One-Dimensional Warranty Policies Analysis for Remanufactured Products in Reverse Supply Chain

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Abstract: This paper presents a non-renewable basic one-dimensional combination warranty policy analysis for an Advanced Remanufacturing-To-Order system for Sensor-embedded products (SEPs). The goal of the proposed approach is to determine how to predict a non-renewing one-dimensional Free Replacement and Pro-Rata combination warranty period for the disassembled components and remanufactured products using the sensor information about the age of every end-of-life (EOL) retrieve products on hand to meet remanufactured product and component demands while minimizing the cost associated with warranty and maximizing manufacturer's profit. Different simulation scenarios are explained and a case example is presented for illustration of the model applicability.

Key Words: Warranty Analysis, End-of-life, Remanufacturing, Sensor embedded products, Simulation, One-dimensional, Combination warranty.

1. Introduction

The accelerated rate of technology development and customers' desire for newer models are resulting in shorter product life cycles and an increase in rates of product disposal. As a result, landfill sites and natural resources are reaching a critical state, forcing governments to mandate tighter environmental regulations on manufacturers. When products are deemed no longer useful, firms reclaim them to fulfill the requirements of these new regulations, raising customers' awareness of environmental issues in the process. Special facilities created for product recovery minimize the amount of waste sent to landfills, as materials, parts, and components from the end-of-life (EOL) products pass through stages of retrieval, recycling, refurbishment, and remanufacturing. Additionally, the economic benefits from such facilities make product recovery an increasingly attractive option [14].

The chief concern in such product recovery processes is the uncertainty in quantity and quality of recoverable materials, due primarily to the lack of any information about the condition of components before disassembly. The obvious solution is to test every component after disassembling them. This, however, can harm the profitability of a remanufacturer depending on testing time and testing costs. Furthermore, if the test shows the component is non-functional, then all the allocated time and resources are wasted.

The quality of a remanufactured product is a concern for consumers. Therefore, the consumers are unsure if the remanufactured products will satisfy performance expectations. This ambiguity about a remanufactured product could lead the consumer to decide against buying it. With such apprehension held by consumers, remanufacturers often seek market mechanisms that provide assurance about the durability of the products. One strategy that remanufacturers often use is to offer warranties on their products. Warranty, by definition, is a contractual obligation incurred by a manufacturer (vendor/seller) in connection with the sale of a product. The purpose of warranty is to establish liability in the event of a premature failure of an item or the inability of the item to perform its intended function. The contract specifies the promised product performance and when it is not met, the redress available to the buyer as compensation. Product warranties have several major functions: First, as insurance and protection, permitting buyers to transfer the risk of product failure to sellers. Second, product warranties can also signal product reliability to customers. Finally, the sellers use warranties to extract additional profitability. There are a few articles and books that consider warranty policies for new products' supply chain management. None, however, consider warranty for the remanufactured products' reverse and closed-loop supply chain management.

The next section presents a literature review in relevant areas. Advanced Remanufacturing-To-Order system used in the study is stated in Section 3. Section 4 describes the Design-Of-Experiments study process. One-Dimensional Product Warranty is presented in Section 5. Notation and Formulation used in this study are discussed in Section
2. Literature Review

This section provides a literature review on the issues considered in this research. First, a brief review on environmentally conscious manufacturing and product recovery are presented. Then, discussion on smart sensor-embedded products studies is offered. Finally, brief discussion on product warranty.

2.1 Environmentally Conscious Manufacturing and Product Recovery

The number of studies dealing with the end-of-life (EOL) phase of a product has attracted a lot of attention from researchers [11],[17],[20]. This is due to environmental factors, government regulations and public demands, and then again, to potential economical profits that could be obtained by implementing reverse logistics and product recycling resolutions. Manufacturers try to deal with consumer awareness towards environmental concerns and stricter environmental regulations by building up facilities which involve the minimization of the amount of waste sent to landfills by recovering materials and components from returned or EOL products [12].

During product recovery, the disassembly process plays an important role since it allows for selective separation of desired parts and materials. EOL products consisting of missing and/or nonfunctional components raise the uncertainty factor associated with the disassembly yield. Sensor-embedded products (SEPs) eliminate most uncertainties involved with EOL management by providing life-cycle information [13],[29]. This includes information about the contents of each product and component conditions that enables the estimation of remaining useful life of the components. Once the data about the product is captured, it is possible to make optimal EOL decisions without any preliminary disassembly or inspection operations [16],[18],[19]. After the components are retrieved, the products can be remanufactured.

