Components’ Rejuvenation in Production with Reused Elements

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Abstract: Recapturing value from used goods and wastes has recently become one of the companies’ key area of interest. Reusing of products can bring direct advantages because company uses recycled materials or recovered elements instead of expensive raw materials and new components. Reusing of products has become a factor of competitiveness for modern companies. This relates primarily to manufacturers who are obligated to collect their products, which have failed during warranty period. The main objective of this paper is to present models that allow to estimate cost-effectiveness of reusing the returned elements in new production.

Keywords: recovery, reuse, reliability, rejuvenation.

1. Introduction

Recapturing value from used goods and wastes has recently become one of the companies’ key area of interest. Reusing of products can bring direct advantages because company uses recycled materials or recovered elements instead of expensive raw materials and new components. Reusing of products has become a factor of competitiveness for modern companies. This relates primarily to manufacturers who are obligated to collect their products, which have failed during warranty period.

The main objective of this paper is to present models that allow to estimate cost-effectiveness of reusing the returned elements in new production. Presented models take into account various forms of recovery through the possibility of components’ rejuvenation. The paper focuses on the rejuvenation opportunity in production with reused elements. It presents the cost model of the reusing policy, the models allowing to estimate the probability of reusable element return and the expected age of returns. This models are necessary to build the cost model and to develop it into model considering the profitability of returned elements’ rejuvenation. The chosen results coming from each model are presented together with their brief analysis.

The first part of the paper contains literature survey, which is a summary of work that has been done around the theme of research.

2. Literature Survey

Based on the studied literature [e.g., 1, 3, 21] it is possible to define the article area of interest, which includes the following products:

1. Returns from the inside of the company: surplus raw materials, defective products rejected by quality control, by-products and wastes;
2. Returns from distribution phase: damaged or unsold products, excess inventory;
3. Returns from final user: parts replaced during the maintenance process, products that fail during warranty period which repair was impossible and other and waste.

Based on the classification presented in [21] it is possible to specify the following types of recovery: direct reuse/resale, repair, refurbish, remanufacturing, cannibalization, recycling. Description of the different recovery options was presented in [3, 5, 21]. Cannibalism has been described in [2, 8, 19, 20].

The problem of the design of products suitable for the recovery has been widely discussed in the literature, for example in the following articles [9, 10, 13].

Forecasting the number of returns is also an important part of planning the production process and recovery. In papers [16-18] authors present reliability based model of planning the production process. They also use reliability theory to predict how many returns can be reused. In the literature one can also find the other models describing the planning and implementation of production and the recovery processes (eg, [1, 4, 6, 7]). Review of the literature relating to production planning systems that use remanufacturing as the method of recovery are shown in [14].

In the literature one is also possible to identify other areas of interest of scientists. In [22 the authors analyze the impact of the quality of the returned products on the costs of recovery processes. In [15] the authors convince the reader of the benefits of shortening product life cycle.

Literature review that have been done so far allowed to define the main shortages of existing models:

1. most of models assume single-component product and they are usually based on the assumption that recovered products are as good as new ones,
2. very few models use reliability theory to optimize manufacturing and the threshold age of returns, but none of them gives any guidelines what kind of recovery technology or method should be applied,
3. there is a lack of models that allow to estimate cost-effectiveness of reusing policy.

3. Assumptions

On the basis of literature overview the aims of the paper were established. It proposes the model based on the several assumptions:

1. A company produces an object composed of two elements (A and B) being in the series reliability structure, thus every element failure causes a failure of the whole object.
2. Components’ failures are independent on one another.
3. If the product fails during the warranty period, it is returned to the manufacturer who is obliged to pay some penalty cost (e.g., the cost of a new product).
4. A returned component may be reused in a new product if it is upstate after return and was not reused before (the second reusing is not allowable). Thus, every return capable to further work may be: reused without any activities, recovered in order to improve its condition with an additional cost or disposed.
5. Reliability functions of the two components are known.

