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International Journal of Advanced Manufacturing Technology (ISSN 0268-3768, eISSN 1433-3015)

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Citation Details

Citation for the version of the work held in 'OpenAIR@RGU':

XU, Y, SANCHEZ, J. F. and NJUGUNA, J., 2014. Cost modelling to support optimised selection of the end of life options for automotive components. Available from *OpenAIR@RGU*. [online]. Available from: http://openair.rgu.ac.uk

Citation for the publisher's version:

XU, Y, SANCHEZ, J. F. and NJUGUNA, J., 2014. Cost modelling to support optimised selection of the end of life options for automotive components. International Journal of Advanced Manufacturing Technology, Volume 73 (1-4), pp. 399-407.

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The final publication is available at Springer via http://dx.doi.org/10.1007/s00170-014-5804-9

COST MODELLING TO SUPPORT OPTIMISED SELECTION OF THE END OF LIFE OPTIONS FOR AUTOMOTIVE COMPONENTS

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ABSTRACT

In automotive sector, the End-of-Life components, especially the uni-material components e.g. steel, plastics etc., traditionally normally go to material recycling. However, this conventional disposing approach has nowadays moved towards the secondary utilization approach which closes the loop in the material flow process, i.e. reuse via remanufacturing, reconditioning, and repairing etc. However, the economic benefit of different End-of-Life options for automotive components remain unclear, there is a need to quantitatively evaluate the economic benefit of different End-of-Life options.

This project aims to develop a cost estimation model to assess the cost-effectiveness between recovery alternatives for End-of-Life automotive components. Firstly, the remanufacturing process for automotive components has been modelled consisting different stages and activities involved. Thereafter, the cost elements in each stage and the cost drivers for each cost element have been identified; cost breakdown structure has been established. Next, cost estimation relationships between cost elements and cost drivers have been established. A cost estimation model has been developed, validated and implemented in MS Excel@ platform. Finally, two case studies about comparison of different End-of-Life options for crankshaft and composite oil pan has been performed, it has been shown that the developed cost model can inform which End-of-Life option is more cost effective.

Keywords:

Product Recovery, Remanufacture, Recycle, Cost estimation, End-of-Life

Nomenclature:

EoL: End-of-Life

OEM: Original Equipment Manufacturer

1 BACKGROUND

1.1 Product End-of-Life scenario

Products reaching End-of-Life (EoL) phase have several End-of-Life options such as landfill, incineration, recycle, repair, remanufacturing, reuse, or a combination of these. Traditionally the EoL products were often disposed or went to material recycling, however this approach has nowadays moved towards a recovery (secondary utilization) approach. Four alternative End-of-Life options (repair, recondition, remanufacture and recycle) are illustrated in figure 1.

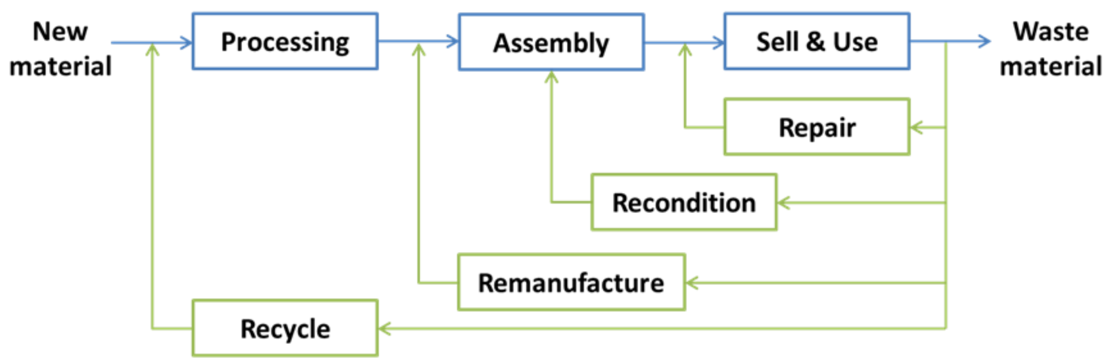

Fig. 1 End-of-Life options [1[1]]

The EoL options of repair, recondition and remanufacture represent “secondary market” processes which differ from each other in terms of the work content required, the performance obtained and the warranty carried, as depicted in figure 2. Repairing simply corrects specified faults in a product and reconditioning usually does not return used products to the original specifications [2[2]]. Remanufactured products, on the other hand, meet the original equipment manufacturer (OEM) specifications offering the same warranty of a new equivalent product.