2.2 Smart Sensor Embedded Products

The expansion of technology has allowed manufacturer to build smart sensors in smaller sizes and lower cost. The acquisition of the essential life-cycle components of a product with smart sensor embedded is presented by Zeid et al.[31], Vadde et al.[30]. Other research aims to explore if the use of embedded sensors will improve the efficiency of product life-cycle management. A comprehensive survey on the commercial sensor systems used in health management for electronic products and systems done by Pecht [27]. Fang et al.[7] conducted another comprehensive survey about reviewed the current practices toward the development of embedded smart sensors in products in two primary aspects, namely, embedding smart sensors in products and representing and interpreting sensor data.

To provide easy access for retrieving, updating, and managing of information in the product life-cycle radio-frequency identification (RFID) tags have been Kiritsis et al.[21], Parlikad and McFarlane [26]. The practical and economic impact of using RFID in alleviating the quality uncertainty associated with the remanufacturing processes has been investigated by Kulkarni et al.[22]. Ferrer et al.[8] stated an application of RFIDs where active RFID can be used for easy identification and localization of components within a remanufacturing facility and passive RFID can be permanently tagged onto components of remanufacturable products at the beginning of their service life. The retrieved information from embedded smart sensors product has been studied in product EOL recovery processes decision making.

2.3 Product Warranty

The quality and reliability of a remanufactured product is a concern for the buyers. That is, the buyers are unsure if the remanufactured products will provide the anticipated performance. This opacity about a remanufactured product could point the consumer against buying it. With such apprehension held by buyers, remanufacturers often seek market mechanisms that provide assurance about the reliability of the products. One tactic that the remanufacturers often use is to offer warranties on their products [5],[6],[25]. Product warranties have different major functions. First is insurance and protection, permitting buyers to transfer the risk of product failure to sellers [15]. Then, product warranties can also signal product reliability to customers [4],[9],[28]. Finally, the sellers use warranties to extract additional profitability [24]. There are a few articles and books that consider warranty policies for new products’ supply chain management. There are only a handful of papers that consider the warranty for remanufactured products’ reverse and closed-loop supply chain management [1] [3]. Modeling and analyzing the warranty cost for used product is a new research field with a limited number of publications. The warranty policy and its effect on consumer behavior has been studied by Liao et al.[23]. The study proposed a mathematical-statistical model where decisions involve pricing of returned used products (cores), the degree of their remanufacturing, selling price and the warranty period for the final remanufactured products to investigate the joint optimization of remanufacturing, pricing and warranty decision-making for end-of-life products [23].

3. Advanced Remanufacturing-To-Order System Description

The Advanced Remanufacturing-To-Order (ARTO) system deliberated in this study is a product recovery system. A sensor embedded Refrigerator is considered here as an example product. Based on the condition of EOL AC, it goes through a series of recovery operations like the one shown in Figure 1. Refurbishing and Repairing processes may require reusable components to meet the demand of the product. This requirement satisfies the internal and the external component demand. Both are satisfied using disassembly of recovered components.

EOL Refrigerators arrive at the ARTO system for information retrieval using radio frequency data reader which is stored in the facility’s database. Then the Refrigerators
go through a six-station disassembly line. Complete disassembly is performed to extract every single component. Table 1 represents the precedence of relationships between the refrigerator components. There are nine components in a Refrigerator consisting of, evaporator, Metal Cover, Solenoid Valve, Temperature Controls, Evaporator, motor, condenser, fan, Aluminium Radiator, and compressor. Exponential distributions are used to generate the disassembly times at each station, interarrival times of each component's demand, and interarrival times of EOL AC. All EOLPs after retrieval of the information are shipped either to station 1 for disassembly or, if EOLP needs only repair for specific component, to the corresponding station. Two different types of disassembly operations, viz., destructive or nondestructive, are used depending on the component's condition. If the disassembled component is nonfunctional (broken, zero remaining life), then destructive disassembly is used making sure that the other components' functionality is not damaged. The unit disassembly cost for a functional component is higher than nonfunctional component. After disassembly, there is no need for component testing due to the availability of information on components' conditions from sensors. It is assumed that the demands and life cycle information for EOLPs are known. It is also assumed that retrieval of information from sensors costs less than actual inspection and testing. Recovery operations differ for each SEP based on its condition and estimated remaining life. Recovered components are used to meet components and spare parts demands, while recovered or refurbished products are used for product demands. Also, material demands are met using recycled products and components. Recovered products, and components are characterized based on their remaining life times and are placed in different life-bins (e.g., 1 year, 2 years, etc.) waiting to be retrieved via a customer demand. Underutilization of any product or component could happen when it is qualified for a higher life-bin and is placed in a lower life bin because the higher life bin is full. Any product, component or material inventory which is greater than the maximum inventory allowed is assumed to be extra and is used for material demand or disposed. To meet the product demand, repair and refurbish options could also be chosen. EOLP may have missing or nonfunctional (broken, zero remaining life) components that need to be replaced or replenished during the repairing or refurbishing process to meet certain remaining life requirement. EOLP may also consist of components having lesser remaining lives than desired, and for that reason might have to be replaced.

