance of metallic automotive components. It involves the consideration of all four life-cycle stages of the products, including LCA method, and integration of the 6R activities - Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture.

3.1 Terminologies of the 6R Methodology

Based on the definitions of the 6R activities developed by the Institute for Sustainable Manufacturing (ISM) at the University of Kentucky, descriptions to these terminologies that are relevant to the study are given below, in order to better assist the illustration the 6R decision flow. The *Reduce* activity aims at reducing the use of various kinds of materials and resources, and reducing the generation of wastes and emissions. A functional component can be *reused* by utilizing them in a new product, or as a component to make the same new products or different product assemblies, after this useable component is disassembled from its old product. By using remanufacturing processes, a worn out/broken/used product can be restored to its original specifications. The worn out/used product can also be further modified and upgraded with new specifications by redesigning the EOL product into a new product. The *remanufactured* product will become a functional unit that preserves equivalent and sometimes even superior features in terms of quality and functionality, reliability and performance, lifetime and appearance. It should also at least endure another full life-cycle. EOL products made of recyclable materials can be converted into new materials through recycling processes; otherwise, non-recyclable materials would be disposed to landfill. Recycled materials can subsequently be used in the form of raw materials to make either the same or different new products. *Recycling* can also be applied to recover energy from EOL products in some cases. *Redesign* can be performed for the purpose of increasing the use of recovered materials or components from their earlier EOL generations to produce improved next generation products, either the same or totally different products. From the perspective of functionality, the newly redesigned products should show superior features and performance compared with the older generations. Their related processes across the entire life-cycle should consume fewer resources and generate fewer wastes as well.

3.2 The 6R Decision Flow for Metallic automotive Components

The virgin materials are formed to chunk pieces at the PM stage. The components produced and assembled into products at the M stage go through its U stage. When the valuable life of metallic automotive components comes to an end at this stage, several decisions for various 6R activities can be made at its PU stage. Figure 1 illustrates the 6R decision flow for metallic automotive components. If the material cannot be recovered for use as either material or energy, then it goes to landfill. If the EOL products are recoverable, the first activity to consider is reuse. After a preliminary inspection and a full cleaning, components eligible for reuse can be directly used for assembly to make new products. If the components are not qualified for reuse, remanufacture is the next activity to consider. If the components do not have serious defects such as damaging cracks, and if their original specifications can be

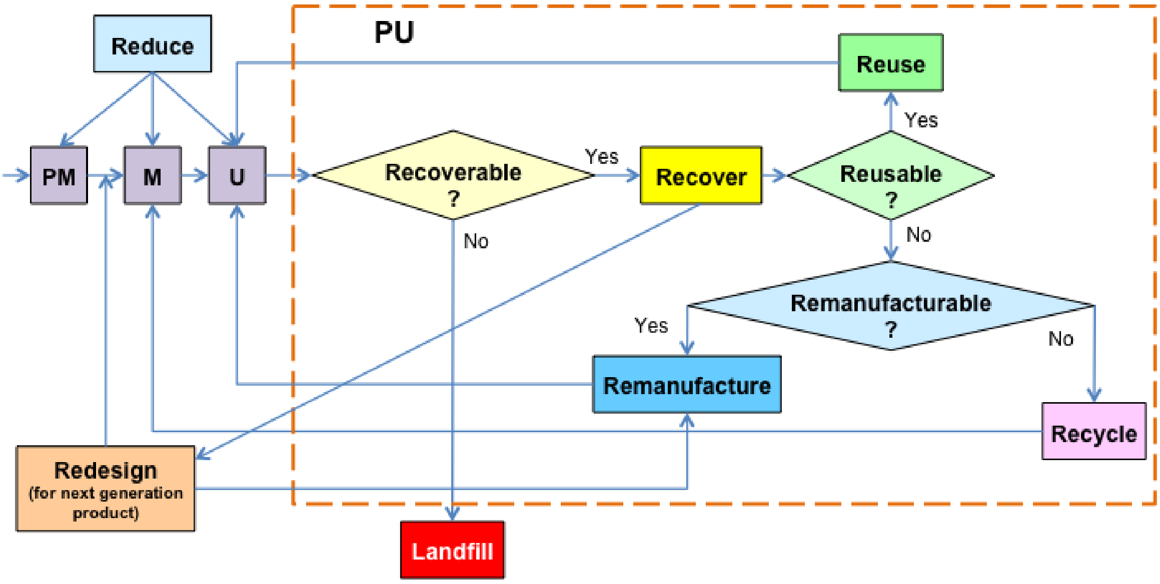

Figure 1: The 6R decision flow diagram across four life-cycle stages of metallic automotive components