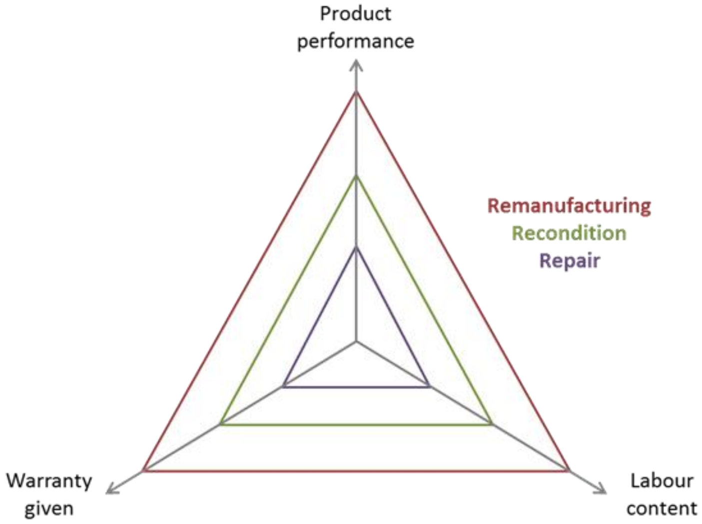

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Fig. 2 Hierarchy of product recovery options [2]

The EoL option of recycling, on the other hand, recovers value from the product at material level [3[3]]. The original form of the product is destroyed and materials are reprocessed (through chemical or physical reprocessing) so that the original or useful degraded material is recovered [4[4]]. These materials can be reused in production of original parts if the quality of materials is high, or else in production of other parts [5[5]].

1.2 EoL of automotive components

European Commission's ELV Directive encourages the reuse of components which are suitable for reuse, and encourage recycling the materials from those components that aren't suitable for reuse when environmentally viable [6].

In automotive sector, material recycling has been the traditional EoL practice for automotive components. Other EoL options, such as re-use and remanufacturing, still account for a small portion of vehicle recovery [7[7]], and original automotive manufactures are not widely engaged with these recovery methods. This is due to several obstacles: Firstly, most EoL automotive components were not designed for being recovered [77]. Moreover, the dramatic increase in the amount of car models over the past two decades has made difficult for remanufacturers to benefit from economies of recovering and reusing components [8[8]]. In addition, the supply chain for remanufacturing and reuse of components presents significant uncertainties, which makes more difficult the application of these EoL options [9[9]]. Finally, alternative recovery methods, such as complex post shredder technology that can be used for recycling, are becoming more financially attractive [10[10]].

European Commission's ELV Directive encourages reuse and recovery of automotive components for a sustainable development [6]. From Figure 1 and Figure 2, remanufacturing, reconditioning, and repair are supposed to be more sustainable EoL options than recycling. Nonetheless, economic, legislative, technological and ethical factors are contributing to the increase of recovery and reuse of components. Especially profitability is a key factor from manufacturers' perspective. So a more reliable cost estimation is needed so the manufactures can use it to assess if recovery and reuse of components is profitable or not. [11[11]].

1.3 Cost estimation and evaluation of End-of-Life strategies

There are several models and methods to assess product recovery options from an economic perspective. For assessing single EoL option, Fei et al. (2008) combined target costing methodology and activity-based costing in order to facilitate the accounting and control of costs in remanufacturing [12]. Shih et al. (2006) proposed an economic model to perform cost-benefit analysis in recycling [13] and Dantec (2005) evaluated the cost of recycling compliance in automotive sector [14].

In addition, some methodologies have been developed to estimate the cost in assessing and comparing alternative EoL strategies. Ferrer (2000) suggested an economic model at the strategic level that aims to provide insight concerning the economic feasibility of reuse, remanufacturing, and recycling [15]. Lee et al. (2010) developed a decision model to evaluate the economics of the remanufacturing and disassembly processes considering environmental legislation [16]. Bras and Emblemsvåg (1995) analysed the uncertainty regarding the product recovery process and developed an activity-based cost model for use in the design phase [17]. Hesselbach and Herrmann (2001) performed product and process oriented benchmarking to develop strategies for recycling. From this research work, the recycling ratio and the total End-of-Life cost are determined, and the recyclability of a product is determined based on multiple criteria [18]. Coates and Rahimifard (2006) introduced a structured costing framework to economically assess the recovery of EoL products [19] while Gregory et al. (2006) applied process-based cost modeling to evaluate the recycling of EoL electronics [20].

Some methodologies estimating cost of product's End-of-Life options were focused on a single aspect of product recovery systems. In particular, much attention has been devoted to cost estimation for disassembly operations. Lambert (2003); Tang et al. (2004); Johnson and Wang (1989) and Ewers et al. (2001) assessed the economic consequences of the disassembly process trying to determine the optimal sequence and degree of disassembly [21, 22, 23, 24]. Shu and Flowers (1999) evaluated how a joint design influences the cost of remanufacturing.