4. Design-Of-Experiments Study

According to a comprehensive study for the quantitative evaluation of the SEPs on the performance of a disassembly line conducted by Ilgin and Gupta,[18], it was shown that smart SEPs are a favorable resolution in handling remanufacturing customer uncertainty. To test this claim on ARTO, we built a simulation model to represent the full recovery system and observed its behavior under different experimental conditions. ARENA program, Version 14.5, was used to build the discrete-event simulation models. A three-level factorial design was used with 51 factors that were considered each at 3 levels. These were identified

| Component Name         | Station Code | Preceding Component |
|------------------------|--------------|---------------------|
| Refrigerator Components and precedence relationship |
| Metal Cover            | 1 A          |                    |
| Motor                  | 2 B          | A                   |
| Solenoid Valve         | 3 C          | A, B                |
| Condenser              | 3 D          | A, B, C             |
| Fan                    | 4 E          | A, B, C, D          |
| Aluminium Radiator     | 5 F          | A, B, C, D          |
| Evaporator             | 5 G          | F                   |
| Compressor             | 6 H          | F, G                |
| Temperature Control    | 6 I          | H                   |

Table 1 Refrigerator Components and precedence relationship

Fig. 1 ARTO System’s recovery processes
101 experiments to accommodate 54 factors upon three
levels or equal to a system’s degrees-of-freedom. The Precisely,
Orthogonal arrays provided a way to only conduct a mini-
mal set of all the possible combinations was picked. The
selection method of an experiment’s number is called a
classification method. A new method of conducting
experiments was proposed was to model possible
curvature in the response function and to handle the case of
nominal factors occurring at 3 levels. The parameters,
factors, and factor levels are given in Table 2 and Table 3.
A full-factorial design with 54 factors at 3 levels requires
an extensive number of experiments (viz., 5.815E+25). To
reduce the number of experiments to a practical level, a
small set of all the possible combinations was picked. The
selection method of an experiment’s number is called a
partial fraction experiment, which yields the most infor-
mation possible of all the factors that affect the perfor-
mance parameter with minimum number of experiments
possible. For these types of experiments, Taguchi (1986),
enacted specific guidelines. A new method of conducting
the experimental design was to use a special set of arrays
called orthogonal arrays (OAs) that were built by Taguchi.
Orthogonal arrays provided a way to only conduct a min-
imal number of experiments. In most cases, orthogonal
array is more efficient when compared to many other sta-
tistical designs. The minimum number of experiments that
are required to conduct the Taguchi method can be calcu-
lated based on the degrees of freedom approach.

So, the number of experiments must be greater than or
equal to a system’s degrees-of-freedom. The Precisely,
$ L_{109}^{34} $ (i.e., 109 = [(Number of levels -1) x Number of Fac-
tors] +1) Orthogonal Arrays were chosen because the de-
gree of freedom ARTO system is 101, meaning it requires
101 experiments to accommodate 54 factors upon three
different levels. Additionally, orthogonal array assumes
that there is no interaction between any two factors.
Furthermore, for validation and verification purposes
animations of the simulation models were built along with
multiple dynamic and counters plots. 2,000 replications
with six months (eight hours a shift, one shifts a day and
5 days a week) were used to run each experiment. Arena
models calculate the profit using the following equation:

$$ \text{Profit} = SR + CR + SCR - HC - BC - DC - DPC - 
TC - RMC - TPC - WC $$

where $ SR $ is the total revenue generated by the product;
component and material sales during the simulated run
time; $ CR $ is the total revenue generated by the collection
of EOL refrigerators during the simulated run time; $ SCR $ is
the total revenue generated by selling scrap components
during the simulated run time; $ HC $ is the total holding
cost of products, components, material and EOL refrig-
erators during the simulated run time; $ BC $ is the total
backorder cost of products, components and material dur-
ing the simulated run time; $ DC $ is the total disassembly
cost during the simulated run time; $ DPC $ is the total dis-
posal cost of components, material and EOL refrigerators
during the simulated run time. $ TC $ is the total testing cost
during the simulated run time; $ RMC $ is the total remanu-
facturing cost of products during the simulated run time;
$ TPC $ is the total transportation cost during the simulated
run time; $ WC $ is the total warranty cost.
### Table 3 Factors and factor levels used in design-of-experiments study