restored by remanufacturing, they can be transported to the manufacturing plant after the material deposition process. If the components suffer from serious defects that they cannot be restored to their original specifications by means of remanufacturing, then material recycling will be an alternative practice. After a sequence of recycling processes, the materials can be recovered and reused in the form of raw materials to make either the same or different products. In this case, either the materials or the components can be reused within a closed-loop. Ultimately, virgin materials would be no longer needed to produce the next generation products.

Recovered material can also be used either in manufacturing or in remanufacturing through redesigning of next generation products that can use the recovered end-of-life material from the previous generation of products. Multiple closed-loop material flow could be achieved with this 6R methodology.

4 TOTAL LIFE-CYCLE MODELING OF METALLIC AUTOMOTIVE COMPONENTS WITH VARIOUS PRODUCT EOL OPTIONS

In previous work, one of the EOL product options, recycling the EOL metallic automotive components-was presented [7]. In order to comprehensively examine the effects on using different 6R-based EOL product activities, this section presents the analysis using two other Rs, the reuse and remanufacturing.

The modeling work is based on the same assumption as in [7] that the chosen product is a stand-alone manufactured component from a single material. All outputs of 6R activities are assumed to be used for producing the same components, not for other products. Metallic automotive components are made of alloy steel. The proportions of components reused, remanufactured and recycled are assumed to be consistent with the rates established for each of these activities. The metrics selected for the analysis and the *ProdSI* evaluation stay unchanged as well. The modeling work is carried out within the LCA software environment SimaPro 7.3. Eco-indicator 99 (H) is used as the assessment method.

4.1 Modeling the Reused EOL Products

Figure 2 illustrates a map of processes needed for four life-cycle stages to <u>reuse</u> the EOL products.

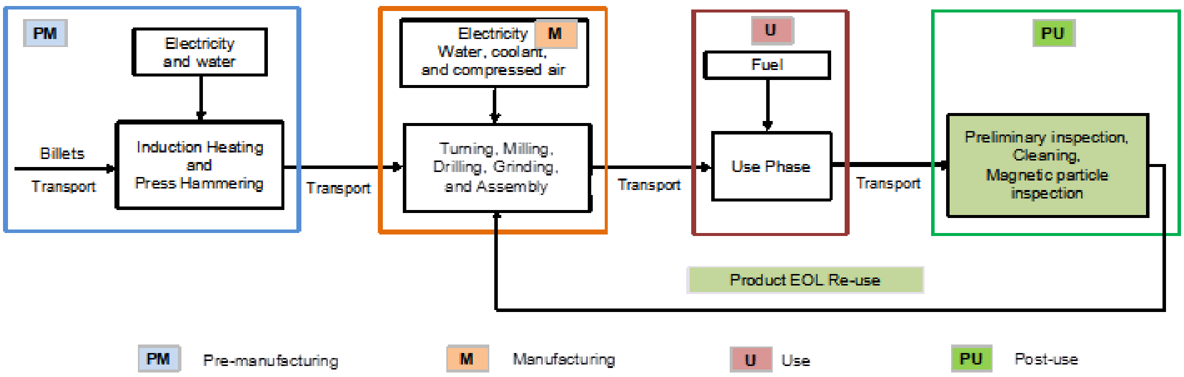

Figure 2: Process map across four life-cycle stages for reusing EOL products.

Mass of Hazardous Material Use

The same approach discussed in [7] was followed. Due to space limitations, the detailed process of computation cannot be presented in the paper. Calculated results show that in the PM and M stages the mass of hazardous material use decreases linearly as a direct effect of fewer virgin materials used.

