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Quantification of End-of-life Product Condition to Support Product Recovery Decision

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Abstract

This paper proposes concept to decide end-of-life (EoL) product recovery option, followed by methods to quantify product condition. A case study is presented using refrigerator crankshaft to illustrate the implication of product condition on product recovery decision making. The product condition comprises wear-out life of the product, change of dimension and cleanliness level. The advantage from the proposed concept is twofold - firstly, knowledge learned and embedded resources from EoL products able to get back to the product life cycle chain as a closed loop and, secondly, the most favourable EoL product recovery option can be made wisely. With thorough understanding of EoL product condition, it enables original equipment manufacturers (OEMs) to make quick and informed decision.

Keywords: End-of-life; product recovery; waste management

1. Introduction

By end of this year, there will be more than 100 million personal computers and more than 500 million mobile phones being disposed globally. Thanks to growth of middle class population around the world, demand for industrial product has gained momentum throughout the world especially in emerging market. At the same time, the life span for these products has been reduced gradually over the years due to consumer behaviour. For example, developed country tends to own 4 years average lifetime for computer, while developing country own 5 to 6 years of average lifetime [1].

What does human do with millions of obsolete products? Most of the obsolete products are being recycled in one way or another. However, the methods are unsystematic, not effective (in terms of energy and cost), hazardous due to mishandling and end up as landfills. This is because the team who is responsible for the recycling does not have the knowledge of the product, no recycling process, no support of advance technology, no established recycling channel and no connection with the manufacturer. All the reasons mentioned above are critical criteria for an effective recovery process which can create values from the EoL product.

At the current state of affairs, used goods can either be channeled wholly into refurbishing facilities, have their repairable parts salvaged, or be stripped down to their core materials to be recycled. While Thierry et al [2] and Hesselbach et al [3] lament the deficiency of information in the existing infrastructure, which impede the plan of EoL product recovery. Parlikad et al. resolves the deficiency of information using RFID-based automated identification approach to improve product recovery decision [4]. However, this method touches user's privacy baseline, which the idea is unlikely realistic when comes to consumer products. Others researchers improve eco-efficient of product based on EoL strategies during product design [5], while Ziout et al. illustrates the method to identify stakeholders that affect the EoL decision [6]. All in all, uncertainty of return product condition remains a concern to OEM, which they have no clue where to start the recovery activity if take-back regulations

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are implemented and manufacturers were to fulfil these regulations. This study proposed a method to quantify EoL product condition, which the outcome reveals cost and environmental impact from product recovery for further analysis.

The product recovery concept in this paper focuses on original equipment manufacturer (OEM), who has all knowledge of the product. The knowledge of the product includes the design, manufacturing and reliability data. This information shall be used to compare and determine the condition of the returned product. Quantification is the factor used to describe the condition of the used product. This factor is tied to the product and can be operating temperature, vibration level, physical appearance and so on. These results tell the condition of the used product shall determine the best recovery decision, which includes reuse, remanufacture, recycle or dispose (incineration).

Each of this recovery decision comes with its own economic aspect which covers cost and time. The cost and time spent for recovering shall be effective and make economy sense. Besides economic aspect, each recovery decision can be measured in terms of eco-efficiency, which combines economic and environmental considerations. The third aspect that decides the recovery process would be the product performance. For instance, a reusable product should at least still perform as new product condition for a certain period of remaining life, while a remanufacturable product could be reprocessed up to a like new condition product.

The challenges of incorporating economic, environmental, societal and ecologic has led to many researchers develop the methods as tools to tackle these tasks [7-10]. The methods and the scope of system are the main distinction among the tools.

2. Product recovery decision making framework

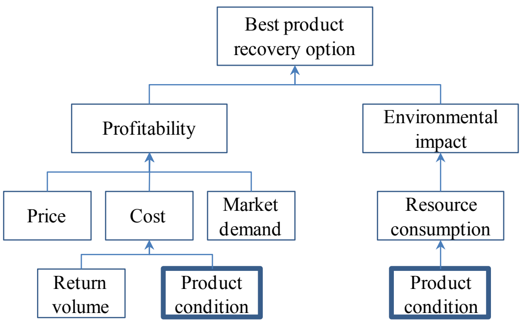

Figure 1 Decision making concept for EoL product recovery

A decision making framework on selecting the best recovery option is illustrated in Figure 1. The recovery options, namely, reuse, remanufacture, recycle and dispose (incinerate). The details of decision making based on different options are explained in [11]. In order to make a realistic business decision and carry out the corporate social responsibility (CSR), profitability and environmental impact based on the recovery option are assessed. The profitability of a business mainly depends on the selling price which reflects a product's value, cost and market demand (number unit of sold). On the other hand, product return volume and product condition are the factors that impact on cost. Environmental impact is the other key criteria in deciding recovery option. Depending on the product condition, resource consumption such as usage of electricity in operation, fuel in transportation and raw material has large impact to the environment. The EoL product condition stated in profitability and environmental branch are the same.