| No | Factor                                              | Unit          | Levels   |
|----|-----------------------------------------------------|---------------|----------|
| 1  | Mean arrival rate of EOL Refrigerators              | Products/hour | 10 20 30 |
| 2  | Probability of Repair EOLPs                         | %             | 5 10 15  |
| 3  | Probability of a non-functional Solenoid Valve      | %             | 10 20 30 |
| 4  | Probability of a non-functional motor                | %             | 10 20 30 |
| 5  | Probability of a non-functional fan                  | %             | 10 20 30 |
| 6  | Probability of a non-functional compressor          | %             | 10 20 30 |
| 7  | Probability of a missing Solenoid Valve              | %             | 5 10 15  |
| 8  | Probability of a missing motor                       | %             | 5 10 15  |
| 9  | Probability of a missing fan                         | %             | 5 10 15  |
| 10 | Probability of a missing compressor                 | %             | 5 10 15  |
| 11 | Mean non-destructive disassembly time for station 1 | Minutes       | 1 2 3    |
| 12 | Mean non-destructive disassembly time for station 2 | Minutes       | 1 2 3    |
| 13 | Mean non-destructive disassembly time for station 3 | Minutes       | 1 2 3    |
| 14 | Mean non-destructive disassembly time for station 4 | Minutes       | 1 2 3    |
| 15 | Mean non-destructive disassembly time for station 5 | Minutes       | 1 2 3    |
| 16 | Mean non-destructive disassembly time for station 6 | Minutes       | 1 2 3    |
| 17 | Mean destructive disassembly time for station 1     | Minutes       | 0 1 2    |
| 18 | Mean destructive disassembly time for station 2     | Minutes       | 0 1 2    |
| 19 | Mean destructive disassembly time for station 3     | Minutes       | 0 1 2    |
| 20 | Mean destructive disassembly time for station 4     | Minutes       | 0 1 2    |
| 21 | Mean destructive disassembly time for station 5     | Minutes       | 0 1 2    |
| 22 | Mean destructive disassembly time for station 6     | Minutes       | 1 1.5 2  |
| 23 | Mean Assembly time for station 1                    | Minutes       | 1 1.5 2  |
| 24 | Mean Assembly time for station 2                    | Minutes       | 1 1.5 2  |
| 25 | Mean Assembly time for station 3                    | Minutes       | 1 1.5 2  |
| 26 | Mean Assembly time for station 4                    | Minutes       | 1 1.5 2  |
| 27 | Mean Assembly time for station 5                    | Minutes       | 1 1.5 2  |
| 28 | Mean Assembly time for station 6                    | Minutes       | 1 2 3    |
| 29 | Mean demand rate Metal Cover                        | Parts/hour    | 10 15 20 |
| 30 | Mean demand rate for Solenoid Valve                 | Parts/hour    | 10 15 20 |
| 31 | Mean demand rate for Temperature Controls           | Parts/hour    | 10 15 20 |
| 32 | Mean demand rate for Evaporator                     | Parts/hour    | 10 15 20 |
| 33 | Mean demand rate for Motor                          | Parts/hour    | 10 15 20 |
| 34 | Mean demand rate for Condenser                      | Parts/hour    | 10 15 20 |
| 35 | Mean demand rate for Fan                            | Parts/hour    | 10 15 20 |
| 36 | Mean demand rate for Aluminium Radiator             | Parts/hour    | 10 15 20 |
| 37 | Mean demand rate for Compressor                     | Parts/hour    | 10 12 17 |
| 38 | Mean demand rate for 1 Year AC                      | Products/hour | 5 10 15  |
| 39 | Mean demand rate for 2 Years AC                     | Products/hour | 5 10 15  |
| 40 | Mean demand rate for 3 Years AC                     | Products/hour | 5 10 15  |
| 41 | Mean demand rate for Refurbished AC                 | Products/hour | 5 10 15  |
| 42 | Mean demand rate for Material                       | Products/hour | 5 10 15  |
| 43 | Percentage of Good Parts to Recycling               | %             | 90 80 70  |
| 44 | Mean Metals Separation Process                      | Hour          | 1 1.5 2  |
| 45 | Mean Copper Recycle Process                         | Minutes       | 1 1.5 2  |
| 46 | Mean Steel Recycle Process                          | Minutes       | 1 1.5 2  |
| 47 | Mean Fiberglass Recycle Process                     | Minutes       | 1 1.5 2  |
| 48 | Mean Dispose Process                                | Minutes       | 1 2.5 3.5|
| 49 | Maximum inventory level for AC                      | Products/hour | 10 15 20 |
| 50 | Maximum inventory level for Refurbished Refrigerator| Products/hour | 10 15 20 |
| 51 | Maximum inventory level for Refrigerator Component  | Products/hour | 10 15 20 |
| 52 | Level of Preventive Maintenance effort              |               | 0.5 0.6 0.7|
| 53 | Number of Preventive Maintenance to perform         | #             | 2 3 4    |
| 54 | Time between each Preventive Maintenance            | Months        | 1 2 3    |