Several mathematical programming models have been found to be used in selecting EoL options. Lee et al. (2001) and Hula et al. (2003) mathematically incorporated the economic aspect by defining objectives such as maximization of net profit or minimization of costs associated with EoL alternatives [25,26]. Similarly, Tan and Kumar (2008) suggested a linear programming model [27] and Das and Yedlarajiah (2002) proposed a mixed integer program in order to assess EoL options [28]. Fujimoto and Ahmed (2001) also developed a mathematical method to obtain the ideal product life and take back period considering economics, technical and legislative factors [29].

Multi-criteria decision making approach has been used to select recovery strategies. Bufardi et al. (2004) analysed product recovery options by evaluating the economic, environmental and social factors associated with each End-of-Life alternative as well as considering the preferences of the decision maker [30]. Chan and Tong (2007) used grey relational analysis to evaluate EoL strategies in terms of material selection [31]. Ghazalli and Murata (2011) developed an AHP and case-based reasoning method to assess EoL options [32]. Remery et al. (2012) considered economic, legislative and environmental factors for evaluating the various options for the End-of-Life scenario using the TOPSIS decision-making method [33]. Mergias et al. (2007) suggested a methodology that relies on the PROMETHEE technique to select product recovery strategies for ELV [34]. Jun et al. (2009) proposed a multi-objective procedure for product recovery optimization [35] while Mangun and Thurston (2000) incorporated cost, quality and environmental aspects into product portfolio design for component reuse [36].

1.4 Research motivation

It is important to recover ELV and their components by using optimized EoL option. Reuse of products should be perceived when appropriated (rather than recycle materials from components) are encouraged by the ELV Directive [6]. The selection of optimized EoL options needs support to reliable cost estimation of EoL options, particularly the recovery and reuse of components. However literature review found that most existing economic models were focused on cost assessment of traditional EoL options, especially recycling; and some others were focused only on one single aspect of product recovery systems, e.g. on disassembly operations. In addition, the majority of existing models assessed cost benefit at macro level by adopting approaches like mathematical programming and multi-criteria decision making methodologies. These methodologies can give indicative information to support decision making. But they don’t give enough confidence on the real economic benefit. For automotive EoL strategies, there is no evidence of existing cost model that use adequate detailed EoL process information to estimate cost of each EoL option. This study aims to develop such a cost model to provide a more reliable support to selection of optimized EoL options for automotive components.

2 Remanufacturing process for automotive components

Two automotive components were selected in this research, i.e. steel crankshaft and thermoplastic composite oil pan as shown in figure 3. Steel crankshaft is selected because this is a core component and ideally it can be reused to retain the value embedded through the manufacturing process. The oil pan is selected in the study because it’s made of composite material and the reuse option for composite components has good opportunities to explore.

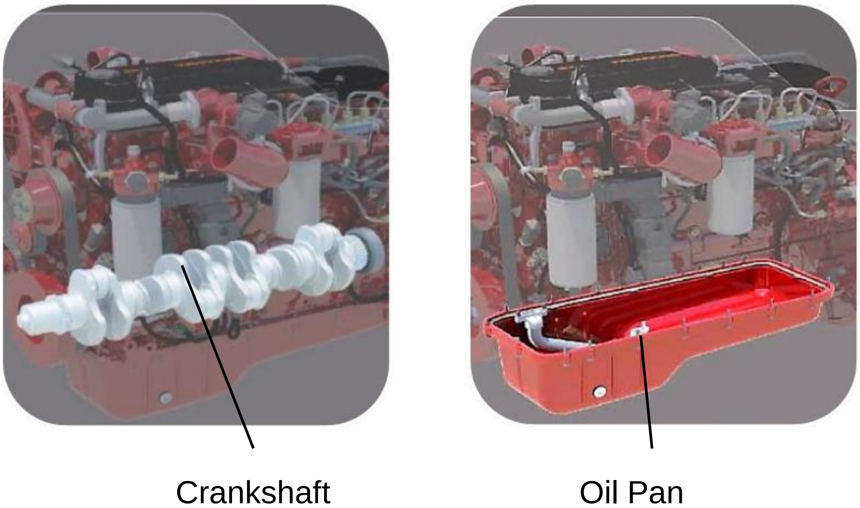


Fig. 3 Automotive components selected in case studies

The general remanufacturing process is expressed in figure 4. The process includes disassembly of retired products (called core), cleaning, recondition and replacement of components, reassembly and final testing.