Several assumptions have been made as follow.

- Take-back regulations are enforced by the government
- OEMs adhere to the regulations
- Transportation cost for product take back is considered as sunk cost across all recovery options

2.1. Definition

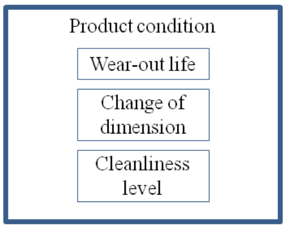

Figure 2 Components of product condition

EoL product mentioned in this paper refers to returned product, which the product no longer satisfies users. Besides, product condition is referring to the component or part of a system. As shown in Figure 2, product condition consists of wear-out life (ie. in terms of cycle, frequency, hours, etc.), change of dimension from the original measurement, and cleanliness level. In other case, the product condition could be the fatigue strength, corrosion, creep and to name a few.

Measurement of wear-out life is able to estimate the remaining life of a product or component after it is collected from user. For most mechanical parts, the remaining life can be estimated by comparing the date of manufactured and predicted life span modelled by manufacturer from reliability test.

Change of dimension is one of the common mechanisms observed in failure machines or machine parts, where it results in loss of material by mechanical removal. This information not only informs the performance of the product, more importantly it provides a clue to cost computation based on different recovery option, and thus estimate the optimal profit. The critical problem to solve here involves searching for best method to detect loss of material and how to patch the loss of material.

Cleanliness level of a returned product is another important indicator to quantify a product condition. The contaminated or dirty surface causes bad heat dissipation, lowering flow rate and thus affect the internal pressure and so on. With a layer of contaminant or dirt covers on the surface, it is impossible to patch the loss material for reuse. Moreover, the dirtier a part is, more steps and cost to clean the part are required.

2.2. EoL Product Assessment Structure

From the identified product condition mentioned above, a return product will be checked accordingly as shown in the flowchart in Figure 3. Wear-out life of the product is first determined, if the usage life is over the design life, the part is sorted out as non-reusable part, which the recovery options are recycle or dispose. Otherwise, the part will be checked for the dimension changed. If the part dimension is within the reusable limit (design specification), the part is suitable for reuse after cleaning. On the other hand, the part is considered for remanufacturing if the dimension changed is over the limit. Determination of cleanliness level of the part is necessary for cost analysis. This would allow the decision maker to decide on other recovery option if the cost of cleaning is high. As for the case of reuse, recovery cost inclusive cleaning cost is always lower than remanufacture a part.

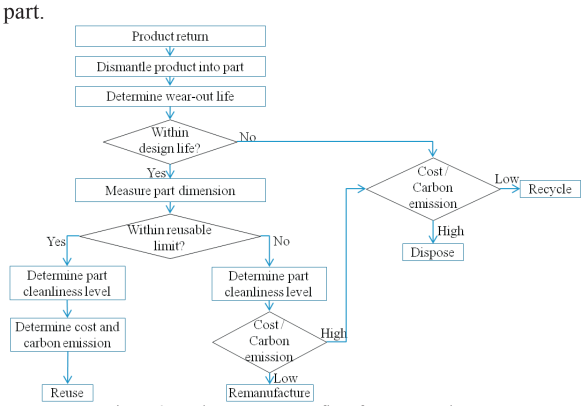

Figure 3 Product assessment flow for EoL product

3. Quantification Method for EoL Product Condition

When a product returned, it will be evaluated for the recovery cost and impact to the environment based on each recovery option [11]. Cost of making new part, cost of reuse and remanufacture are computed using equation (1). The cost of recycle and dispose are calculated using equation (2), where the cost of manufacturing a new part is included so that all options will end up with a finished part that permits fair comparison. In the equations, the EoL product condition, change of dimension and the cleanliness level are the function of operational cost. Thereby, looking into product condition gives an insight on the overall recovery cost.