5. **One-Dimensional Product Warranty**

To purchase any product, typically a buyer compares features of a product with other competing manufacturers. In many cases the competing manufacturers make similar products with comparable features such as cost, special characteristics, quality and credibility of the product and even insurance from provider. In these cases, after sale factors such as discount, warranty, availability of parts, repairs and other additional services play a role. In such a situation, these factors will be very noteworthy to the buyer, especially the warranty since it further assures the buyer of the reliability of the product [10].
The objective of the warranty is to promote the product’s quality and guarantee its performance to assure both the remanufacturer and the buyer. There are many different available simple and combination warranty policies. The combination warranty results when warranty terms change at one or more points in time during the warranty interval, $[0, W_I]$. Warranty coverage in each subinterval may follow a different warranty policy. The most common combination in nearly all types of applications is an initial period of Free Replacement warranty (FRW) coverage, followed by a usually longer period under Pro-Rata warranty (PRW). In a combination FRW/PRW policy, the remanufacturer agrees to provide the consumer with a replacement or repair free of charge up to time $W_1$ from the initial purchase, $[0, W_1)$. Any failure that occurs during the $[W_1, W)$ period results in pro-rated refund.

### 6. Notation and Formulation

The nomenclature used in this paper is given in Table 4.

| Parameters | Definition |
|------------|------------|
| $L$ | Life cycle (remaining life) |
| $A$ | Age at failure |
| $W$ | Warranty period |
| $W_I$ | Sun-interval of warranty period |
| $Y$ | Excess age of renewal process associated with failures in the period $[0, W_1)$ |
| $F_w(Y)$ | Time when the warranty term changes from FRW to PRW |
| $F_{11}(.)$ | Distribution function for times to first failure |
| $S(Y)$ | Linear refund function |
| $M_{iu}(.)$ | Renewal function |
| $F_{iu}(.)$ | Distribution function for the first failure in the period $[W_1, W]$ |
| $C_d(W_1, A)$ | Warranty cost to the remanufacturer in the period $[0, W_1)$ for an item with sensor embedded |
| $C_b(W_1; W; Y)$ | Cost to the buyer in the period $[W_1, W)$ for an item of excess age $Y$ |
| $C_s(W_1; W; Y)$ | Warranty cost to the remanufacturer in the period $[W_1, W)$ for an item of excess age $Y$ |
| $C_b(W_1; W; A)$ | Cost to the buyer for an item of age $A$ with sensor embedded |
| $C_d(W_1, W; A)$ | Total warranty cost to the remanufacturer for item of age $A$ with sensor embedded |
| $C_o$ | Operational cost per item |
| $C_r$ | Repair cost per item |
| $C_s$ | Sale price per item |
| $C_i$ | Total warranty cost for the $i$th independent simulation run |
| $S$ | Standard Error |
| $K$ | Number of independent simulation run |
| $\alpha$ | Confidence interval significance level |

The expected number of failures in $[0, W_1)$ is given by:

$$E[N_s(W_1; A)] = F_{11}(W_1)$$

Therefore, the expected warranty cost to the remanufacturer for failures in $[0, W_1)$ is given by:

$$E[C_d(W_1; A)] = C_d[F_{11}(W_1)]$$

$$+ \int_0^{W_1} M_{iu}(W_1 - x) dF_{11}(x)$$

(2)

For failures over the interval $[W_1, W)$. It needs the excess age, $Y$, when the warranty term changes from FRW to PRW is given by:

$$F_W(Y) = F_{11}(Y + W_1)$$

$$- \int_0^{W_1} [1 - F_{11}(Y + W_1 - z)] dM_{iu}(z)$$

(4)

Let the linear refund function given by:

$$S(Y) = \begin{cases} 
C_s(A) \left(1 - \frac{W_1 + Y}{W_1}\right), & \text{if } 0 \leq Y \leq W_1
\end{cases}$$

$$0 \quad \text{if } Y > (W - W_1)$$

(5)

