Treatment of Reliability for Reuse and Remanufacture

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Abstract

Summarized are approaches addressing reliability in reuse (without repair) and remanufacture.

To support the design of a product whose life cycle involves reuse without repair, two types of reliability data (time to failure and quality-deterioration data) were used in the simulation of the material flow during the life cycle. For management of material flow, reliability models were developed and applied to predict quantities of returned products and reusable components for each time period. The predicted results can be used for production planning in manufacturing firms using reusable parts as well as new parts.

A reliability model was developed and validated to better describe populations of systems that undergo repairs performed during remanufacture or maintenance. Remanufacturer waste streams of several products were analyzed to reveal remanufacture difficulties. A modified FMEA uses the results of waste-stream analyses and considers ease of detection and repair of failure in conjunction with waste-stream contribution of failure modes in design for remanufacture.

1. Introduction

Take-back legislation and public awareness concerning the environment have caused manufacturers to undertake efforts in recycling and reuse. Depending on product type, manufacturers choose between methods of recycling and reuse including material recycling, thermal recycling, reuse without repair, and remanufacture. Reuse without repair and remanufacture are environmentally and economically superior to the other methods. Therefore, much attention by manufacturers and academics is directed toward reuse without repair and remanufacture. In both remanufacture and reuse without repair, the reliability of components is important since the essential goal is part reuse. In this paper, we summarize several approaches we have taken to treat reliability in the context of reuse without repair and remanufacture.

2. Reliability for reuse without repair

The following two sections summarize approaches that address reliability in the context of reuse without repair.

2.1. Reliability model for material-flow simulation

To perform recycling and reuse, manufacturers must design appropriate products' life cycles and supply chains involving product recovery and disassembly. A simulation-based approach was proposed for this purpose [1-3]. This approach uses colored petri nets to model and simulate the flow of materials (i.e., products, subassemblies, parts, raw materials, regenerated materials, wastes, etc.), money flow and their control throughout a product's life cycle. In this approach, two types of reliability data (time to failure and quality-deterioration data) of components are used during the simulation.

Time to failure is assigned to each part by generating exponential or Weibull random numbers when the part is newly produced in the simulation. The exponential or Weibull distribution for generating the random numbers differs from one type of part to another. The time to failure of a product is calculated by using the times to failure of its components and assigned to the product as its attribute. The relationship between the time to failure of a product and those of its components depends on the type of the reliability system (e.g., parallel, series, and m/n systems) for the product.

The times to failure are used mainly in the simulation of usage and end-of-life stages. The time to failure of a product is used to constantly check whether the product fails during the simulation of usage stage. The time to failure of a part is used to judge whether the part included in a disposed product can be reused. In this study, it is assumed that a part can be reused if its residual life (i.e., the time to failure – the period that the part has been used for) surpasses a threshold value.

In addition to the times to failure, material qualities (e.g., purity and strength) are given to each part. In some cases, instead of time to failure, material quality is used to judge whether a part can be reused. Either time to failure or material quality is chosen for the decision, depending on the part type and material. Material qualities may also be used as criteria for choosing other end-of life options (i.e., material recycling, thermal recycling, and disposal to landfill). Some of the material qualities are selected and assigned to a part, depending on the type of the material and/or its usage purpose. This study takes account of the deterioration in the material qualities during product usage. Deterioration models, which differ from one type of deterioration to another, are used for the simulation of the deterioration. This study also considers the deterioration occurring at recycling stages. In this deterioration, a certain value is subtracted from a material quality every time the material is recycled. When virgin and regenerated materials are mixed, the material qualities of the mixed material are determined according to the mixing ratio.

The simulation using the two types of reliability data can reveal the relationship between the reliability of parts and environmental impact, including waste and natural-resource-depletion issues. The simulation also enables us to examine how the reliability affects the economical aspect (i.e., cost, benefit, and profitability) of the life cycle of a product.