Fig. 4 Generic remanufacturing processes [12[37]]

For the selected two automotive components, their remanufacturing processes comprise three main phases: cleaning, inspection and recondition, the detailed process is shown in figure 5. Within the recondition phase, several remediation possibilities have been considered depending on the type of component and the results from the inspection phase.

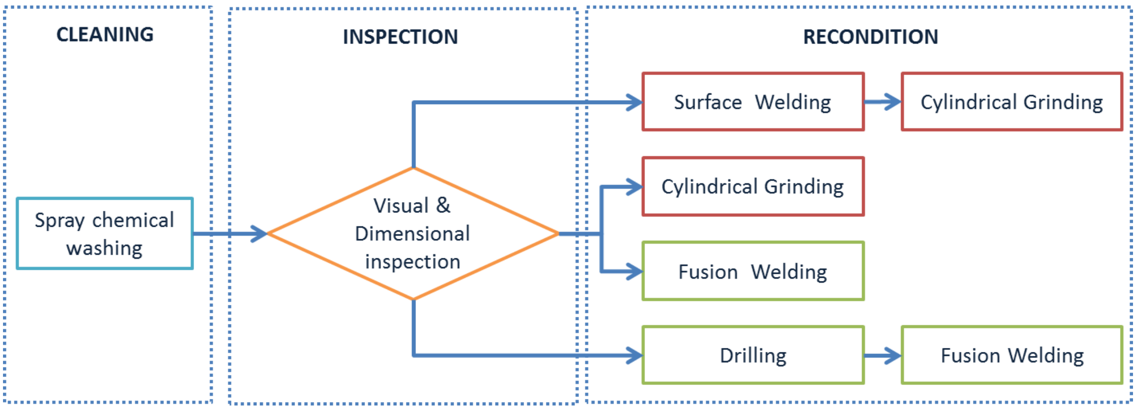


Fig. 5 Remanufacturing process for the selected automotive components

(1) Cleaning phase

The selected technique for cleaning the two components in this research is spray chemical washing based on the literature [13, 14[38], [39]] and industrial questionnaire survey. It involves the application of a pressurized cleaning solution (water plus detergent) to the components.

(2) Inspection phase

a) Steel crankshaft inspection: According to the literature [15[40]], visual inspection is used to detect superficial damage such as cracks, wear, corrosion or burnt at the surface of the crankshaft journals. Then, the diameter of journals is gauged by using portable measurement devices. The result of the inspection will determine the rectification solution to be adopted: a1) to rectify the damage by removing material, and therefore, reducing the size of the journal, without compromising the performance requirements; or a2) to rectify the damage by adding material to build up the desired dimension of the journal without compromising the performances requirements.

b) Thermoplastic composite oil pan inspection: The typical damage of composite oil pan is perforation caused by low velocity impacts [16[41]]. Visual inspection constituting adopted methods is used to detect the damage of composite oil pan.

(3) Recondition phase:

a) Steel crankshaft recondition: The recondition techniques described by Shettigar [17[42]] and confirmed by the industrial questionnaire survey conducted in this research include

- Cylindrical grinding: This machining method removes damaged material from the journal using an abrasive wheel as the cutting tool.
- Surface Welding: This material addition method deposits weld steel on the journal surface. In particular, the CMT (Cold Metal transfer) welding technique, first introduced by Fronius International GmbH in 2004, was adopted. The main advantage of this technique is reduced distortion introduced resulted by significant less heat transferred to the metals in this process. A grinding operation is needed after the CMT welding operation so that the surface roughness can meet the requirement.

b) Thermoplastic composite oil pan recondition: The adopted recondition techniques [18[43]] include

- Fusion welding: it involves heating and melting the material on the bond surfaces of the oil pan and the patch plug (additional material introduced in the damaged region) and then pressing together for solidification and consolidation. In particular, the ultrasonic welding technique, that uses high frequency mechanical vibration to weld parts, was adopted. A drilling operation may be required prior to the fusion welding in order to clearing out the damage.

3 Cost Model Development

3.1 Cost estimation process

The cost estimation process followed in this study is illustrated in figure 6Fig. , which was adopted from NASA [19[44]]. The process comprises the following steps: understand cost estimation requirements, select cost estimation technique, develop cost breakdown structure (CBS), identify cost drivers, develop cost estimation relationships (CERs), collect data, implement cost model and validation the cost model.