4. Notation

\( F_1(t) \) – the unreliability function of a product containing a reused component,
\( F_2(t) \) – the unreliability function of a product comprised of all new elements,
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\[ C_{A,B} \] – the cost of a new element purchasing, respectively A or B,
\[ C_M \] – the cost of element indication before reusing,
\[ C_O \] – the expected cost of claims resulting from lower reliability of the product in the warranty period,
\[ c_o \] – the unit cost of a product failure during warranty period incurred by the manufacturer,
\[ C_R \] – the total cost of all activities including additional recovery operations: decomposition, cleaning, preparing returned element to reusing in a new production,
\[ f_{A,B}(t) \] – pdf of the time to failure respectively of A or B element.
\[ E_R(T_{A,B}) \] – the expected age of returned A or B element,
\[ P_{A,B}(T_W) \] – the probability that a reusable element (A or B) will return to a manufacturing system during warranty period,
\[ R_{A,B}(t) \] – reliability function of A or B component in t moment,
\[ T \] – the age of a returned element,
\[ \Delta T \] – the period, by which the item will be rejuvenated by additional recovery operations,
\[ T_W \] – the length of a warranty period of the object,
\[ Z(T, \Delta T, T_W) \] – the total expected profit resulting from the components’ reusing,

5. Cost Model of the Reusing Policy

A producer who is obliged to collect his products, which have failed during warranty period, should look for potential benefits that may result from the fact. Returned products may be a new, alternative source of components to be used in a future production. To indicate if the returns may be reused, a producer should estimate the expected profit resulting from using mix of new and old elements instead of the new ones [12]:

\[ Z(T, \Delta T, T_W) = C_B - C_R(T, \Delta T) - C_M - C_O(T, \Delta T, T_W), \] \quad (1)
\[ C_O(T, \Delta T, T_W) = c_o[F_1(T, \Delta T, T_W) - F_2(T_W)], \] \quad (2)

The formula 1 presents the cost model, estimating the expected profit resulting from the reusing policy, i.e., from the fact that a more expensive new elements may be replaced by the older one, coming from a product returned from the market. This reusing policy has a point under one basic condition, that the expected cost of additional activities (cleaning, rejuvenating, indicating) and the cost of lower reliability of a reused component will be lower than the cost of purchasing of a new element.

The basic problem when one wants to assess benefits of the reusing policy is to estimate these costs, especially the cost of lower reliability of the reused element or the cost of rejuvenation of return, if there is such opportunity. It requires some additional models allowing to estimate basic parameters influencing on these costs, are proposed in the next part of the paper.

6. The Age of Reusable Components

The profitability analysis of various options of the reusing policy requires to know or assume all the parameters of the policy. Most of them are decision variables of a producer or depends on market environment, e.g., warranty period length, cost components, etc. They may be determined more or less precisely. The hardest to estimate are parameters pertaining to reliability characteristics of manufactured product components. Moreover, in combination with warranty features, they have direct impact on the number and the age of reusable returns and thus – on the efficiency of the reusing policy.
Undoubtedly the fact whether reusable components appear in a manufacturing system is the key factor for potential of a reusing policy application. The probability of such event may be estimated on the foundation of manufactured product reliability resulting from individual features of its components and their reliability dependence. The third important factor, which has a great influence on the accessibility of reusable components in a manufacturing system is the warranty period length.

The probability that a reusable element will return to a manufacturing system during a warranty period may be expressed as follows:

\[ P(T_W) = \int_0^{T_W} f_A(t) \cdot R_B(t) \cdot dt, \quad (3) \]

According to the equation 3 the reusable element B may appear in a manufacturing system under two conditions:
1. its co-component (A in this case) has failed during a warranty period (series reliability structure),
2. element B is still upstate at the moment of A element failure.

For simplicity in the further parts for the paper only component B is considered as reusable. The model is identical for its co-component (A).

The probability \( P(T_W) \) may be used to estimate the next key factor of the reusing policy – the expected age of reusable returns:

\[ \mathbb{E}_R(T_B) = \int_0^{T_W} t \cdot f_A(t) \cdot R_B(t) \cdot dt, \quad (4) \]

The formulae 4 indicates the expected age of the B components assuming that the probability of their return during a warranty period is equal zero:
1. for products whose lifetime is longer than the warranty (element B is not returned),
2. for products returned because of a failure of the B element (element B is downstate and cannot be reused).