2.2. Reliability model for production management

In addition to the design of a life cycle, management of material flow is important to reuse. However, the following issues make the management difficult:

1. The timings and quantities of returned products and reusable components are unknown.
2. The condition of returned products is unknown until they are disassembled and inspected.

A production management method that addresses the first issue was proposed [4]. This method first predicts the quantities of returned products and reusable components at each time period by using reliability models. Using the predicted results, the method performs production planning based on Material Requirement Planning (MRP). In this section, the prediction method based on reliability models is summarized.

This prediction method assumes the following:

A1. Products are used until they fail.
A2. Products are returned as soon as they fail.
A3. A component can be reused if its residual life surpasses a threshold value.
A4. Components are neither repaired nor refurbished. Therefore the residual lives of components cannot be lengthened.
A5. The failure of each component occurs independently of other components' failures.
A6. Components cannot be reused more than two times.
A7. The past demand of a product is known and/or its future demand is forecasted.

To predict the quantity of returned products, this method uses the probability that a product purchased at time t fails in the interval between ta and tb, $P_{ta-tb}(t)$, which is described by:

$$P_{ta-tb}(t) = F(tb-t-tu) - F(ta-t-tu) \tag{1}$$

where $F(t)$ is the probability of failure before t, and tu is the mean time from the time when a product is purchased to the time when the product starts to be used. $F(t)$ differs from one product structure to another.

Using the probability, the quantity of returned products that fail in the interval between ta and tb, N_{ta-tb}, is predicted by:

$$N_{ta-tb} = \int_0^{ta-tu} \left\{ d(t) \cdot P_{ta-tb}(t) \right\} dt \tag{2}$$

where $d(t)$ is the density function of the demand, which satisfies the following equation.

$$D_j = \int_{(j-1)r}^{jr} d(t)dt \tag{3}$$

where D_j is the demand of the product at time period j and r is a length of one time period such as one week.

Similarly to the equation (2), the quantity of reusable component Ci (i=1, 2, …) included in the products that fail in the interval between ta and tb is described by:

$$N_{ta-tb}^{Ci} = \int_0^{ta-tu} \left\{ d(t) \cdot P_{ta-tb}^{Ci}(t) \right\} dt \tag{4}$$

where $P_{ta-tb}^{Ci}(t)$ is the probability that a product purchased at time t fails in the interval between ta and tb but component Ci (i=1,2,…) included in the product can be reused. $P_{ta-tb}^{Ci}(t)$ differs from one product structure to another. For example, if a product is a series system composed of two components $C1$ and $C2$, $P_{ta-tb}^{C1}(t)$ is as follows:

$$P_{ta-tb}^{C1}(t) = \int_{ta-tu-t}^{tb-tu-t} \left(f_2(tz) \cdot (1 - \int_0^{tz+tr} f_1(l)dl) \right) dtz \tag{5}$$

where $f_i(t)$ (i=1, 2) is the failure probability density function of component Ci and tr is a threshold value of residual life. This equation means that a product fails by the failure of component $C2$, which occurs in the interval between ta and $tb,$ while component $C1$ has been working and its residual life is more than tr. If a product includes some other types of subsystems (e.g., parallel or m/n subsystem), the equation representing the relationship between $P_{ta-tb}^{Ci}(t)$ and $f_i(t)$ (i=1, 2,…) becomes more complex. An example of the equation for a product including a parallel subsystem was shown in [4].

3. Reliability in remanufacture

In the next three sections, approaches that address reliability in the context of remanufacture are summarized.

3.1. Reliability modeling for remanufacture

Remanufacture involves the production-batch disassembly, cleaning, repair or replacement of parts, and reassembly of products for reuse. Since the essential goal of remanufacture is part reuse [5], the reliability of components is important. A reliability model was developed to better describe populations of systems that undergo repairs performed during remanufacture or maintenance [6].