In the M stage, the mass of hazardous material use contains mainly used coolant; it also includes other forms of hazardous contents, such as fumes and metal debris. The used coolant is 100% recycled in the manufacturing plant. Value for the U stage stays zero as the components do not generate any hazardous materials during its U stage. Constant trends apply to all subsequent individual metrics for both M and the U stages analyzed in this study. In the PU stage, the amount of hazardous material use increases as the ratio of reused EOL product increases. This is because more product EOL activities are involved along with the increased reuse of old products. The total mass of hazardous material use for four life-cycle stages drops linearly when the ratio of reused EOL product varies from 0% to 90%. This trend can be represented equation (1), where the mass of hazardous material use for reusing EOL products is expressed as a function of the ratio of reused EOL product (x_1). The function is obtained by fitting a curve to the trend line. The mass of hazardous material use is measured as mg/ unit.

$$y^{reuse}_{mh\_total} = -40108\, x_1 + 40129 \quad (1)$$

Energy Use

Calculated results also show that in the PM and the M stages the amount of energy use is a combination for both, due to the fact that less numbers of products are manufactured when some EOL components are reused. Consequently, reduced need for virgin materials results in a decrease in the energy use at these two stages. In the PU stage, the energy use increases linearly when the ratio of reused EOL product increases. The total energy use for four life-cycle stages decrease as expected when the ratio of reused EOL product varies from 0% to 90%. This trend can be expressed by equation (2). The energy use is measured as MJ/ unit.

$$y^{reuse}_{eu\_total} = -149.4\, x_1^2 - 269.67\, x_1 + 9326.1 \quad (2)$$

Water Use

Also, in the PM and the M stages, the water use decreases linearly because it is directly related to the amount of virgin materials used. In the PU stage, the water use shows an increase as the ratio of reused EOL product increases to 20%. The growth in water use is due to the effect of turning on the entire EOL operating system. Then, it reduces slowly along with the percentage of reusing EOL products changes from 20% to 90%. Total water use for four life-cycle stages increases as the ratio of EOL product reused increases to 20%, and then it drops as the percentage increases to 90%. This trend can be expressed by equation (3). The water use is measured as Kg/ unit.

$$y^{reuse}_{wu\_total} = 3061.7\, x_1^3 - 5210.9\, x_1^2 + 1843.1\, x_1 + 637.52 \quad (3)$$

Greenhouse Gas Emissions

In the PM and the M stages, the Greenhouse Gas emissions decrease linearly due to the decreasing amount of virgin material used. It can be observed that the major contribution of the GHG emission comes from the U stage, because a vehicle consumes a large quantity of energy. The Greenhouse Gas emissions in the PU stage shows an increase when the ratio of reused EOL product increases to 20%, then it drops slowly when the percentage of reusing EOL products changes from 20% to 90%. The total Greenhouse Gas emission for four life-cycle stages shows a linear decrease, and it can be expressed by equation (4). The the Greenhouse Gas emission is measured as MJ/ unit.

$$y^{reuse}_{ge\_total} = -107.93\, x_1 + 278479 \quad (4)$$

Direct Cost

Table 1: Unit cost used in this study

Direct Cost	Unit Price
Labor cost	$15/hour
Material cost	$2.12/Kg
Electricity cost	$0.0505/kWh
Water cost	$1.52/ton

Table 1 provides the unit costs that are used to calculate the total direct cost in this study. The same data are used for scenarios of remanufacturing and recycling EOL products. The labor cost is directly proportional to the hours of workforce involved in the processes at each product life-cycle stage. All the other economic metrics selected - material cost, energy cost, and water cost - are directly related to the amount of usage for each metric. The total direct cost can be computed by summing up the individual costs for each varying ratio of reused EOL product. A decreasing trend can be observed. This trend can be expressed by equation (5). The direct cost is measured as $/unit.

$$Y^{reuse}_{dc\_total} = -41.51 x_1 + 184.19 \quad (5)$$

4.2 Modeling the Remanufactured EOL Products

In the PM stage, induction heating and press hammering are the processes needed to transform steel billets into chunk pieces. In the M stage, manufacturing processes involve turning, milling, drilling, grinding, and product assembly. In the PU stage, remanufacturing processes include preliminary inspection, cleaning, magnetic particle inspection, and material deposition. This is the stage where the original states of the product can be restored.