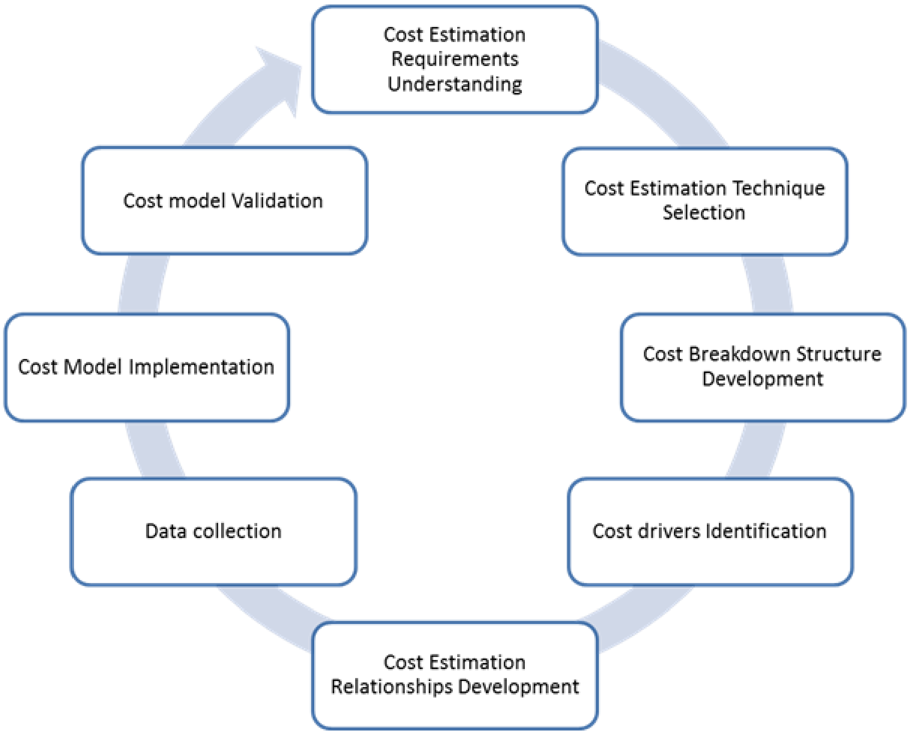


Fig. 6 Cost estimation process

The key requirement for the cost model is to be able to understand the cost difference between different EoL options for the crankshaft and oil pan components. For meeting this purpose, activity based costing (ABC) technique was selected in the cost model development. The ABC technique estimates the cost by firstly identifying the activities that are needed to remanufacture the components, secondly the type of resources needed by each activity. Then amount of the consumption of different resources is calculated, so that cost can be calculated.

3.2 Cost breakdown structure

Based on the remanufacturing process for the crankshaft and oil pan shown in figure 5, main activities in the process were identified. The main cost elements for each activity were then identified determined. The developed cost breakdown structure (CBS) is shown in Fig. 7. As it can be seen from the figure, the main remanufacturing cost include labor cost, materials cost and machine cost (including depreciation, power and consumables cost etc.).