Then the expected warranty cost to remanufacturer resulting from a failure in $[W_1, W)$ is given by:

$$E[C_d(W - W_1; Y)] = C_d(A) \left(1 - \frac{W - W_1}{W_1}\right) F_W(W - W_1)$$

$$- \left(\frac{1}{W_1}\right) \int_0^{W - W_1} Y dF_{iu}(Y)$$

(6)

Combining the costs over the two intervals, we have

$$E[C_d(W_1, W; A)] = C_d[F_{11}(W_1)] + \int_0^{W_1} M_{iu}(W_1 - x) dF_{11}(x)$$

$$+ C_s(A) \left(\frac{W - W_1}{W_1}\right) F_W(W - W_1) - \left(\frac{1}{W_1}\right) \int_0^{W - W_1} Y dF_W(Y)$$

(7)

### 7. Numerical Example

The example here considers a non-renewing one-dimensional FRW/PRW policy for the remanufactured Refrigerator product with three different remaining lives (1 year, 2 years and 3 years) with three different warranty periods (1 month, 2 months and 3 months). Under this warranty, all failed items are repaired or replaced at no cost to the buyer if the failure occurs within the warranty period $[0, W_1)$. Then, any failed item in the interval $[W_1, W)$ will result in a refund on a pro-rata basis. The warranty expires when the age limit is reached. The other data used for implementation of the model is shown in Table 5.
8. Results

The total expected warranty costs to the remanufacturer under the above assumptions are given in Table 6. The ARENA 14.7 program was used to compute the expected number of failures and expected cost to remanufacturer values by carrying out 2,000 independent simulation runs. As can be seen, the expected warranty cost increases with the age of the item at sales, as to be expected. For instance, from Table 6 a 1 year remaining life refrigerator has cost of the warranty $ 78.66, which is 23.13% of sales price, $ 340. Therefore, if the total cost of the 1 year refrigerator to the remanufacturer is $ 156 and it sells for $ 340, the cost to the remanufacturer, including warranty, is $ 156.00 + $ 78.66 = $ 234.66. The confidence interval for the mean of K independent simulation runs with K = 2,000 is shown in Table 7. The confidence interval is given by:

\[ \tilde{C}(K) \pm t_{K-1, \alpha/2} \frac{\sqrt{s^2(K)}}{k} \]

\[ s^2(K) = \frac{\sum (c_i - \tilde{C}(K))^2}{k-1} \]  

(8)  

(9)

For 1-year remaining life sold with 0.5-year warranty we can claim with 90% confidence that the expected warranty cost is in the interval [74.40, 78.03]. The confidence interval for a 3-years remaining life sold with 2-years warranty is [66.84, 90.45].
Table 7: Standard Error and Confidence Interval on FRW/PRW policy

