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Abstract

Remanufacturing is an end-of-life product recovery strategy whereby used products are restored to the original equipment manufacturer (OEM) standard and receive a warranty at least equal to a newly manufactured product. Current end-of-life product recovery decision-making approaches are focused on technical and economic factors neglecting crucial areas such as customer demand and legislative pressure which are pertinent in the decision-making process, more importantly in the case of remanufacturing. Additionally, there is lack of a holistic approach that adopts an inclusive methodology for analysing multiple conflicting factors: ecological, technical, economic, business and social aspects simultaneously.

This paper presents our research works on evaluation of remanufacturing for product recovery at strategic level. The paper identifies key end-of-life decision-making factors that aid for assessing the feasibility of remanufacturing. A Product Recovery Multi-Criteria Decision Tool (PR-MCDT) is proposed to evaluate the viability of conducting remanufacturing form an integrated point of view i.e. by simultaneously taking into account technical, economic, environmental, business and societal aspects. The main benefits of this tool are, a) the decision maker has the opportunity to consider key factors such as customer demand, legislative pressure and new technologies in the decision-making process, b) the tool helps to evaluate different end-of-life options under several often-conflicting criteria which are not necessarily quantitatively defined, c) the decision-making tool takes into account the preferences of the decision-maker in evaluating the feasibility of end-of-life strategies. An example is presented and discussed to illustrate the applicability of the tool for selection of product retirement option. The PR-MCDT is used by senor/middle management level to provide an early stage feasibility analysis of adopting remanufacturing for a general product type.

Keywords: Remanufacturing, End-of-life strategy, Product Recovery, Multi-criteria decision tool

1 Introduction

The global crisis in resource scarcity, population growth and climate change impacts are placing pressure to ditch the traditional “Make-Use-Dispose” economic model and adopt "make, use, return" as our collective mantra by joining the circular economy. The implementation of extended producer responsibility (EPR) in new governmental legislation, together with the growing environmental and economic concern, demands that original equipment manufacturers (OEMs) to take care of their products after they have been discarded by the consumer [1]. Product recovery has become increasingly important towards transitioning to a circular economy. Product recovery management aims to close the loop throughout the product life cycle [2].

Product recovery management (PRM) is the management of all used and discarded products, components, and materials to recover as much of the economic and ecological value as possible thereby reducing the quantity of discarded waste[3]. End-of-life product recovery strategies include Remanufacture, Repair, Recondition, Cannibalization, Redesign, Refurbish and Recycle [3] [4]. All these end-of-life options are distinct from one another and selecting the best suitable product recovery option should take several factors into consideration [5].

Remanufacturing is one of the most important and emergent product end-of-life strategy [6] for increasing resource efficiency and realizing circular economy [7]. Remanufacturing is defined as "a process of returning a used product to at least original equipment manufacturer (OEM) performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent"[8].

Several studies have focused on evaluating the feasibility of conducting remanufacturing at strategic level. Dumande [9] developed PLETS model, a product life cycle extension technique for product end of life management. [10] and [11] uses multi-attribute decision making approach to select the best product recovery alternative in reverse logistics. Chen and Wu [12] applied extension of the End of Life Design Advisor (ELDA) tool using a neutral network model, while Gehin [13] developed a tool called Repro^2 designed to evaluate product suitability for remanufacture based on product profiles. [14] developed a multi-objective optimization model to identify optimal product recovery solution. Strategic evaluation of remanufacturing is critical to ensure strategic decisions, which then promote success of the company [15].

Current end of life product recovery decision-making approaches are centred on economic and technical factors neglecting other equally influential aspects which are pertinent in the decision-making process such as **market demand, social trends and legislative pressure**. This is highly significant in the case of remanufacturing. Additionally, there is lack of a holistic approach that uses an inclusive methodology to assess and evaluate the viability of conducting remanufacturing form an integrated point of view i.e. by taking into account technical, economic, environmental, business and societal aspects simultaneously.

