Evaluation of Product Reusability based on a Technical and Economic Model:
A Case Study of Televisions

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Abstract—In the field of sustainable manufacturing, reusing of old products or components is considered as the most environmentally friendly strategy among all other strategies. However, the decision of reusing old components of a used product confronts many uncertainties such as the quality level of the used components and the economic aspect of reusing them compared to producing a new component. This paper presents an integrated technical and economic model to evaluate the reusability of products or components. The model introduces some new parameters, such as Product Value and Product Gain, to assist the decision between reuse, remanufacture or disposal. In order to handle uncertainties, a Monte Carlo simulation using @RiskTM is utilized. The results show that the model is capable to assess the potential reusability of used products, while the use of simulation significantly increases the function of the model in addressing uncertainties. A case study of televisions is used to demonstrate the applicability of the model using extensive time-to-failure data for the major parts of a television set. Furthermore, a direction of future work is outlined and briefly discussed.

Keywords—reusability; reliability; decision-making; televisions; technical and economic model; uncertainties; simulation

I. INTRODUCTION

In the manufacturing area, recycling of used products becomes the most popular strategy in place. However, it is only the first step towards sustainability. A more environmentally viable strategy in terms of preserving resources and energy is the reuse of used parts, sub-assemblies, or entire products. Since the quality of used products and the economic aspect of the reuse are uncertain, an assessment model that integrates all influencing factors is required to guide industries to evaluate their products for reuse [1-2].

II. THE ASSESSMENT MODEL

A. The Objective

The objective of the model is to provide industries with a simple indicator representing the potential reusability of a product that considers all necessary factors in the whole product’s life cycle. The model incorporates quality or technical aspect of products after the first lifetime and economic aspect of reuse strategy.

A premise of this model is that the reuse of parts in existing products is always a more environmentally friendly option than either making new parts or using recycled parts. Introducing environmental costs into the model will definitely tilt the result further toward the selection of reuse. But these costs will not be added to the model presented in this paper in order to keep it simple and as conservative as possible.

B. Definitions and Structure

For the model, three new parameters have been defined, namely Product Gain (PG), Product Value (PVL), and Product Life Cycle Cost (PLCC). They are related as indicated in (1).

\[ \text{PG} = \text{PVL} - \text{PLCC} \]  \hspace{1cm} (1)

The Product Gain, PG, represents the monetary outcome from the sales of the product or component after deducting product life cycle cost.

The Product Value, PVL, represents the technical performance or quality status of the product, which can be measured by the Product Effectiveness, PE. Reliability is used as the basis for estimating the quality of a product or component. For a new product, reliability can be set to 100%, and this means that PE = 1. The dollar value is introduced by using the market prize, MP, as the multiplier as shown in (2).

\[ \text{PVL} = \text{MP} \times \text{PE} \]  \hspace{1cm} (2)

Product reliability can decrease over time through the use of the product. Consequently, if a product is re-used, its PE may be smaller than the PE of the new product. Whether or not PE decreases over time depends entirely on the type of the product or component.

The Product Life Cycle Cost, PLCC, represents all costs that occur during the product’s life cycle phases. PLCC has to be calculated separately for a new product and a reused product since the life cycle phases are slightly different between these two options.
The phases for a new product are material phase, manufacturing phase, usage phase and end-of-life phase. For a reused product the phases are procurement phase, remanufacturing phase, usage phase, and end-of-life phase. The procurement phase covers the activities of collection and transportation of used products. The remanufacturing phase covers all activities for recovering and re-working of used components to restore them to a “like-new” condition [1].

“Like-new” condition implies that an old component will perform as good as a new one. To perform as good as a new one, it is not necessary for a component or a product to retain 100% of its technical content. Usually a component is designed and manufactured above the expectation of customers, meaning that it already holds a higher technical status than it required. Therefore, if its reliability decreases over time, the remaining reliability is still possibly higher or equal to the expectation of customers. In this situation, manufacturers should determine the threshold value for their component’s reliability. Reuse of old components could be only undertaken if the reliability of old components is higher or equal to the threshold value [3].

Consequently, if the performances of an old and a new component are equal, their costs during usage and end-of-life phase are assumed to be equal. Therefore these two phases have no influence on the decision process and they do not appear in the cost calculation.