For this reason to assess the expected age of returned, reusable components the formulae 4 should be developed to be conditional:

\[ \mathbb{E}_R(T_B) = \int_0^{T_W} t \cdot f_A(t) \cdot R_B(t) \cdot dt \int_0^{T_W} f_A(t) \cdot R_B(t) \cdot dt, \quad (5) \]

The model given in the equation 5 estimates the expected age of the return under condition that it has returned during a warranty period. In practice, this age should be taken into consideration when one assesses the profitability of the reusing policy. In the further parts of the paper the age calculated according to the formula is used.

7. Sensitivity Analysis of the Expected Age of Returns

Results of the formulas 3-5 has been checked for the sake of their convergence with the results obtained using a simple Monte Carlo simulation. The convergence of chosen results are depicted in figures 1-3. The pictures also present a short sensitivity analysis of the factors having the greatest influence on the expected age \( \mathbb{E}_R(T_B) \) and the probability \( P(T_W) \).
Figure 1: The expected age of returned B element for a range of warranty period length \( T_w \) and various MMTF of the returned, reusable B component \( (E(B)) \), \( E(A) = \text{const} = 100 \).

Figure 2: The expected age of returned B element for a range of warranty period length \( T_w \) and various MMTF of the B co-component A \( (E(A)) \), \( E(B) = \text{const} = 500 \).

Figure 3: The probability \( P(T_w) \) for a range of warranty period length \( T_w \) and various MMTF of the B co-component A \( (E(A)) \), \( E(B) = \text{const} = 500 \)

Figures 1-3 shows the convergence between results obtained according to the formulas presented in the paper and Monte Carlo simulation. Moreover, chosen examples presents the influence of a few, most important parameters on the expected age of returns and the probability of return. All the figures prove a strong relation between returns’ characteristics and a length warranty period. The shorter time when product may be returned has an effect in lower probability of return as well as younger elements to reuse (gray circles).

The figures also allow drawing the conclusion on the influence of the mean time to failure (MTTF) of the reusable element (B) and its co-component (A in this case) on the expected age of returns. Independently on the MTTF of the B component, its expected age when it returns from the market is the same, but the change of MTTF of A component has a strong impact on return characteristics (black circles). Longer time to failure of the A component causes that returned elements B are older than in the case of short lifetime of the element A.

8. Profitability of the Reusing Policy

On the base of the above presented models one may estimate the potential of the reusing policy. The aim of this part of the paper is to present a short sensitivity analysis of costs
and profits resulting from the reusing policy, estimated on the base of the expected age of reusable component.

The Figures 4, 5 depict the probability that during the next warranty period after reusing component B will be a cause of a product failure. There are presented two cases – both elements A and B are new in a product and new element A is combined with a reused element B. In contrast to the previously observed relationships, the increase of the element B unreliability in a product depends mainly on: a length of a warranty period and MTTF of the B component (Fig. 5). It is worth to notice that for very long TW and short MTTF of the B component (Fig. 5 – black circle), the reliability of a product does not change and reaches value of zero.

**Figure 4:** The difference (dF) between unreliability of new and reused element during the next warranty period after reusing for a range of warranty period length (TW) and various MTTF of the B co-component A (E(A)), (E(B) = const = 500)

**Figure 5:** The difference (dF) between unreliability of new and reused element during the next warranty period after reusing for a range of warranty period length (TW) and various MTTF of the returned, reusable B component (E(TB)), (E(A) = const = 100).

**Figure 6:** The total expected profit resulting from the components’ reusing for a range of warranty period length (TW) and various MTTF of the B co-component A (E(A)), (E(B) = const = 500, C_B = 200, C_R = 0, c_o = 1000, C_M = 1)

**Figure 7:** The total expected profit resulting from the components’ reusing for a range of warranty period length (TW) and various MTTF of the returned, reusable B component (E(TB)), E(A) = const = 100, C_B = 200, C_R = 0, c_o = 1000, C_M = 1).