The aim of this paper is to identify EoL decision-making factors and incorporate them into a holistic methodology to evaluate the feasibility of conducting remanufacturing. The viability of remanufacturing is evaluated with the relevant technical, economic, environmental, business and social criteria. The research objective of this paper is therefore to answer the following questions: -

- ✓ Which key factors should be considered in the evaluation of remanufacturing with respect to the relevant technical, economic, environmental, business and social criteria?
- ✓ How to evaluate the feasibility of conducting remanufacturing holistically by analysing the different types of factors: ecological, technical, economic, business and social factors simultaneously?

The rest of the paper is organized as follows. Section 2 presents the research methodology used to answer the research questions. In section 3 the multi-criteria decision making approach is discussed and key decision-making factors used to assess the feasibility of remanufacturing are presented. Subsequently in section 4 the application of the method to a case is discussed. Finally, conclusions are drawn by summarizing the main findings of the study.

2 Research Methodology

As introduced in section 1, the goal of this research is to identify key decision-making factors and integrate into the proposed holistic decision-making tool that evaluates the viability of remanufacturing for product recovery by taking in to account ecological, technical, business and societal aspects simultaneously.

A comprehensive literature review was undertaken to identify key decision-making factors that used to assess the viability of conducting remanufacturing. Firstly, an exhaustive list of factors was presented and then the decision-making factors were sorted into main categories by the authors. Afterwards, factors from each category were evaluated based on literature review and expertise from G-SCOP laboratory. Based on the analysis, key decision-making factors were identified in regard to technical, economic, business, environmental and societal aspect and the most important factors are incorporated into decision making criteria. Based on findings from literature and feedback from expertise, most important factors pertinent to consider in the decision-making process are accentuated.

The multi-criteria decision making approach has been chosen as methodology to evaluate the feasibility of conducting remanufacturing at strategic level. An iterative and multi-level procedure is used for selecting an appropriate multi-criteria decision making methodology. The decision-making approach advised economic, environmental and societal indicators which will be integrated into the evaluation process. To show the application of the decision-making approach an illustrative example is presented based on a case study on an automotive engine. To simplify the complexity of the problem only the main components of the engine are considered.

3 Result and Discussion

3.1 Multi-Criteria Decision Tool

A Product Recovery Multi-Criteria Decision Tool (PR-MCDT) is proposed to evaluate the viability of adopting remanufacturing for product recovery. The six basic steps that grid the approach are as follows: (1) selection of potential end-of-life strategies, (2) scoping of end-of-life strategies, (3) selection of relevant indicators, (4) assessment of end-of-life strategies, (5) analysis and evaluation of EoL strategies, (6) refinement of strategies and final evaluation. Figure 1 shows the main steps of multi-criteria decision tool.