Basically, there are two components in PLCC, which are product cost, $C_p$, and environmental cost, $C_e$, as shown in (3). However, since reuse is presumed to be a greener option, to simplify the evaluation the environmental cost is temporarily not included in the calculation. This simplification would not influence the decision, as the integration of the environmental cost will favor the reuse implementation. In other word, it can be said that the ignorance of the environmental cost will be the baseline for the evaluation.

$$\text{PLCC} = C_p + C_e$$  
(3)

Where:

- $C_p$ = Product cost
- $C_e$ = Environmental cost

The cost calculation for a new component can be seen in (4) and (5) as follows:

$$C_{\text{Pnew}} = C_{\text{mat}} + C_{\text{man}} + C_{\text{oc}}$$  
(4)

$$C_{\text{Enew}} = C_{\text{Emat}} + C_{\text{Eman}}$$  
(5)

Where:

- $C_{\text{mat}}$ = Material cost
- $C_{\text{man}}$ = Manufacturing cost (including processes, assembly, labor and overheads costs)
- $C_{\text{oc}}$ = Operational cost (including administration, marketing and distribution)
- $C_{\text{Emat}}$ = Environmental cost for material phase
- $C_{\text{Eman}}$ = Environmental cost for manufacturing phase

For an old component, the cost calculation for reuse option is shown in (6) and (7).

$$C_{\text{Preu}} = C_{\text{pro}} + C_{\text{rem}}$$  
(6)

$$C_{\text{Ereu}} = C_{\text{Epro}} + C_{\text{Erem}}$$  
(7)

Where:

- $C_{\text{pro}}$ = Procurement cost (including collection, take back, transport, and storage)
- $C_{\text{rem}}$ = Remanufacturing cost (including disassembly, cleaning, sorting, testing and reprocessing)
- $C_{\text{Epro}}$ = Environmental cost for procurement activities
- $C_{\text{Erem}}$ = Environmental cost for remanufacturing

C. Decision Making Process

The model works by first calculating PG for each of these two options: producing a new component (NC), and reusing an old component (OC). Then a comparison is carried out using (8).

$$\Delta \text{PG} = \text{PG}_{\text{OC}} - \text{PG}_{\text{NC}}$$  
(8)

A positive value of $\Delta \text{PG}$ indicates the potential for reusing old components, whereas a zero or negative value of $\Delta \text{PG}$ points to unfeasibility of reuse. If $\Delta \text{PG}$ is zero or negative, a sensitivity analysis can be carried out to investigate the major factors determining the negative value and to learn how the model behaves under different circumstances. If the reason for a low value of $\text{PG}_{\text{OC}}$ is the PE, the situation cannot be changed unless the product is re-designed. However, if the reason is the PLCC, a cost reduction exercise can be carried out in order to increase the possibility of reuse. As a result, the model can reveal some re-design suggestions for more environmentally friendly products and systems.

III. SIMULATION

A. The Need for Simulation

In many situations people have to deal with uncertainties and the risks associated with these uncertainties. Particularly in reuse strategy, the existence of uncertainties is obvious. For instance, industries have no idea when and why exactly the customer will dispose of their goods. Uncertainty of the usage intensity at customers’ site is also hidden from industries, and this will also heavily influence the quality of the products at the end of their first life. Furthermore, uncertainties are also involved in the cost calculation. For instance, the unknown location of the disposal of the products - they can be rusty, bent, broken, or good - will also vary, thus influencing the disassembly cost.

Methods to deal with uncertainties vary from group decision to the use of multi-attribute indices and statistical tools. Among various existing statistical tools, Monte Carlo simulation is the classic approach to handle uncertainties. It is also the selected approach for this purpose in the proposed assessment model.

In this research, simulation is carried out using @Risk Software Version 4, an “add-in” for Microsoft Excel [4]. The model is developed based on the assessment model explained above, and the uncertainties are defined using relevant probability distributions from past practical experiences. Monte Carlo simulation is based on random sampling from probability distributions to calculate the average results and the confidence interval for a set of input parameters. The @Risk add-in for Excel allows the user to define the probability distributions and the number of iterations to be used in the simulation. The software calculates the average results and the confidence interval for a set of input parameters.
Carlo sampling types is used and a minimum of 10,000 iterations is selected.

B. The Assumptions

There are two sets of assumptions used in this model. The first set is the set of assumptions used to describe uncertainty in the @Risk simulation, while the second set is the set of assumptions used in the mathematical formulation. In the first set, assumptions are made for the length of the first lifetime, the distance of the collection, the disassembly time, the cleaning and sorting time, and the testing time. In the second set, assumptions are made for the utility of the transportation device, the level of disassembly, cleaning, and testing techniques (i.e. manual, semi automated, and fully automated), and the reprocessing cost relevant to the technical condition of a component at the end of its lifetime.

IV. A TELEVISION CASE STUDY

A. Backgrounds

As part of an ongoing research project on the reuse of appliances, televisions have been selected to demonstrate the applicability of the proposed method. The specifications of the selected product line, a 14-inch color television, are shown in Table I. This particular type of television was chosen because it has been released several years ago and has become one of the most popular products. Therefore sufficient data is available for the reliability assessment.