The cost effects of the reusing policy, including the cost of the unreliability increase, is presented in Figures 6, 7. For the assumed parameters one may observe a great variation of the cost results. The figure 6 presents the total profit of the reusing policy for some range of TW and MTTF of A element (not reusable). Shorter warranty periods makes the reusing policy more profitable, because of the low reliability decrease and high probability that a reused element will survive the period. On the other hand longer MTTF
of the A component together with a longer warranty period (black circle in Fig. 6) makes the policy quite unprofitable, because of the higher difference between reliability of a new and reused component B.

The Figure 7 depicts the profitability results of the reusing policy for various lengths of a warranty period and MTTF of the reusable, B component. The area indicated in the black circle seems to be very profitable, but in practice it reflects zero-reliability case, which may be noticed in the figure 5 and represents the cases when the reusing policy is not possible to apply (too short MTTF of an element).

9. The Rejuvenation of Returns

The aim of the last part of the paper is present the model considering possibility of rejuvenation and present its exemplary results.

The cost model of the reusing policy (Eq. 1) assumes the two cost components are directly combined with recovery options of reusable returns: the cost of recovery operations and the expected cost of increased product unreliability during the next warranty period of a product. The relationship between them is inversely proportional, but not necessarily linear and continuous. The first cost component depends only on the range of recovery operations and is some function of the period by which the item will may be rejuvenated ($\Delta T$). The second – the cost of increased reliability depends on the same factor ($\Delta T$), the age of retuned component and a length of a warranty period.

In order to increase the profitability of the reusing policy, sometimes a manufacturer may execute activities, which will improve the state of a reusable component. These maintenance actions may “rejuvenate” the element to decrease the probability of its failure in a next warranty period. The unreliability function of a product in the case of rejuvenating may be calculated as follows [11]:

$$R_B(T, \Delta T, T_W) = \frac{R_B(T-\Delta T+T_W)}{R_B(T-\Delta T)} \quad (6)$$

The model 6 may be now included in the profitability model. For the limited space of the paper only one chosen result of the reusing profitability with elements rejuvenation is presented in the Figure 8. The research has been conducted for the same cost values as in the previous cases, except the unit cost of preparing of the returned element to reusing in a new production: $CR(\Delta T=1) = 1$.

**Figure 8:** The total expected profit resulting from the components’ reusing for a range of warranty period length ($T_W$) and various periods by which the returned, reusable B component is rejuvenated ($dT$), $E(A) = 100$, $E(B) = 500$, $C_B = 200$, $C_R = 1$, $c_o = 1000$, $C_M = 1$).
The reusing policy is profitable for all the tasted cases of warranty periods and rejuvenation possibilities, for the assumed unit cost. The best results are visible when warranty period is very short ($T_W = 50$). Then, the rejuvenating is not profitable and the total profit increases when a period of rejuvenation increases (black circle). On the other hand when a warranty period becomes longer and is close to the MTTF of a returned element (gray circle), rejuvenation is very profitable.

10. Conclusions

The reusing policy applied in production processes reflect the current drive of manufacturers to search new methods of cost reduction as well as customers to use eco-friendly products. The policy has a great potential, which has been started to explore nowadays. However, the reusing policy, as any other economy strategy, should be carefully examined whether is profitable or not for given market conditions. The paper is the one of the few from the area, where authors try to model various variants of the reusing policy using reliability theory.

The paper focuses on the components’ rejuvenation opportunity in production with reused elements. It presents the cost model of the reusing policy, the models allowing to estimate the probability of reusable element return and the expected age of returns. The models are necessary to include it in the cost model and to develop it into model considering the profitability of returned elements’ rejuvenation. The chosen results coming from every model are presented together with their brief analysis.

The basic conclusions, which may be drown from the analysis pertain the costs of the reusing policy. The basic cost that determines the policy effects is usually the cost of lower reliability of product containing reused element. However, it strongly depends on the relation of the length of a warranty period, reliability characteristics (e.g., MTTF) and the age of a component, which may be reused. When the relation between them is unprofitable, it is worth to consider an opportunity to rejuvenate the reusable element. The additional fact that should be emphasized is a great influence of a co-component’s lifetime on the probability of return and its expected age. Thus, when two cooperating elements have similar reliability characteristics, the reusing policy is little profitable.

References

[8]. Hirsch, W. M., M. Meissner and C. Boll. Cannibalization in Multi-component System and the


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