| Components | W | Standard Error (S) | 90% Confidence Interval |
|------------|---|--------------------|------------------------|
|            |   | RL = 1 | RL = 2 | RL = 3 | RL = 1 | RL = 2 | RL = 3 |
| Metal Cover | 0.5 | 0.52 | 0.75 | 1.15 | $11.82 | $12.75 | $13.41 | $14.76 | $10.20 | $12.30 |
|            | 1  | 1.31 | 1.92 | 2.02 | $12.45 | $14.85 | $13.65 | $17.19 | $9.63 | $13.32 |
|            | 2  | 2.53 | 2.89 | 3.33 | $18.15 | $22.80 | $17.70 | $22.98 | $8.79 | $14.85 |
| Solenoid Valve | 0.5 | 0.57 | 0.84 | 1.28 | $11.55 | $12.60 | $13.23 | $14.79 | $10.05 | $12.29 |
|            | 1  | 1.47 | 2.17 | 2.27 | $12.87 | $15.57 | $13.05 | $16.98 | $9.30 | $13.44 |
|            | 2  | 2.84 | 3.25 | 3.74 | $17.64 | $22.83 | $16.98 | $22.92 | $8.31 | $15.15 |
| Temperature Controls | 0.5 | 0.64 | 0.95 | 1.45 | $5.43 | $6.63 | $4.77 | $6.51 | $4.44 | $7.08 |
|            | 1  | 1.65 | 2.43 | 2.55 | $6.42 | $9.45 | $7.80 | $12.24 | $3.57 | $8.22 |
|            | 2  | 3.19 | 3.65 | 4.20 | $8.07 | $13.89 | $9.00 | $15.66 | $2.28 | $9.96 |
| Evaporator | 0.5 | 0.82 | 1.20 | 1.83 | $2.58 | $4.08 | $2.16 | $4.35 | $1.11 | $4.47 |
|            | 1  | 2.10 | 3.09 | 3.24 | $2.88 | $6.72 | $1.59 | $7.23 | $0.12 | $6.08 |
|            | 2  | 4.06 | 4.63 | 5.33 | $2.67 | $10.05 | $2.07 | $10.63 | $1.05 | $8.13 |
| Motor | 0.5 | 0.73 | 1.08 | 1.63 | $11.91 | $13.26 | $11.10 | $13.05 | $10.29 | $13.29 |
|            | 1  | 1.86 | 2.75 | 2.88 | $12.12 | $15.54 | $10.41 | $15.42 | $9.39 | $14.64 |
|            | 2  | 3.61 | 4.12 | 4.74 | $16.14 | $22.74 | $12.93 | $20.46 | $7.80 | $16.47 |
| Condenser | 0.5 | 0.61 | 0.89 | 1.35 | $3.39 | $4.47 | $2.55 | $4.17 | $2.04 | $4.50 |
|            | 1  | 1.54 | 2.27 | 2.38 | $4.29 | $7.11 | $2.73 | $6.87 | $1.44 | $5.79 |
|            | 2  | 2.98 | 3.40 | 3.92 | $3.87 | $9.33 | $2.43 | $8.67 | $0.21 | $7.38 |
| Fan | 0.5 | 0.61 | 0.89 | 1.35 | $6.99 | $8.10 | $5.55 | $7.17 | $4.89 | $7.35 |
|            | 1  | 1.54 | 2.27 | 2.38 | $9.00 | $11.82 | $5.37 | $9.54 | $4.11 | $8.46 |
|            | 2  | 2.98 | 3.40 | 3.92 | $10.23 | $15.66 | $7.23 | $13.47 | $3.03 | $10.20 |
| Aluminum Radiator | 0.5 | 0.58 | 0.85 | 1.30 | $1.47 | $2.52 | $0.78 | $2.34 | $0.06 | $2.31 |
|            | 1  | 1.49 | 2.19 | 2.30 | $1.71 | $4.44 | $0.51 | $4.53 | $0.51 | $4.35 |
|            | 2  | 2.88 | 3.29 | 3.79 | $2.76 | $8.04 | $0.63 | $6.63 | $1.62 | $4.92 |
| Compressor | 0.5 | 0.58 | 0.85 | 1.30 | $8.19 | $9.27 | $7.41 | $9.87 | $6.63 | $9.03 |
|            | 1  | 1.49 | 2.19 | 2.30 | $9.87 | $12.60 | $8.55 | $12.27 | $6.39 | $10.59 |
|            | 2  | 2.88 | 3.29 | 3.79 | $12.69 | $17.94 | $10.83 | $16.86 | $5.31 | $12.24 |
| Refrigerator | 0.5 | 0.76 | 1.11 | 1.70 | $74.40 | $78.03 | $70.44 | $75.78 | $68.37 | $76.47 |
|            | 1  | 1.94 | 2.85 | 2.99 | $74.88 | $84.18 | $75.87 | $84.90 | $68.67 | $82.98 |
|            | 2  | 3.75 | 4.29 | 4.93 | $84.48 | $102.42 | $81.81 | $102.30 | $66.84 | $90.45 |

9. Conclusion
The warranty cost for remanufactured products was evaluated in this paper using the combination Free Replacement and Pro-Rata Warranty (FRW/PRW) for different warranty periods. The main objective was to introduce the idea of providing a non-renewable basic combination warranty for a remanufactured product using the sensor information about the age of every remanufactured product on hand to meet demands while minimizing the cost associated with warranty and maximizing remanufacturer’s profit. A simulation model was used to optimize the system and predict the warranty period that should be assigned to every disassembled component and remanufactured product.