<table>
<thead>
<tr>
<th>Feature</th>
<th>TBS (Turbo Boosting System), EYE, CATV/ Hyper Band, PSM (Picture Status Memory), CSM (Color Status Memory)</th>
</tr>
</thead>
</table>

The list of the main components and their quantity in a television set can be seen in Table II. The contribution of each component to the cost of good sold (CoGS) of a television is shown in the last column of Table II. Those values are calculated by using the number of sales, the number of surviving units that form the suspension data are also calculated by using the number of sales, the percentages of market distribution, and the number of units that indicates the suspension status. Suspension status means that indicates the failure status of the relevant component and “S” presents in a form as shown in Table IV. The letter “F” indicates the failure status of the relevant component and “S” indicates the suspension status. Suspension status means that the units are still fully functioning when the data is collected. Over the three years period, more than 800 failure data were recorded for all components.

<table>
<thead>
<tr>
<th>Feature</th>
<th>TBS (Turbo Boosting System), EYE, CATV/ Hyper Band, PSM (Picture Status Memory), CSM (Color Status Memory)</th>
</tr>
</thead>
</table>

B. Reliability Parameters

In order to determine the reliability parameters of each component, an intensive data collection that includes the time-to-failure for each individual component, the sales of selected television set, and the distribution of the product in the market area, has been conducted.

Sample time-to-failure data pertaining to components are shown in Table III. Most of the data in this table are self-explanatory. The time-to-failure, in days, is simply the difference between purchasing date and failure date.

<table>
<thead>
<tr>
<th>Model</th>
<th>Purchasing Date</th>
<th>Failure Date</th>
<th>Failed Part</th>
<th>Diagnosis</th>
<th>Time-to-Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA14D72</td>
<td>03/11/93</td>
<td>16/12/00</td>
<td>Capacitor</td>
<td>Malfunction</td>
<td>2600</td>
</tr>
<tr>
<td>CA14D72</td>
<td>03/12/93</td>
<td>15/08/01</td>
<td>Fuse</td>
<td>Failed</td>
<td>2812</td>
</tr>
</tbody>
</table>

As failure only happens to a few units sold, the number of surviving units has to be calculated to determine the reliability parameters. For this purpose, the field situation as shown in Fig. 1 is used to determine the number of failed units and surviving units.

From X units sold, only 97% will stay in the Maintenance Center (MC) coverage area while the other 3% will leave the coverage area to other regions. Among those that remain in the coverage area, only around 80% are registered with the authorized MC. This percentage indicates the potential of reporting any failure occurrence. The other 20% percent would be taken to unauthorized maintenance providers or friends if a problem occurs and the units need repair. From the registered products, a maintenance database containing times to failure of components over a three-year period was kept. In addition to that, the number of surviving units that form the suspension data are also calculated by using the number of sales, the percentages of market distribution, and the number of units that fail.

[Figure 1. The distribution of television in the market]

All data for determining the reliability parameters are then presented in a form as shown in Table IV. The letter “F” indicates the failure status of the relevant component and “S” indicates the suspension status. Suspension means that the units are still fully functioning when the data is collected. Over the three years period, more than 800 failure data were recorded for all components.
The data was then analyzed using the Weibull distribution to reveal the main parameters and to calculate the remaining reliability of the components. Weibull analysis is widely used in reliability analysis and is a powerful tool that can provide a pragmatic solution [3,5]. The distribution is characterized by two parameters, a scale (η) and a slope (β). The scale parameter (η) is defined as the life of the product at which 63.2% of all units will fail, while the slope parameter (β) is defined as the mode of failure [6]. Referring to the well-known bathtub curve, β<1 indicates an infant mortality, β=1 a random failure, and β>1 a wear out failure. If t represents the lifetime, the reliability can be calculated as indicated in (6).

\[
R(t) = \exp \left[ - \left( \frac{t}{\eta} \right)^{\beta} \right] \tag{6}
\]

Weibull analysis is performed by a popular software tool, the Weibull ++ software version 6.0 [5]. The software allows the users to select the appropriate portfolio by entering the characteristics of the data. In this case, the data properties entered are the time-to-failure, the suspension time, the number of failed units, the number of suspended or censored units, and the “F” or “S” status of each relevant data.

Based on the information provided, the software calculated the reliability plot for each component. An example of a Weibull reliability plot for several components is shown in Fig. 2. For this analysis, the selected options include 2-parameter Weibull distribution, Maximum Likelihood Estimation (MLE), Fisher Matrix, and median rank methods.