Mass of Hazardous Material Use

In the PU stage, the amount of hazardous material use shows a increase when the ratio of remanufactured EOL product increases. A larger slope of increase can be observed when comparing the scenario of reusing the old products. This is because powered steel deposition is the additional process needed for remanufacturing. The total hazardous material used for four life-cycle stages shows a linear decrease when the ratio of remanufactured EOL product varies from 0% to 90%. This trend can be expressed by equation (6), where the mass of hazardous material use for remanufacturing EOL products is expressed as a function of the ratio of remanufactured EOL product *(x_2)*.

$$y^{remfred}_{mh\_total} = -40025\, x_2 + 40129 \quad (6)$$

Energy Use

In both the PM and the M stages, the amount of energy use decreases because fewer virgin materials are involved when EOL products are remanufactured. In the PU stage, having more remanufacturing activities involved leads to an increase in energy use when the ratio of remanufactured EOL product increases. This is especially due to the process of thermal spray for powered material. The total energy use for four life-cycle stages increases when the ratio of remanufactured EOL product varies from 0% to 90%. This trend can be can be expressed by equation (7).

$$y^{remfred}_{eu\_total} = -148.7\, x_2^2 - 880.85\, x_2 + 9326.1 \quad (7)$$

Water Use

In the PM and the M stages, the water use decreases linearly as a result of remanufacturing old products. In the PU stage, the water use shows a large increase as the ratio of remanufactured EOL product increases, since large quantity of water is needed for the cleaning process. Total water use for four life-cycle stages increases when the ratio of remanufactured EOL product varies from 0% to 90. This variation can be expressed by equation (8).

$$y^{remfred}_{wu\_total} = -1116.7\, x_2^2 + 3447.5\, x_2 + 684.07 \quad (8)$$

Greenhouse Gas Emissions

In the PM and the M stages, the Greenhouse Gas emissions decrease linearly because of less involvement of the virgin materials. In the PU stage, the Greenhouse Gas emission shows a slight increase. The total Greenhouse Gas emission for four life-cycle stages decreases when the ratio of remanufactured EOL product varies from 0% to 90%. This linear trend can be expressed by equation (9).

$$y^{remfred}_{ge\_total} = -99.7\, x_2 + 278479 \quad (9)$$

Direct Cost

The total direct cost shows a slight decrease. Comparing with the value of the scenario for reusing the EOL products, the slope of decrease is smoother. This is because more energy, water, and labor are needed for the additional material deposition process. This trend can be expressed by equation (10).

$$Y^{remfred}_{dc\_total} = -3.77 x_2^2 - 2.46\, x_2 + 183.94 \quad (10)$$

5 PRODUCT SUSTAINABILITY ASSESSMENT FOR DIFFERENT PRODUCT EOL SCENARIOS BY USING THE *PRODSI* METHODOLOGY

By using the Product Sustainability Index (*ProdSI*) methodology to assess the product sustainability performance, scores for sub-indices and the final *ProdSI* are calculated for each EOL product option. To effectively compare the differences in the product sustainability among various EOL product activities, data normalization, weighting, and data aggregation methods are made consistent. Measurements of 100% landfill are used as basis for data normalization since it is considered as the worst-case scenario. Equal weighting is applied throughout the computation, when values are aggregated to the next higher level. From the results shown in Table 2, strength and weakness of the areas of product sustainability with each EOL product options can be observed. The comparison is also visually presented in Figure 3. The numerical range 0 to 10 represents the level of progression. The higher the score, the more sustainable the product is. Score 8 represents an "excellent" status, score 6 stands for "good" condition, score 4 represents an "average" level, and score 2 means "poor" condition. Total *ProdSI* scores indicate that disposing the products at their EOL is the least sustainable EOL activity while reusing the old components is the most sustainable practice as expected. Comparing between the options of remanufacturing and recycling of the EOL products, material recycling has turned out to be more sustainable than component remanufacturing in this case, based on the assumptions made prior to modeling four life-cycle stages of metallic automotive components.