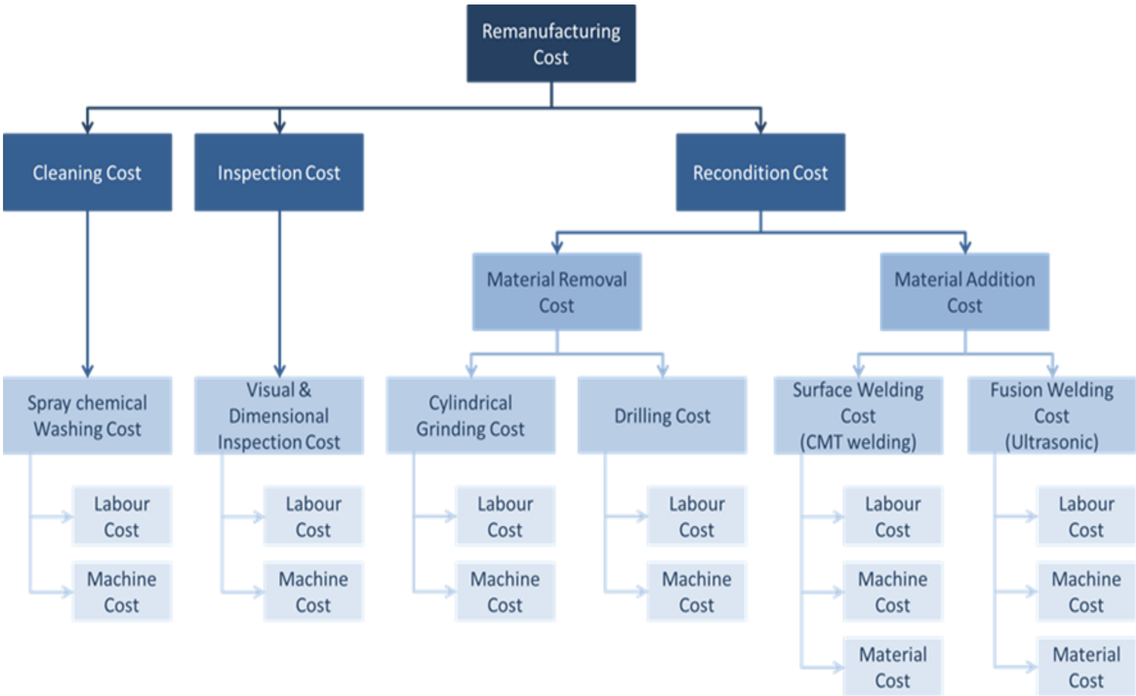


Fig. 7 Cost breakdown structure for selected automotive components

3.3 Cost drivers

Cost drivers are the parameters and variables that affect the cost of the different activities involved in the remanufacturing process of the selected automotive components are presented. The cost drivers were identified based on the information gathered from the literature, feedback from academic experts and data collected from the industrial questionnaire. The cost drivers for each activity and cost element are shown in Table 1.

Table 1 Cost drivers for selected automotive components

	Labour Cost	Machine cost	Material cost
Cleaning	Surface area		n/a
Inspection	Surface area		n/a
Recondition	Initial journal diameter		
	Final journal diameter		
	Journal length		
	Number of journals		
	Oil pan thickness		

3.4 Cost estimation relationships

Cost estimation relationships (CERs) means that each cost element is expressed as a function of the cost drivers. The CERs were developed for each cost element in the CBS using the identified cost drivers. For example for the machine cost in crankshaft remanufacturing (adding materials by welding technique), it was calculated by the following process. The direct machine cost is calculated by equation 1:

$$C_{dm} = \left(R_{power} + R_{consum}\right) \times t_{op} \quad (1)$$

Where

C_{dm} : Direct machine cost (£)

R_{power} : Power rate (£/min)

R_{consum} : Consumables rate (£/min)

t_{op} : Operation time (min)

The power rate R_{power} and consumable rate R_{consum} are calculated by statistics based on the historical data; the operation time t_{op} is calculated by using equation 2.

$$t_{op} = \frac{V_t}{R_{surf\_weld}} \quad (2)$$

Where

t_{op} : Operation time

V_t : Total volume to be deposited

R_{surf_weld} : Surface welding process rate (cm^3/min)

The surface welding deposition rate R_{surf_weld} is calculated by statistics based on the historical data, and the total deposition volume V_t is calculated by equation 3

$$V_t = \frac{V_e}{E_a} \quad (3)$$

Where

E_a: Material deposition efficiency (%) which measures the effectiveness of the welding deposition process, it represents the percentage of deposited material in all consumed material.

V_e is effective volume to be deposited, and is calculated in equation 4 by using the identified cost drivers final journal diameter and initial journal diameter

.

$$V_e = \frac{\pi \times l}{4} \times \left({d_f}^2 - {d_i}^2\right) \quad (4)$$

Where

l : Journal length (cm)

d_i : Initial journal diameter (cm)

d_f : Final journal diameter (cm)

4 Cost model validation and implementation

The developed cost model has been validated in terms of the cost estimating methodology, remanufacturing process, cost breakdown structure, cost drivers and cost estimating relationships. Face-to-face interviews were carried out with experienced experts: One has over 10 years of experience in cost estimating and was mainly used for validate the cost estimation methods and process. The other one is an engineer who has extensive experience in automotive industry and knowledge about remanufacturing process, and was used mainly for validating the recondition process for both Crankshaft and Oil Pan. Both experts had confirmed the identified activities and factors affecting the cost of remanufacturing the selected automotive components. The cost drivers, CERs and the overall logic of the cost estimation model had also been confirmed. Moreover, relevant data used in the cost estimation model had also been checked and was to be within their reasonable ranges.

The developed cost model had been implemented in MS Excel®. Cost estimation equations, and relevant data regarding remanufacturing activities and materials had been built into the spread sheets.

5 Case studies

Two case studies were conducted for assisting the selection of optimised EoL options by using the developed cost model for crankshaft and oil pan. For the purpose of selecting optimised EoL options, data and results were normalised so relative cost comparison between different EoL options were conducted.

(1) Comparison of crankshaft EoL options

The inputs used for crankshaft EoL cost estimation is shown in Table 2.