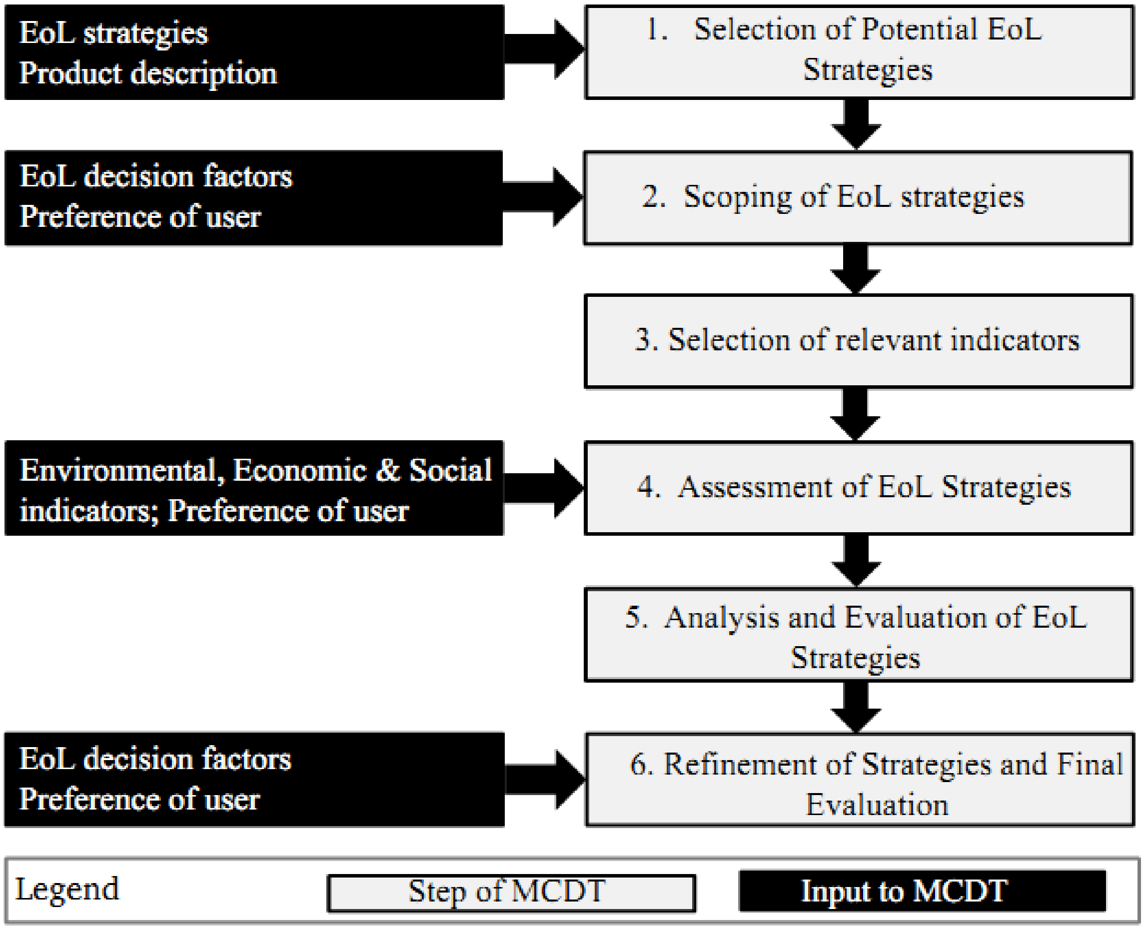

Figure 1: Multicriteria Decision Tool (MCDT)

MCDT is capable to consider product EoL selection from an integrated point of view i.e. by simultaneously taking into account environmental, technical, economic, societal and business criteria [16]. The main benefit of this **methodology comprises, the decision maker has the opportunity to consider constraints such legislation, new technologies and market demand**. The decision-making approach also takes into account the preferences of the user in the evaluation process of end-of-life strategies. A brief description of each step of the tool is presented below.

i. Selection of Potential End-of-life Strategies

The definition of product recovery EoL strategies constitute the description of the product and associated potential EoL options. In this first step of MCDT approach, the decision-maker identifies potential EoL product recovery strategies and is unlimited by any constraints.

Product recovery EoL options includes Repair, Recondition, Remanufacture, Cannibalization, Refurbish and Recycle. Table 1, presents a summary of main product recovery strategies. An EoL option is considered as a product recovery strategy, if it fulfils three main criteria: collection of used products, reprocessing of a recovered product and redistribution of the processed product [3].

A potential product recovery EoL strategy is a possible candidate for evaluation and comparison during the decision-making process [17]. In multicriteria decision literatures, list of potential candidate strategies are generally called alternatives or actions [18]. A functional description of the product is decisive for the remanufacturing company to be able to achieve high level EoL treatment. The description of the product provides relevant information regarding the characteristics of the product as well as its functional use for the consumer [19].