$$C_k = C_{op-k} + C_{oh-k} + C_{proc-k} + C_{dep-k}\,, \quad k = 1,2,3 \qquad (1)$$

$$C_k = C_{op-k} + C_{oh-k} + C_{proc-k} + C_{dep-k} + C_1, \; k = 4,5 \qquad (2)$$

$$C_{op-k} = C_{mat} + \sum_{j=1}^{n} C_{process-j} + C_{labour} \qquad (3)$$

C_k = Cost of option k, where
k = 1 (making new)
k = 2 (reuse)
k = 3 (remanufacture)
k = 4 (recycle)
k = 5 (dispose)
$C_{op\text{-}k}$ = Operational cost (including direct material, process, direct labour)
$C_{oh\text{-}k}$ = Overhead cost (including indirect labour, rent, utilities)
$C_{proc\text{-}k}$ = Procurement cost (including collection, transport, take back)
$C_{dep\text{-}k}$ = Machine depreciation cost (assume straight line depreciation over 5 years)
$C_{process\text{-}j}$ = Cost of process *j*, *j=1,2,3…*

Similarly, analysis on the product condition gives hint to the environmental impact. Carbon dioxide (CO_2) is used as an indicator for environmental performance in this study, where the emissions are mainly coming from activities in the manufacturing processes, shows in equations (4) to (6).

$$EI_k = EI_{op-k} + EI_{proc-k}\,, \qquad k = 1,2,3 \qquad (4)$$

$$EI_k = EI_{op-k} + EI_{proc-k} + EI_1\,, \qquad k = 4,5 \qquad (5)$$

$$EI_{op-k} = \sum_{j=1}^{n} EI_{process-j} \qquad (6)$$

EI_k = Environmental impact caused by option *k*, where
k = 1 (new)
k = 2 (reuse)
k = 3 (remanufacture)
k = 4 (recycle)
k = 5 (dispose)
$EI_{op\text{-}k}$ = Environmental impact caused by operation activities (include processes)
$EI_{proc\text{-}k}$ = Environmental impact caused by procurement activities (include collection, transport)
$EI_{process\text{-}j}$ = Environmental impact caused by process *j*, *j=1,2,3…*

3.1. Wear-out life

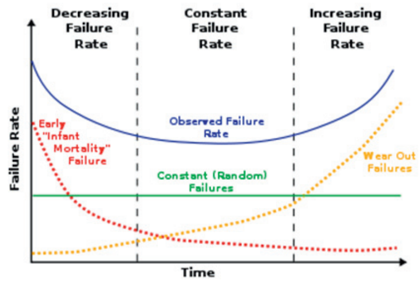

Figure 4 Bathtub curve [12]

The bathtub curve (in Figure 4) is widely used in reliability engineering. It describes a particular form of the hazard function which comprises three parts. The first part is a decreasing failure rate (early failures), second part is a constant failure rate (random failures) and third part is an increasing failure rate (wear-out failures) [12].

The life spans of a product or component usually follow one of the curves described above. This curve can be predicted and modelled by manufacturer during product development phase by collecting and analyzing data through running reliability testing. The manufacturer can also do the same for a subsystem. The widely used methods to determine the reliability of the product are tests such as accelerated life test, endurance, temperature cycling and so on.

This information will help manufacturer to determine the remaining "safe to use" period when the component is collected from known period of usage. Every product has a unique serial number which can be traced back to the manufactured date. However, to accurately predict the remaining life of the product, it is important to consider also the usage behavior, frequency of usage within a period of time, unexpected operation of the product outside product specification. The outcome from wear-out life valuation enables decision maker to make quick decision on whether to reuse the product or component.

3.2. Change of dimension

There are many methods to detect loss of material and many are costly. In any case, the method selected must be the most cost effective and accurate. A simpler method to measure dimension change is using profilometer, where the stylus moves relative to the contact of surface. The measurement method using profilometer could be economical, however, it is time taken. Another advanced method for thickness measurement called electron energy loss spectroscopy (EELS) is introduced. The theory behind this method is electrons scattering and energy loss. With the known original dimension, analysis method could be programmed and absolute dimension changed values can be accurately determined in milliseconds. Nevertheless, the equipment could be several times more expensive than profilometer. Taking recovery of high value product and large volume into consideration, return on investment of the advanced machine will be recovered in long term.