Table 2 Crankshaft input parameters

	Crankpin journal	Main journal
Total number	4	5
Initial diameter (mm)	50,00	58,00
Final diameter (mm)	54,00	60,00
Length (mm)	30,00	26,00
No. journals to be repaired	4	5

The remanufacturing cost breakdown resulted from this case study is shown in figure 8. The recondition operation cost represents the majority of the total remanufacturing cost. In particular, the surface welding cost takes 74% of the total cost and the grinding cost takes 14% of the total remanufacturing cost. In terms of cost categories, labour cost is the main cost contributor, which accounts for the 53% of the remanufacturing cost.

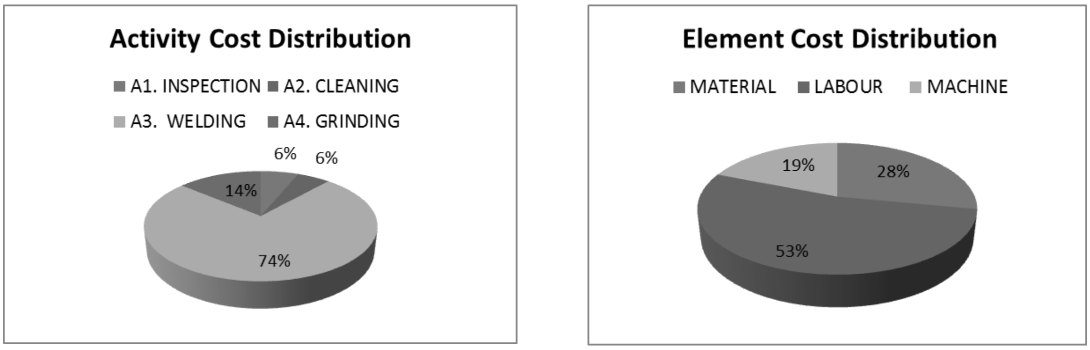


Fig. 8 Crankshaft remanufacturing cost distribution

Sensitivity analysis was conducted to see which EoL option is cost effective at different scenario (with different inputs). Figure 9 represents how the remanufacturing cost is varied by the difference between final and initial journal diameter, Recycling cost is assumed to be consistent and estimated by only considering the crankshaft materials recovery. As can be seen from the figure 9, the remanufacturing cost goes up as the difference between diameters increases; and positive difference between final and initial diameter (material addition) leads to more costly remanufacturing than negative difference (material removal). Also, if positive diameter difference is greater than 4.5 mm, i.e. to add materials more than 4.5 mm for reconditioning, recycling becomes more cost-effective than remanufacturing.

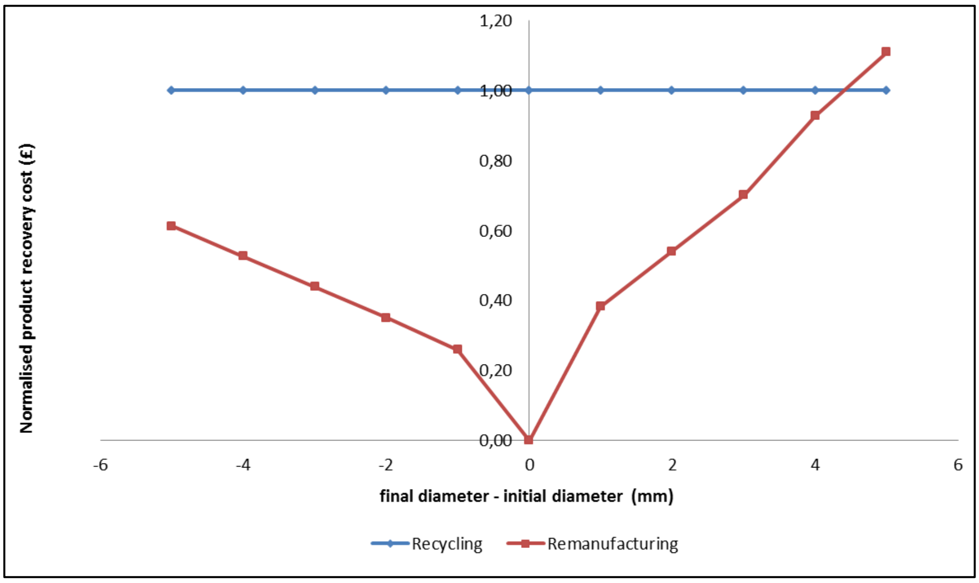


Fig. 9 Diameter difference vs. cost of EoL options

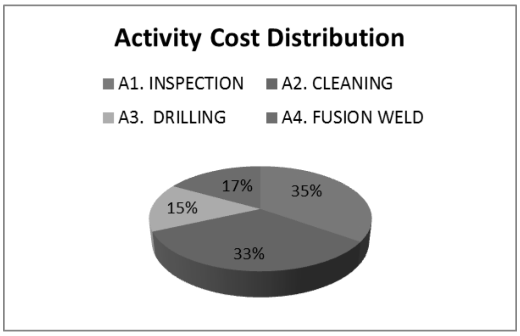
(2) Comparison of oil pan EoL options

The inputs for the oil pan case study are as shown in Table 3.