Table 1: Product recovery strategies

Definition of Product Recovery Strategies	Source
Remanufacture is an end-of-life product recovery strategy whereby used products are restored to the original equipment manufacturer (OEM) standard and receive a warranty at least equal to a newly manufactured product.	[20][21][22]
Recondition involves returning the quality of a product to a satisfactory state level (typically less than a virgin standard/new product) giving the resultant product a warranty less than of a newly manufactured equivalent.	[23][24]
Repair is an activity of returning a used product in to "working order" by fixing/replacing specified faults in a product using service parts.	[22][23][25][26]
Recycle is an activity where discarded materials are collected, processed and used in the production of new materials or products.	[4][20]

ii. Scoping of End-of-life Strategies

After defining potential EoL strategies, this step gives the decision maker an opportunity to take a look of defined product recovery strategies against a set of feasibility criteria for the refinement of viable EoL alternatives. The purpose of step 2 is to eliminate non-conforming scenarios during initial steps decision-making process based on various constraining influences such as technological, business, legislative and societal aspects that influence the feasibility of a particular EoL strategy. Table 2 shows a list of decision-making factors used in refinement of potential EoL strategies.

The screening process of the EoL strategies is mainly qualitative. The selected EoL options from the screening process will be considered in the following steps of the decision-making process. The selection of a potential EoL product recovery option should be based on the information available related to the activity and experience of the decision-maker [17].

Table 2: Categorization of EoL decision making factors

Category	List of key factors
Ecological (Environmental)	*Human health (HH) *Ecosystem Quality (EQ) *Resources (R)
Legislation	***Compliance with legislation**/ EU legislation/WEEE *Compliance with new legislation
Market	***Customer demand (Market demand)** *****Competitive pressure
Social	*Additional job creation ***Level of customer satisfaction** *Consumer perception *Safe working environment *Customer relations

Business	***Return core volume** ***Consumption model** *Degree of damage *Return rate (Timing of product return)
Economic	***Financial cost of operating remanufacturing business** *Quality requirement of remanufactured product *Resell price *Possible obsolescence of an assembly
Technical	* **Technical state (EoL condition of returned products)** *Advancement in technology *Availability of recovery facilities *Presence/Removability of Hazardous content * Processibility *Separability of materials

iii. Selection of relevant indicators

The implementation of EoL strategy to recover a product at its end-of-life has environmental, economic and societal impact. These impacts are measured by appropriate indicators to formulate a judgement on the selection of the best compromise EoL strategy. The selection of relevant indicators may be accomplished from a predefined list where the decision-maker decides based on EoL situation or develop his/her own individual indicators [16][19]. According to [17], indicators should be specified on the bases of direction of preference (maximization/minimization), scale (qualitative/quantitative) and unit of measurement. Table 3 shows an example of indicators.

Table 3: List of Indicators

List of Indicators (I)	Name	Unit	Goal
Environmental (I_1)	EoL impact indicator	Eco-indicator points (Pt)	Minimizing
Economic(I_2)	Net recoverable value	Euro	Maximizing
Societal (I_3)	Number of employees to perform the scenario	Integer number	Maximizing

iv. Assessment of End-of-life Strategies

Once the end-of-life indicators and potential product recovery strategies were selected, the next step will be an evaluation of each EoL strategies with respect to the defined indicators. Potential EoL alternatives (Alt 1, Alt 2, Alt 3 …Alt N) with respect to the evaluation criteria (I_1, I_2, I_3 …IN) were presented in table 4 [27]. After completing evaluation of strategies, strategies with a very bad (lowest) score will be eliminated. End-of-life options which do not fail to have on any indicator a worst value are considered on the second evaluation [17].

Table 4: Table of evaluations

	Indicator 1 I_1	Indicator 2 I_2	Indicator 3 I_3	…	Indicator n In
EoL alternative 1 Alt 1	(Alt 1, I_1)	(Alt 1, I_2)	(Alt 1, I_3)		(Alt 1, In)
EoL alternative 2 Alt 2	(Alt 2, I_1)	(Alt 2, I_2)	(Alt 2, I_3)		(Alt 2, In)
EoL alternative 3 Alt 3	(Alt 3, I_1)	(Alt 3, I_2)	(Alt 3, I_3)		(Alt 3, In)
EoL alternative 4 Alt 4	(Alt 4, I_1)	(Alt 4, I_2)	(Alt 4, I_3)		(Alt 4, In)