Different from many other system reliability models, this model describes repair during remanufacture or maintenance as leaving the system in neither same-as-new nor same-as-old states. Furthermore, this model allows system modification, in which failed parts are replaced with components with different failure characteristics. This feature more accurately portrays many instances of component replacement during remanufacture or maintenance, but is not accommodated in many previously existing reliability models. Replacement components may have different failure properties from the original components because of different suppliers of replacement parts, system upgrade or reconfiguration, or installation conditions during remanufacture or maintenance that are different from original manufacture.

The model represents a population of systems as a collection of populations of the constituent components. Part failure can result in replacement of the part with a component of the same or different type, or in replacement of the system. When only a portion of the system is replaced, the remaining parts of the system either remain unchanged or are reconfigured to accommodate the replacement component. The age distribution of each part population determines the failure characteristics of the corresponding part. The model describes series systems in which the components have densities of time to failure that can be represented by the two-parameter Weibull distribution.

The basic model behavior simulates replacement of failed parts with components of the same type; this fundamental behavior was experimentally validated. Simulations of the common practice in remanufacture to replace failed parts with components of a different type were then performed. Reliability theory necessary to predict system failure from the failure characteristics of the constituent parts in series was outlined. Finally, the model was applied to a mechanical series system to compare life-cycle costs of various combinations of component selection.

Jiang et al. [7] investigated the stochastic behavior of the reliability model for repairable systems subject to system modifications. The steady-state behavior of the model was studied and expressions for reliability indices at steady state were derived. Two different repair policies were considered: the perfectly maintained, where failed parts are replaced as soon as the failure occurs, and the discretely maintained, where replacements are made at predetermined times. Under both policies, the theoretical analyses performed support simulation results, showing that population average age and replacement rate reach steady state. During steady state, the model behaves like a Homogeneous Poisson Process with a constant replacement rate. Explicit expressions of reliability indices of the system at steady state were obtained. Finally, an example in the tire-retreading industry illustrated application of the model.

Jiang et al. [8] modified the reliability model to accommodate population-size changes and validated the model using failure data from industry. Size changes to a population of parts were classified as pulse disturbances or continuous disturbances. For pulse disturbances, it was shown that the replacement rate experiences a transient behavior but eventually reaches steady state. For continuous disturbances, it was shown that the steady-state value of replacement rate varies but is centered at the steady-state value for the corresponding constant-size population. Furthermore, the time duration between size variations has little influence on the centerline of the replacement rate.

Actual failure data, collected from a part population replacement process under continuous disturbance, were analyzed. Using a counting process, the replacement rate was calculated. The failure density function for the part population was obtained through curve fitting. This failure density function was then used to simulate the corresponding replacement process to compare to the failure data. Comparison of actual data to simulation results showed that the reliability model for a part population replacement process under continuous disturbance could be used to approximate an actual replacement process.

3.2. Analyses of remanufacturer waste streams

Parts that cannot be reused by the remanufacturer enter the waste stream, examination of which reveals insights about remanufacture difficulties. The remanufacturer waste streams of electrical motors, toner cartridges, valves and telephones were analyzed to support product design that facilitates remanufacture [9, 10]. The results of this research were presented in a format that allows a designer to determine the relevance of the products studied to products being designed.

Lund identified the top product sectors by number of remanufacturers as automotive aftermarket parts, electrical apparatus (transformers, motors, switch gear), toner cartridges and retreaded tires [11]. The waste stream of automotive remanufacturers was described in [12, 13]. [10] includes the next two largest product sectors, electrical motors and laser-printer toner cartridges. Two other product sectors with remanufacturers in the Toronto area, valves and telephones, were also studied. Data was grouped into five categories according to similarity in product type and remanufacture process: 1 - toner cartridges at large companies, 2 - toner cartridges at small companies, 3 - electrical motors, 4 – telephones, and 5 - valves. Data from large and small toner-cartridge remanufacturers were kept separate due to processing differences. The large company had more automated, assembly-line processes. At the small companies, one operator often performed all processes on a core.