Among the 23 components listed in Table II, only 14 components were reported as failures over the three years period. Therefore, reliability analysis can only be done to the failure data of the first 14 components as reported in the first part of Table V.

![Weibull unreliability curve for capacitor, CRT, and DY](image)

Figure 2. Weibull unreliability curve for capacitor, CRT, and DY

For the other 9 components, the reliability parameters were adopted from industrial standards and handbooks [6-7]. Based on the input of the industrial partner and the available standard design, the reliability data for these 9 components in a typical 14-inch TV were determined and shown in the second part of Table V. It should be remarked that in most standards the exponential distribution represents well the product’s performance during the stable phase in its lifecycle. If λ is the hazard rate, the reliability formula for Exponential distribution is shown in (7).

\[
R(t) = \exp[−λt] \tag{7}
\]

**TABLE IV. TIME TO FAILURE / SUSPENSION DATA FOR CAPACITOR**

<table>
<thead>
<tr>
<th>Event ID</th>
<th>Number in State (units)</th>
<th>State F or S</th>
<th>State End Time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10000</td>
<td>F</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
<td>1183</td>
<td>S</td>
<td>906</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

C. Model Implementation

An Excel-based model has been developed to apply the assessment model for all components. The reliability parameters resulting from the previous step and all cost information are entered into the model as well as the probability distributions for relevant inputs. The model was simulated using @Risk software.

In order to run the simulation and calculate the parameters, some assumptions have been used. They are as follows:

- The life span of a TV is between 7 to 15 years, which equals to 2555 to 5475 days.
- Products have been taken back through a pooling system, meaning that customers drop the used products at an assigned collection center. Then the used products are transported to the disassembly center using a 4-ton truck with average load of 100 TV units (the average weight of 14-inch TV is around 10kg). Current practices suggest that the distance between collection center and manufacturing site varies from 25 to 100 km with the most likely distance being around 50 km.
- The normal carrying capacity of the vehicle is 4 ton. Within the normal capacity, the petrol consumption remains constant, which is 1 liter per 8 km (0.125 l/km). If the load is more than the normal capacity, the petrol consumption will gradually increase by 0.005 liter per km per additional kg of weight.
- The price of 1 liter of petrol is AS1.
• Australian labor cost is assumed to be A$15 per hour.
• Considering the level of standard design for an average product, typical customer requirement of quality, and past experiences of product performance, the threshold reliability is determined as 0.9. This means that, if the reliability of a used component is still over 0.9 at the end of the first life, then this component could be used for a second lifetime. In contrast, if its reliability falls below 0.9, then this component is unlikely to be reused.
• As there are many brands of TV’s collected, each brand in a small number of units, the disassembly of TV’s must be done manually, while cleaning, sorting, and testing are performed either manually or by using semi automatic tools or machines.
• Reprocessing cost is affected by the technical status of a component. The worse the physical condition of a component, the higher the cost will be.
• Probability distributions used as inputs to the simulation are shown in Table VI.

<table>
<thead>
<tr>
<th>Variable (Unit)</th>
<th>Distribution/Formula</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usage life (days)</td>
<td>Uniform(2555.0,5475.0)</td>
<td>4009.28</td>
<td>848.60</td>
</tr>
<tr>
<td>Distance (km)</td>
<td>Triang(25, 50, 100)</td>
<td>58.15</td>
<td>15.62</td>
</tr>
<tr>
<td>Disassembly time (hour)</td>
<td>Normal(0.5, 0.25, Truncate(0,+Inf ))</td>
<td>0.51</td>
<td>0.23</td>
</tr>
<tr>
<td>Cleaning &amp; Sorting time (hour)</td>
<td>Normal(0.1667, 0.01667, Truncate(0,+Inf ))</td>
<td>0.1668</td>
<td>0.0167</td>
</tr>
<tr>
<td>Testing &amp; Inspection time (hour)</td>
<td>Normal(0.1667, 0.01667, Truncate(0,+Inf ))</td>
<td>0.1668</td>
<td>0.0167</td>
</tr>
</tbody>
</table>

D. Results and Analysis

Basically, the assessment model is used to evaluate the technical and economic feasibility for reusing the old components. The technical feasibility is represented by the value of PE at the end of the first life cycle. The partial economic evaluation is represented by the value of PLCC. However the overall evaluation is represented by the ΔPG value.

Fig. 3 plots the mean, minimum, and maximum values of PE for all components compared to the threshold value of 0.9. The variation of technical feasibility is clearly shown in the graph. In summary, the results show that 11 components, 48% of total components, have the technical potential for reuse, while 12 components, 52% of the total components, cannot be reused. Among the reusable components, 64% can be 100% reused under the simulation scenario.