3.3. Cleanliness level

Cleanliness level of a returned product is another important indicator to quantify a product condition. Inspection of cleanliness level of the part is introduced; however, it depends on the value and type of product to the sensitivity of cleanliness level. For instance, the contaminated or dirty surface of a mechanical part in a compressor might cause bad heat dissipation, lowering flow rate and thus affect the internal pressure and so on. When the product is returned, it is impossible for direct reuse or patches the loss material for reuse with a layer of contaminant or dirt covers on the surface. In industry practice, all parts that require cleaning are treated as the worst case. Thereby, the part cleaning line in production is planned in such a way that higher chemical washing concentration or longer washing time is taken so that all dirt is totally cleaned up.

If cleanliness of a product is particularly important, a manual way of identifying cleanliness level is via visual inspection, which the labour will sort out the dirty part according to his experience. A more accurate and direct method to recognize the cleanliness of part could be using gravimetric measurement, where a highly sensitive scale can detect gross contaminant. To automate the process, this scale can be integrated with EELS to measure the change of part dimension, at the same time attain the cleanliness status. However, one should ensure the change of part dimension before it goes for gravimetric measurement. As refer to Table 1, the lowest level of cleanliness represents very dirty while the highest level of cleanliness stands for clean. A wiping step is introduced to clean the part with lower level of cleanliness instead of having multiple wash cycle, which this step able to reduce the time and cost of washing greatly. However different wiping time is applied according to the cleanliness level. For instance, cleanliness of level 1 requires longer time to wipe as compare to cleanliness of level 2.

Table 1 Classification of cleanliness level

Cleanliness level	Cleanliness measurement and definition	Action taken
1: Very dirty	Total weight – part weight (3 or more unit of gross contaminant)	2 wiping time + wash
2: Dirty	Total weight – part weight (2 unit of gross contaminant)	1 wiping time + wash
3:Clean	Total weight – part weight (1 unit of gross contaminant)	Wash

4. Case Study

4.1. Background

A crankshaft which is a component in refrigerator compressor is selected for the case study. It is one of the costly components from the Bill of Materials (BOM) of compressor. Crankshaft is part of the compressor that converts reciprocating linear piston motion into rotation. As shown in Figure 5, crankshaft is made of eccentric journal and main journal, and the wear takes place at the edge of both journals. When there is change of journal dimension or slugging happen, imbalance mixture of refrigerant and oil will occur. This is followed by imbalance pressure, overheating and break down of valves.

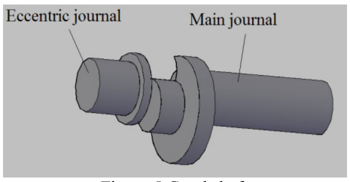

Figure 5 Crankshaft

4.2. Results and Discussion

4.2.1. Wear-out life

From the wear-out analysis (in Figure 6), the part had been used up to the design life, however, it has only reached approximately 16.7% of wear-out as compare to the designed wear-out dimension. In this case, the crankshaft should not be reuse even though there is large margin for wear-out as the functionality beyond this point is unpredictable. To save the part, this information shall feedback to the designer so that appropriate design strategy can be incorporated for better efficiency in terms of cost and benign to environment. For instance, the part could be redesign for longer life span or manufacturer can choose a lower grade material or solution that matches the product technology cycle to avoid over design.

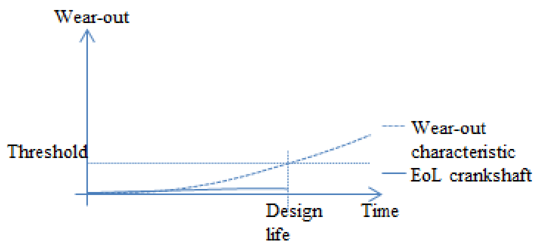

Figure 6 Wear-out life of crankshaft

4.2.2. Change of dimension

As for the case which the part is still within the design life, but product condition exceeded the reusable specification, one should consider the cost incurred due to the extent of part dimension changed. The recovery cost changes with dimension vary from 0.003mm (reusable limit) to 1mm is illustrated in Figure 7. A polynomial graph is fitted on the plot and equation is generated. The breakeven point for cost of remanufacturing is determined with the dimension 0.166mm. Dimension that is above this value is not practical to select for remanufacturing as recovery option. Similarly, as shown in Figure 8, carbon emission from remanufacturing processes increases as the dimension changed larger. From the analysis, remanufacture incurs more carbon emission than recycle when the dimension exceeds 0.057mm and carbon is emitted more than dispose when the dimension over 0.222mm. In this case, manufacturer should make wise decision between the cost and environmental impact at the dimension range of 0.057mm to 0.166mm. In ideal situation, one should set 0.057mm as remanufacturable threshold to gain both benefits on cost and save the environment. On the other hand, manufacturer can always give a weightage (priority) on one over another to set the dimension value in order to attain the best recovery outcome.