Economic indicator: Net Recoverable Value (NRV)

Repair value = Value of component – Repair cost – Miscellaneous cost
Recondition value = Value of component – Recondition cost – Miscellaneous cost
Remanufacture value = Value of component – Remanufacture cost – Miscellaneous cost
Miscellaneous cost = Collection cost + Processing cost
Economic value = Value of component – processing cost – Miscellaneous cost
Net recoverable value = EoL Economic Value – Disassembly cost
Disassembly cost = (Labour to disassemble product × Labour rate) + Tooling costs + Material costs + Overhead costs

Environmental indicator: End-of-Life impact on the Environment (EOLI)

The end-of-life impact (EOLI) of a product can be computed during end-of-life retirement by eco-indicator [28]:

$$EOLI = \sum_{i=1}^{N_T} (IE_i \, W_i)$$

Where:

N_T = total number of materials in the product
IE_i = end-of-life impact of material i
W_i = weight of material i (kg)

$\sum_{i=1}^{N_T} (IE_i \, W_i)$ = end-of-life impact of component i

n= number of materials in component i

The eco-indicator values can be regarded as dimensionless figures. As a name eco-indicator is expressed in eco-indicator points (pt). In eco-indicator lists usually milli-indicator points (mPt) is used which is one-thousandth of a Pt. The end-of-life impact of a material for a specific strategy can be refereed from eco-indicator table [29]. A positive point implies impact imposed on the environment while a negative impact infers impact which is avoided [28].

Social indicator

Name: Number of employees to perform the scenario
Unit: Integer number
Goal: Maximizing number of employees

v. Analysis and Evaluation of End-of-life Strategies

This step involves the ranking of EoL strategies based on the information retrieved from step 2 and the selected environmental, economic and social indicators in step 3. The information and data gathered from each step is critically evaluated to select the most appropriate EoL treatment strategy [19]. Due to the wide range of different multicriteria decision-making approaches, the choice of an appropriate method should be given great attention. It is critical for the decision maker to understand the problem, the feasible alternatives, conflicts between the criteria and level of uncertainty of the data before carrying out the choice to every multicriteria decision-making situation[17].

vi. Refinement of End-of-life Strategies and Final Evaluation

Once the analysis and ranking of potential EoL strategies is completed, further detail analysis should be applied by the decision maker to understand the consequences of selecting the best suitable strategy as a final solution. A critical evaluation of the potential best feasible product recovery strategy should be done against a set of criteria presented in table 2. This step may result in acknowledgement of the candidate strategy as a final solution or may lead to a new iteration of the approach. In case, the user found the result to be unsatisfactory, then the next EoL option is considered and evaluated in the same way as the previous candidate. Alternatively, the procedure will be repeated by considering a new set of EoL strategies and/or a new family of indicators [17] [19].

3.2 End-of-Life Decision making factors

Findings from literature show that economic and environmental decision making factors are widely used to assess the viability of conducting remanufacturing while neglecting other equally important factors such as legislation and societal factors [30] [31]. Social decision-making factors are most valuable to provide feasibility analysis of adopting of remanufacturing at strategic level. Furthermore, there is lack of a holistic approach for analysing and evaluating different types of factors simultaneously.

Based upon a comprehensive literature review and feedback from expertise in the subject domain, key end-of-life decision-making factors used to assess the feasibility of remanufacturing for product recovery were identified and presented (see Table 2). The decision-making factors are categorized into business, technical, economic, environmental, legal and societal aspects.

4 Case study

To exemplify the application of product recovery multi-criteria decision tool (PR-MCDT), an illustrative example of an automotive engine is carried out to show how the approach can be used. At the end-of-life, an engine can follow different routes that have its own consequences from economic, environmental, societal and business point of view. In this specific case, a light fiat engine, is considered with the evaluation of its main components (cylinder block, cylinder head, pistons, connecting rods, crankshaft, Flywheel, Camshaft & Turbo) to simplify the complexity of the problem.