The results show that under the simulation scenario, the components listed in the first column of Table VII can be 100% reused, while the components listed in the second column cannot be reused at all. The third column consists of components that have some potential for reuse. For instance, under the simulation scenario, from disposed televisions, 43.14% of transistor can be reused, while only 19.99% of Panel Work Board (PWB) can be reused.

For a total evaluation of components, that is both technical and economic evaluation, a comparison of PG for new components and old components is demonstrated in Fig. 4. It shows that most of the components in TV have potential for reuse. This conclusion is confirmed by the value of ΔPG represented in Fig. 5.

As suggested by the model, a positive value of ΔPG indicates the potential for reuse, while a negative value points toward infeasibility for reuse. Therefore in Fig. 5, a threshold of zero is highlighted to show the position of ΔPG.

By looking at the distribution of ΔPG for each component, a further investigation has been carried out to find the likelihood of reusing each component under the simulation scenario. The results are shown in Table VIII. Out of 23, 8 components can be 100% reused, while 9 components have no potential for reuse. Six components are in the middle, meaning that they have potential for reuse but cannot be 100% justified as reusable. For the IC, as an example, only 68.21% of the disposed IC can be reused.
The sensitivity analysis reveals that the reliability of components at the end of the first life and the related reprocessing cost become the main drivers for all components that are not feasible for reuse. Other cost factors only have little influence toward the decision. This is reasonable since the collection process is done through a pooling system that greatly reduces the uncertainty of transportation cost.

TABLE VIII. TECHNICAL AND ECONOMIC FEASIBILITY

<table>
<thead>
<tr>
<th>Component ID</th>
<th>100%</th>
<th>50%</th>
<th>0%</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABL FBT</td>
<td>100%</td>
<td>99.99%</td>
<td>99.99%</td>
<td>Transistor</td>
</tr>
<tr>
<td>CRT Capacitor</td>
<td>99%</td>
<td>68.21%</td>
<td>4%</td>
<td>IC</td>
</tr>
<tr>
<td>DY STR</td>
<td>53.30%</td>
<td>53.30%</td>
<td>53.30%</td>
<td>PWB</td>
</tr>
<tr>
<td>Fuse Speaker</td>
<td>34.72%</td>
<td>34.72%</td>
<td>34.72%</td>
<td>Resistor</td>
</tr>
<tr>
<td>Power Cord Antenna</td>
<td>25.49%</td>
<td>25.49%</td>
<td>25.49%</td>
<td>Relay</td>
</tr>
<tr>
<td>Tuner Remote Control</td>
<td>0.69%</td>
<td>0.69%</td>
<td>0.69%</td>
<td>Touch Switch</td>
</tr>
<tr>
<td>Connector Manual</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Diode Casing</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Power Supply</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
</tr>
</tbody>
</table>

V. DIRECTIONS FOR FURTHER RESEARCH

The development and use of the assessment model points out some areas that may require further research in the future, as follows:

- The integration of environmental costs into the model in order to obtain a more complete evaluation. The environmental costs could be simulated along with other factors to provide a better understanding of the implementation of reuse.

- The current model only addresses the possibility of reusing old components for a similar application in the future. For example, components from analog televisions are assessed to be reused in other analog televisions. In other words, the effect of technological change is overlooked in the current model. Therefore, a future research should attempt to incorporate technological advancement into the model.

- The product effectiveness, PE, in the current model is taken to be equivalent to the reliability of each component at the end of the first lifetime. This is essentially a reflection of its physical lifetime, or what is left of its useful life from a functional standpoint. There is another important aspect of ‘reality’ that has not been addressed in this current model: many products are rejected for one reason or another even before its lifetime is over. The current model must find a way to incorporate this so-called ‘value lifetime’ into its developmental framework [8].

VI. CONCLUSIONS

The model described in this paper provides a useful tool to decide upon the potential of reuse of components at the end of their life. Although the result may be somewhat different depending on the assumptions made, the model is able to provide a reasonable basis for decision making. Absolute costing figures are not essential for this purpose since they are used for comparison only. The use of simulation significantly enhances the understanding of the impacts of the contributing factors or parameters in the model.

The implementation of the model in the case of an electronic device like a television shows that there is a potential for parts reuse. This finding should be used as a basis for further research toward the attainment of the reuse of television parts.

Including the environmental cost in the model can only increase the positive component of Δ PG, thus making Δ PG even more positive. Therefore, although in this model the environmental cost is set to zero, the model can be used in an economy driven environment, but still indicating the environmental friendliness of a component.

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