Cores with features that prevent remanufacture are discarded from the remanufacturing process and enter the waste stream. The discarded material, or waste stream, of the remanufacturer is quantified by part count and weight. In addition to part count and weight, the reason for discard of each piece of waste sampled was also recorded. As might be expected, many of the discard reasons involve physical damage to the cores. These were grouped as Product. However, through discussion with the remanufacturing technicians and observation of the process, discard reasons involving the execution of the process were also found. These are called Technique. Additionally, the remanufacturers identified issues outside of their control. For example, market changes and legal issues were grouped as Other. Lastly, there are cores for which no discard reason could be identified. These are grouped as Unknown.

The discard reasons are the obstacles preventing the core from being remanufactured. From a design perspective, it is useful to identify the condition that allowed the obstacle to occur. This information, the root cause of the discard reason, guides designers to avoid problem features in their designs and, further, to incorporate features to promote remanufacturing. Each discard reason is examined to determine a probable root cause. Some root causes are common to all products and are easily generalized to products outside of this study. Other root causes may only be found in one product or data set, however, where it is related to a particular product attribute, it may also be generalized to other products having that attribute. Root causes were grouped into the following four categories: Issues Involving Multiple Influences, Remanufacturing Steps, Working Environment, and Specific Design Features.

The root causes were related to the discard reasons in four tables that correspond to each root-cause group identified above. The first table included root causes that are influenced by many sources where product design may or may not play a role. As this table involves many different stakeholders, it may contain issues over which designers have the least control. The second table contained root causes involving problems with the execution of particular remanufacturing steps, specifically disassembly, assembly and refurbishment. This table may be used to set goals for the product. For example, identifying the goal that the product must be disassemblable for reuse allows the designer to decide how to accomplish this goal. The third table contained root causes relating to a damaging condition in the regular working environment of a product, which the designer should have already considered. This table may serve to emphasize that some of these existing conditions may also be problematic for remanufacturing. The fourth table included root causes tied to the presence of particular design features. This table is specific and prescriptive and is probably the most straightforward to apply. The table indicates where a particular feature causes a particular problem for a particular product.

These tables may serve as reference guides for designers to avoid potential remanufacturing difficulties caused by their product design. In each table, the root causes are in columns, and the discard reasons are rows. A five-sectioned pentagon symbol in the tables contains the proportion of a product waste stream identified with a particular root cause; each section of the pentagon corresponds to one of the five data groups previously identified. Each entry in the table may be read as follows: Problems with column heading causes % of discards in product due to row heading. For example, one entry represents “Problems with Choice of Light Color” causes 18% of discards in “Phones” due to “Discoloration.” Designers would determine the similarity between their products and the ones in this study for applicability of discard reasons and root causes. For example, telephones have a plastic body and are used in the home and office where aesthetics are important. Therefore, discoloration may be a consideration in other plastic products used in the home or office. Also, the proportions of each discard reason may be used to set priorities. Tables by both part count and weight were developed. With this information, designers may be able to avoid obstacles to remanufacturing in their design and facilitate the remanufacturing of their product.

3.3. Failure modes and effects analysis modified for remanufacture

A Failure Modes and Effects Analysis (FMEA) was modified to support design for remanufacture [13,14]. The results of the waste-stream analysis of an automotive remanufacturer were used for this FMEA. The remanufacturer waste stream was assessed to determine factors that impede the reuse of parts. The use of the modified FMEA allows consideration of factors such as ease of detection and repair of failure, in conjunction with contribution to the waste stream of each failure mode, to develop priorities in design for remanufacture.