Step 1: Selection of Potential End-of-life strategies

The first step in this approach is to define the constitution of a set of potential EoL product recovery strategies. The selection of potential end-of-life strategies depends on the type of product and the associated product recovery option. In this specific case study, three potential end-of-life product recovery strategies are defined.

List of Potential Product Recovery Strategies

Alternative 1: Reusing the product with minor service (Disassembly, cleaning, polishing)

Alternative 2: Remanufacturing

Alternative 3: Recycling

Step 2: Scoping of EoL strategies

In this step, potential EoL strategies are evaluated against list of criteria categorized in to legislative, technical, business and societal aspects which is presented in Table 2. Non-conforming scenarios will be eliminated from the list while the remaining ones will be evaluated in the following steps. The selection of relevant EoL strategies depends on the preferences of the user (recovery company), the objective of the problem, experience of the user and constraints from social, market, legislation and technology. It is assumed that potential EoL alternatives of the automotive engine fairly satisfies those requirements. In general, few EoL strategies are interesting for the decision maker from a list of potential recovery options.

Step 3: Selection of relevant indicator

Economic and environmental indicators are used for the evaluation of EoL alternatives. In this illustrative example, social indicator, number of employees to perform recycling and remanufacturing activities is assumed to be relatively matching. The evaluation of the EoL strategies with respect to the indicators is presented in Table 5.

Table 5: evaluation result of potential EoL strategies [32]

	EoL alternative 1 Reuse	EoL alternative 2 Remanufacture	EoL alternative 3 Recycle
Indicator 1(Economic)			
Revenue selling materials (€)			108.46
Steel			5.74
Cast iron			34.85
Aluminium			68.44
Revenue selling engine (€)	612.00	2562.00	
Operating costs	43.47	263.46	158.20
Energy consumption	3.91	24.85	3.50
Workforce costs	39.56	238.60	154.71
Total Revenue (€)	568.53	**2298.54**	-49.75
Indicator 2 (Env.impact)			
Kg CO_2 eq. treatment process	561	10920	502
Kg CO_2 eq. recycling process			337154
Kg CO_2 eq. avoided remanufacturing	28978	72446	
Kg CO_2 eq. avoided raw material extraction	640719	640719	640410
Benefits	-669137	**-702245**	-302754

Based on the evaluation of the potential EoL strategies with the relevant indicators, the decision-maker can eliminate potential options which have low result. In this illustrative example, it appears that the solution can be easily drawn based on table of evaluations. EoL alternative 2 (Remanufacturing) is the best compromise EoL strategy from an integrated point considering environmental, economic & societal indicators.

Before taking the final decision, EoL alternative 2 (Remanufacturing) should be examined in more detail with respect to the list of decision-making factors presented in table 4. Even if from a technical point of view, if remanufacturing of the automotive engine is possible, further investigation should be made to examine the selected strategy with list of pertinent decision-making factors like market demand and compliance with legislation. If it is realized that a the selected EoL option is unsatisfactory, another EoL option should be analysed again based on the ranking of the evaluation or the evaluation process is repeated with a consideration of alternative EoL strategies.

5 Conclusion

In this paper, we proposed a general product recovery multi-criteria decision tool (PR-MCDT) to evaluate the viability of remanufacturing at strategic level. The decision-making tool uses a holistic approach, under several often-conflicting criteria, to assess the feasibility of remanufacturing with respect to relevant business, legal, environmental, social and economic factors and by taking in to account the preferences of the decision maker.

Based on the analysis of literature and feedback form expertise, decision-making factors were also identified in regard to technical, economic, business, environmental and societal aspect. The paper also highlighted key decision-making criteria pertinent to consider in the decision-making process.

The paper dealt with important aspects related to the proposed approach such as definition of EoL strategies, selection of relevant indicators and exploitation of results. The proposed decision-making tool was also applied to an automotive engine case to illustrate the applicability of the approach. The results show that, remanufacturing is a feasible EoL option compared with repair and recycling strategies.

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