References
[1] Alqahtani, A. Y., & Gupta, S. M. (2017). Warranty Cost Analysis within Sustainable Supply Chain. In U. Akkucuk (Ed.), Ethics and Sustainability in Global Supply Chain Management (pp. 1-25). Hershey, PA: IGI Global.
[2] Alqahtani, A. Y., & Gupta, S. M. (2017b). Optimizing two-dimensional renewable warranty policies for sensor embedded remanufacturing products. Journal of Industrial Engineering and Management, 10(2), 73-89.
[3] Alqahtani, A.Y. & Gupta, S.M. (2017c). One-Dimensional Renewable Warranty Management within Sustainable Supply Chain. Resources, 6(16).
[4] Balachander, S. (2001), Warranty signalling and reputation. Management Science, 47(9), 1282-1289.
[5] Blischke, W. R. and Murthy, C. N. P. (1994), Warranty cost analysis. Marcel Dekker, New York.
[6] Blischke, W. R. and Murthy, C. N. P. (1996), Product warranty handbook. Marcel Dekker, New York.
[7] Fang, H. C., S. K. Ong, and A. Y. C. Nee. (2014). Use of Embedded Smart Sensors in Products to Facilitate Remanufacturing. Handbook of Manufacturing Engineering and Technology, 3265-3295.
[8] Ferrer, G., Heath, S. K., & Dew, N. (2011). An RFID application in large job shop remanufacturing operations. International Journal of Production Economics, 133(2), 612-621.
[9] Gal-Or, E. (1989), Warranties as a signal of quality. Canadian Journal of Economics, 50-61.
[10] Godschall, M., Peres, F., Gonzalez, V., Tchangani, A., Crespo, A. and Villeneuve, E. (2011), Integration of warranty as a decision variable in the process of recertification of parts resulting from end-of-life system dismantling, Proceedings of Quality and Reliability (ICQR), IEEE International Conference, 156-160.
[11] Gungor, A. and Gupta S.M. (1999), Issues in environmentally conscious manufacturing and product recovery: a survey. Computers and Industrial Engineering, 36, 811–853.
[12] Gungor, A. and Gupta S.M. (2002), Disassembly line in product recovery. International Journal of Production Research, 40, 2509-2599.
[13] Gupta S.M., & Lambert A.J.D. (eds) (2007). Environment conscious manufacturing, CRC Press, Boca Raton.
[14] Gupta, S. M. (2013). Reverse supply chains: issues and analysis. CRC Press.
[15] Heal, G. (1977), Guarantees and risk-sharing. The Review of Economic Studies, 549-560.
[16] Ilgin, M. A. and Gupta, S. M. (2010), Comparison of economic benefits of sensor embedded products and conventional products in a multi-product disassembly line. Computers and Industrial Engineering, 59, 748–763.
[17] Ilgin, M. A. and Gupta, S. M. (2010), Environmentally conscious manufacturing and product recovery (ECM-PRO): A review of the state of the art. Journal of Environmental Management, 91, 563–591.
[18] Ilgin, M. A. and Gupta, S. M. (2010), Evaluating the impact of sensor-embedded products on the performance of an air conditioner disassembly line. The International Journal of Advanced Manufacturing Technology, 53, 1199–1216.
[19] Ilgin, M. A. and Gupta, S. M. (2011), Performance improvement potential of sensor embedded products in environmental supply chains. Resources, Conservation and Recycling, 55, 580–592.
[20] Ilgin, M. A., Gupta, S. M. and Battaia, O. (2015). Use of MCDM techniques in environmentally conscious manufacturing and product recovery: State of the art. Journal of Manufacturing Systems, 37, 746-758.
[21] Kittritis D, Bufardi A, Xirochakis P (2003) Research issues on product lifecycle management and information tracking using smart embedded systems. Advance Engineering Information 17(3–4):189–202.
[22] Kulkarni, A., Ralph, D. and McFarlane, D. (2007). Value of RFID in remanufacturing. International Journal of Services Operations and Informatics, 2(3), 225-252.
[23] Liao, B. F., Li, B. Y. and Cheng, J. S. (2015). A warranty model for remanufactured products. Journal of Industrial and Production Engineering, 32(8), 551-558.
[24] Lutz, N. A. and Padmanabhan, V. (1995), Why do we observe minimal warranties? Marketing Science, 14(4), 417-441.
[25] Murthy, D. P. and Blischke, W. R. (2006), Warranty management and product manufacture. Springer, London.
[26] Parlikad, A. K., & McFarlane, D. (2007). RFID-based product information in end-of-life decision making. Control engineering practice, 15(11), 1348-1363.
[27] Peck, M. (2008). Prognostics and health management of electronics. John Wiley & Sons, Ltd., Hoboken.
[28] Soberman, D. A. (2003), ‘Simultaneous signaling and screening with warranties’. Journal of Marketing Research, 40(2), 176-192.
[29] Spence, M. (1977). Consumer misperceptions, product failure and producer liability. The Review of Economic Studies, 561-572.
[30] Vadde, S, Kamathii, SV, Gupta, SM, Zeid I (2008) Product life cycle monitoring via embedded sensors. In: Gupta SM, Lambert AJD, Environment conscious manufacturing, 91-103.
[31] Zeid A, Kamarthi S, and Gupta SM (2004). Product take-back: sensors-based approach. In: Gupta SM Environmentally conscious manufacturing IV. Proceedings of SPIE, Vol 5583. Bellingham, 200-206.

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