Table 2: Sub-indices and *ProdSI* score comparisions

	100% Landfill	80% Recycling	80% Re-mfg.	80% Re-use
Economy	5.90	4.84	3.50	7.40
Environment	3.42	6.28	6.01	8.76
Society	6.48	7.68	8.00	7.98
ProdSI	5.25	6.27	5.84	8.05

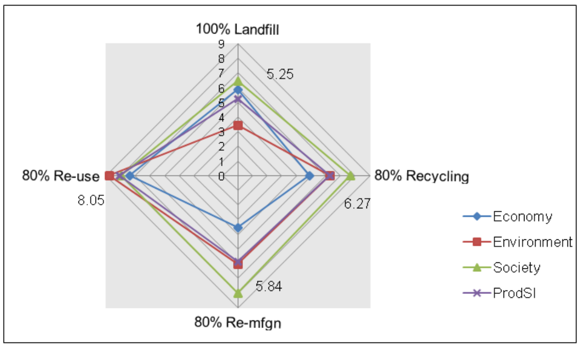

Figure 3: Score comparison for sub-indices and the final *ProdSI* for different EOL product options

6 DISCUSSION

Both analyses from the LCA models and the product sustainability scores validate and prove that the overall product sustainability of metallic automotive components can be improved by applying the 6R methodology. Such achievement can be made from applying a single 6R activity or multiple 6R activities. In this study, the results indicate that products would become more sustainable, when higher ratios of EOL product activities are chosen.

The total values of mass of hazardous material use, energy use, water use, Greenhouse Gas emission, and direct cost show approximate linear relations because the individual metrics selected in the study are directly related to the amount materials involved. However, non-linear correlations will present when other metrics are considered, such as indirect costs, and health and safety related issues.

Metallic automotive components in this study are made of a stand-alone ferrous material. The 6R decision flow and the life-cycle models are product- and industry-specific. When this methodology is applied to another family of products or another industry, the 6R decision flow and LCA models will change. When using this methodology to analyze a product made of composite materials, it will require a much more complex analysis. A combination of multiple LCA models for each type of material involved will be needed. Consequently, its analysis and *ProdSI* evaluation processes should be done for each life-cycle model simultaneously.

While making a complicated product sustainability evaluation is achievable, putting the methodology into practice in the industrial world can be challenging. Even though it is well recognized that enhancing product EOL management is a more sustainable practice, disregarding any product EOL activities is what is often observed, unless it is restricted by regulations. Quite commonly, it is because of technical issues and/or economic reasons.

In previous work, only EOL product recycling was addressed. The rest of the 6R activities are presented in this paper. Interactions and analysis of all 6Rs are completed comprehensively. This is achieved from assessing the effects of all possible EOL product activities simultaneously. As a result, mathematical equations for individual sustainability metrics are expressed with multiple independent variables, which can be used as decision variables for setting up a percentage mix optimization problem. Finally, an optimal mix of product EOL activities can be obtained. Moreover, since the *ProdSI* methodology is metrics-based, and the 6R activities and the individual metrics are interrelated, such mathematical and analytical models can be further used to develop product sustainability optimization models.

7 CONCLUSIONS

In this paper, a new approach for improving the overall product sustainability of metallic automotive components is presented. This method utilizes a total life-cycle approach, the TBL, and the 6R methodology. Four life-cycle stages of metallic automotive components are modeled and analyzed within a LCA software environment. The product sustainability score for each EOL product option is computed by using the *ProdSI* methodology. The *ProdSI* scores confirm that the overall product sustainability of metallic automotive components can be improved from applying EOL product activities. The results provide options to EOL product strategies. This study also shows that a near-perpetual material flow can be achieved, and a single product life-cycle can be expanded to a multiple life-cycles through the use of this new methodology. Therefore, the research results confirm that applying product EOL strategies increase overall product sustainability. Also, the approach presented in this paper provides a basis to the development of multi-objective product sustainability optimization models.

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