Table 3 Oil pan input parameters

Surface area (cm^2)	Thickness (mm)	No. impacts to be repaired	Impact diameter (mm)
4000,00	3,00	1	10,00

The oil pan remanufacturing cost breakdown resulted from this case study is shown in figure 10. The inspection cost and cleaning costs take 35% and 33% of the total remanufacturing cost, respectively. In terms of cost categories, labour cost constitutes the main cost contributor accounting for the 86% of the remanufacturing cost.



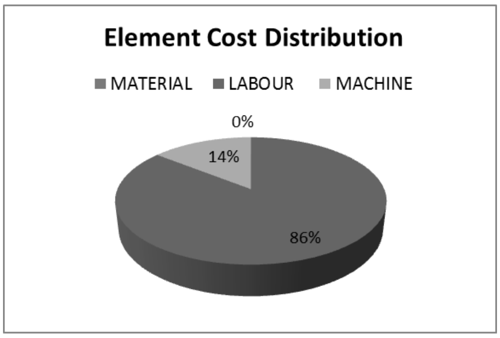


Fig. 10 Oil pan remanufacturing cost distribution

Sensitivity analysis was conducted to see which EoL options are cost effective when the oil pan has different thickness. As shown in the Figure 11, as the oil pan thickness increases, the recycling cost increases faster than remanufacturing cost. In particular, when an oil pan thickness is greater than 2.5 mm, the remanufacturing is more cost effective than the recycling of oil pan.

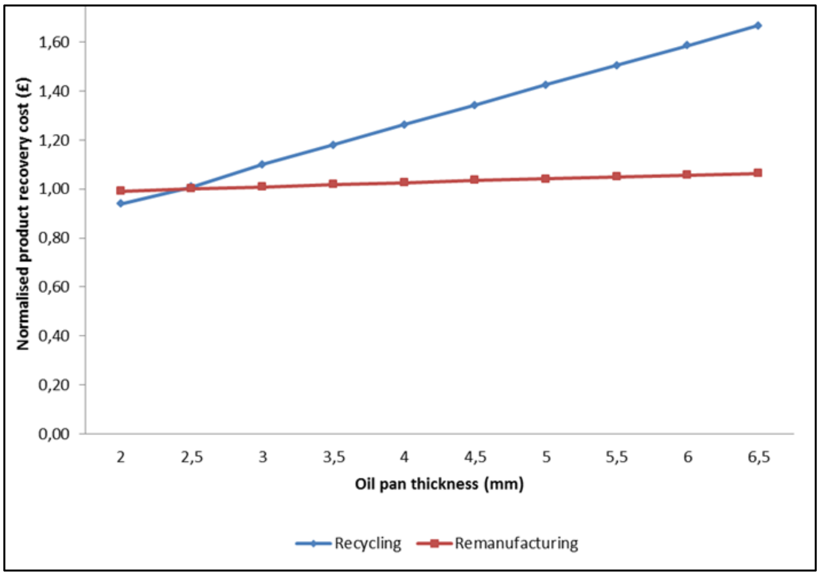


Fig. 11 Oil pan thickness vs. cost of EoL options

6 Conclusion

This research was motivated by the need to quantitatively evaluate the economic benefit of different EoL options for automotive products. The work was particularly focused on two automotive component families, i.e. crankshaft and composite oil pans. A cost estimation model which assesses the cost-effectiveness between recovery alternatives for specific End-of-Life automotive components has been developed. The remanufacturing process for the selected automotive components was modelled first. Thereafter, the cost elements in each stage and the cost drivers for each cost element have been identified. After that, cost estimation relationships between cost elements and cost drivers have been established. The developed cost model has been implemented in MS Excel®, validated via expert judgment and demonstrated through two case studies.

It has been found by the initial case studies that for crankshaft, if the final journal diameter (by remanufacturing) is smaller or less 4.5 mm bigger than the original journal diameter, remanufacturing is a more cost-effective EoL option than recycling; For composite oil pan, if the pan thickness is greater than 2.5 mm, the remanufacturing is a more cost effective option than recycling.

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