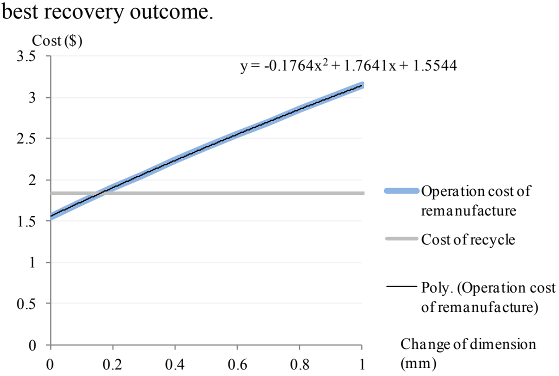

Figure 7 Impact on change of dimension on recovery cost

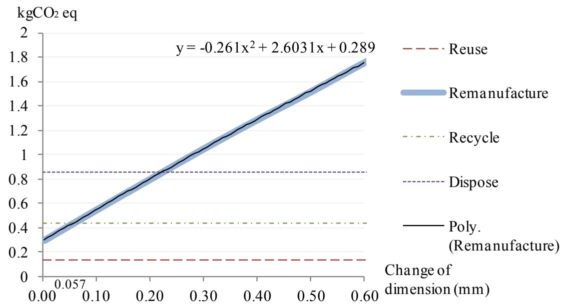

Figure 8 Relationship between change of dimension and carbon emission

4.2.3. Cleanliness level

Figure 9 shows that recovery cost for reuse and remanufacture decreases with the increase of cleanliness level. As the lower level of cleanliness requires less effort and time to clean, therefore, lower operation cost. However, cost of recycle and disposal remain constant regardless of cleanliness level due to the decision made in the earlier part measurement step. As for the part dimension that is above remanufactureable threshold (refer to section 4.2.2), it will take into account for recycle or dispose option. From the plot, it clearly shows that cost of reuse part is the best option regardless of the cleanliness level, if it is within reusable dimension. Else, the part shall consider remanufacture if the level of cleanliness is 4 and above. Recycle will be the cheaper option for a part with cleanliness level of 3, and dispose is the least favourable option if the part has a cleanliness level of 2 and below. However, disposal of crankshaft is not recommended in this case due to the high value of recovered material outweigh the minute cost difference between recycle and dispose. Besides, there is no additional burden to the environment even the return part is at the lowest cleanliness level, because all reusable parts will go through the same washing cycle.

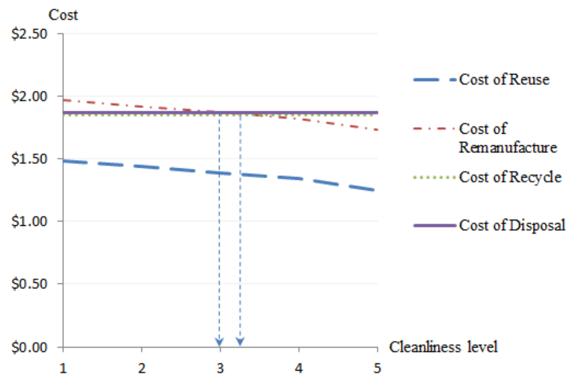

Figure 9 Relationship between cleanliness level and recovery cost

5. Conclusion

In order to make an efficient product recovery system success, EoL product recovery concept that enables manufacturers to make quick and effective decision is proposed. The efficiency lies in understanding the product condition, which the components condition is clearly defined and method to evaluate the component is explained. Crankshaft is used as the component in this case study to illustrate the implication of product condition on recovery cost and environmental impact. The concept demonstrated in the case study essentially increase understanding of the product; create channels for information feedback, lower production costs and environmental impact with the right strategy.

In conclusion, the proposed concept is able to stimulate and support product and process innovation, thus enhancing bottom line performance, delivering cost benefits to the company and ensuring sustainability. This proposal has provided manufacturer a decision making process to manage returned product in different methods (reuse, remanufacture, recycle) and this process can be optimized and customized according to the weightage of profitability and environmental impact. In future, non-technical aspects such as maximizing the return volume to lower production cost, also price setting based on product value and market demand could be studied to better improve product recovery efficiency.

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