Derivation of FMEA Indices

Occurrence

The percentages of each part type entering the waste stream were categorized into the different failure modes. The probability that a part entering the waste stream has a particular failure mode is relevant to the FMEA index of occurrence (OCC). These probabilities were used to derive the OCC index as follows. The largest probability is assigned an OCC value of 10, while the smallest probability is assigned an OCC value of 1. All other probabilities were normalized to these two extremes to obtain corresponding values for OCC.

Detectability

The next FMEA index of interest is DET or detectability. This study related detectability to the point in the remanufacture process that a failure is detected. For example, it is far better that a crack is detected at disassembly, so that an immediate decision can be made whether the crack is repairable and if so, by which processes, than if that same crack were not detected until final assembly. Therefore, the later the detection, the higher the value of the DET index.

Parts were first analyzed with respect to the processing sequence. Data on the percentage of failures detected at the various stations in the processing sequence were collected. The FMEA DET detectability index reflects the concept that the more parts for a particular failure mode that can be detected at an early stage, the better the detectability of that failure mode. Each processing stage is assigned with a weight, based on the location in the sequence. The weighting factors and percentages of parts detected at each stage were first multiplied together. Then, the weighted percentages of different stages were combined to obtain the overall weighted percentage. Finally, the overall weighted percentage is multiplied by 10 to obtain a DET index with a range up to 10.

Repairability

In the FMEA adapted for remanufacture, the severity index (SEV) has been renamed repairability (REP) to reflect the severity of a failure mode for a remanufacturer. Repairability reflects the degree to which parts are successfully repaired by the remanufacturer. Consistent with the index values for SEV, the higher the index for REP the lower the repairability. Data was collected on the proportion of parts that are repaired. The percentage of parts that is not repaired is used to derive the REP indices for failure modes.

Risk Priority Number

Finally, the risk priority numbers (RPN) for each failure mode are determined by finding the product of OCC, DET and REP. Product or process design that decreases the occurrence, detection or repairability indices for high-RPN failure modes would facilitate remanufacture by decreasing the portion of the waste stream that have these failure modes.

4. Summary

The goal of this work is to enable more efficient remanufacture and reuse of products through design and management.

To design a product's life cycle involving reuse without repair, a simulation-based approach was presented. In this approach, two types of reliability data (time to failure and quality-deterioration data) were used to simulate the material flow throughout a product's life cycle.

In addition to the design of a life cycle, the management of material flow through the life cycle is important to recycling and reuse. To manage material flow, reliability models were developed and used for the prediction of quantities of returned products and reusable components at each time period. The prediction results can be used for production planning in manufacturing firms using reusable parts as well as new parts.

Remanufacture involves the production-batch disassembly, cleaning, repair or replacement of parts, and reassembly of products for reuse.

Since the essential goal of remanufacture is part reuse, the reliability of components is important. A reliability model was developed to better describe populations of systems that undergo repairs performed during remanufacture or maintenance. This model allows replacement components to be of a type different from the original components, a common practice in remanufacture that is not accommodated in many previously existing reliability models. The behavior, analysis, modification to accommodate population-size changes, and validation of the model using failure data from industry were performed.

Parts that cannot be reused by the remanufacturer enter the waste stream, examination of which reveals insights about remanufacture difficulties. The remanufacturer waste streams of electrical motors, toner cartridges, valves and telephones were analyzed. The results of this research were presented in a format that allows a designer to determine the relevance of the products studied to products being designed. A Failure Modes and Effects Analysis (FMEA) was modified to support design for remanufacture and use the results of the waste-stream analysis of an automotive remanufacturer. Data gathered at the automotive remanufacturer were used to derive values for the indices of occurrence (OCC), detectability (DET) and repairability (REP) for an FMEA modified for remanufacture. The use of the modified FMEA allows consideration of factors such as ease of detection and repair of failure, in conjunction with contribution to the waste stream of each failure mode, to develop priorities in design for remanufacture. Product or process design that aims to reduce the Risk Priority Number (RPN) of the failure modes identified would facilitate remanufacture.

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