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 fulfil 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

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(Received January 20, 2017)
(Revised March 12, 2017)
(Accepted April 18, 2017)

6. Section 7 presents numerical example Finally, Section 8 and Section 9 present the results and some concluding remarks.

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]. 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]. 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 [?]. 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

Fig. 1 ARTO System's recovery processes

Table 1 Refrigerator Components and precedence relationship

Component Name	Station	Code	Preceding Component
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, E
Evaporator	5	G	F
Compressor	6	H	F, G
Temperature Control	6	I	H

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, Aluminum 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 non-functional (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,[20], 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

Table 2 Parameters used in the ARTO system

Parameters	Unit	Value	Parameters	Unit	Value
Backorder cost rate	%	40	Price for 3 Years Evaporator	\$	15
Holding cost rate	\$ /hour	10	Price for 3 Years Motor	\$	60
Remanufacturing cost	\$	1.5	Price for 3 Years Condenser	\$	25
Disassembly cost per minute	\$	1	Price for 3 Years Fan	\$	20
Price for 1 Year Metal Cover	\$	10	Price for 3 Years Aluminium Radiator	\$	20
Price for 1 Year Solenoid Valve	\$	20	Price for 3 Years Compressor	\$	65
Price for 1 Year Temperature Controls	\$	5	Weight for Metal Cover	lbs.	8
Price for 1 Year Evaporator	\$	5	Weight for Solenoid Valve	lbs.	4
Price for 1 Year Motor	\$	45	Weight for Temperature Controls	lbs.	2
Price for 1 Year Condenser	\$	15	Weight for Evaporator	lbs.	2
Price for 1 Year Fan	\$	15	Weight for Motor	lbs.	6
Price for 1 Year Aluminium Radiator	\$	15	Weight for Condenser	lbs.	12
Price for 1 Year Compressor	\$	50	Weight for Fan	lbs.	3
Price for 2 Years Metal Cover	\$	15	Weight for Aluminium Radiator	lbs.	3
Price for 2 Years Solenoid Valve	\$	30	Weight for Compressor	lbs.	6
Price for 2 Years Temperature Controls	\$	12	Unit copper scrap revenue	\$ /lbs	0.6
Price for 2 Years Evaporator	\$	12	Unit Fiberglass scrap revenue	\$ /lbs	0.9
Price for 2 Years Motor	\$	55	Unit steel scrap revenue	\$ /lbs	0.2
Price for 2 Years Condenser	\$	18	Unit disposal cost	\$ /lbs	0.3
Price for 2 Years Fan	\$	18	Unit copper scrap Cost	\$ /lbs	0.3
Price for 2 Years Aluminium Radiator	\$	20	Unit Fiberglass Scrap Cost	\$ /lbs	0.45
Price for 2 Years Compressor	\$	60	Unit steel scrap Cost	\$ /lbs	0.1
Price for 3 Years Metal Cover	\$	20	Price of 1 Year AC	\$	180
Price for 3 Years Solenoid Valve	\$	35	Price of 2 Years AC	\$	240
Price for 3 Years Temperature Controls	\$	15	Price of 3 Years AC	\$	275
Operation costs for Metal Cover	\$	4	Operation costs for Condenser	\$	1.66
Operation costs for Solenoid Valve	\$	4	Operation costs for Fan	\$	2.34
Operation costs for Temperature Controls	\$	2.8	Operation costs for Aluminium Radiator	\$	0.6
Operation costs for Evaporator	\$	1.2	Operation costs for Compressor	\$	3.4
Operation costs for Motor	\$	4	Operation costs for AC	\$	55

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 as low, intermediate, or high levels. The reason that the three-level designs were 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 information possible of all the factors that affect the performance 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 minimal number of experiments. In most cases, orthogonal array is more efficient when compared to many other statistical designs. The minimum number of experiments that are required to conduct the Taguchi method can be calculated 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,

$L109(354)$ (i.e., $109 = [(Number\ of\ levels - 1) \times Number\ of\ Factors] + 1$) Orthogonal Arrays were chosen because the degree 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:

$$Profit = SR + CR + SCR - HC - BC - DC - DPC - TC - RMC - TPC - WC \quad (1)$$

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 refrigerators during the simulated run time; BC is the total backorder cost of products, components and material during the simulated run time; DC is the total disassembly cost during the simulated run time; DPC is the total disposal cost of components, material and EOL refrigerators during the

Table 3 Factors and factor levels used in design-of-experiments study

No	Factor	Unit	Levels		
			1	2	3
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	1	1
12	Mean non-destructive disassembly time for station 2	Minutes	1	1	1
13	Mean non-destructive disassembly time for station 3	Minutes	1	1	1
14	Mean non-destructive disassembly time for station 4	Minutes	1	1	1
15	Mean non-destructive disassembly time for station 5	Minutes	1	1	1
16	Mean non-destructive disassembly time for station 6	Minutes	1	2	2
17	Mean destructive disassembly time for station 1	Minutes	0	1	1
18	Mean destructive disassembly time for station 2	Minutes	0	1	1
19	Mean destructive disassembly time for station 3	Minutes	0	1	1
20	Mean destructive disassembly time for station 4	Minutes	0	1	1
21	Mean destructive disassembly time for station 5	Minutes	0	1	1
22	Mean destructive disassembly time for station 6	Minutes	1	1	1
23	Mean Assembly time for station 1	Minutes	1	1	2
24	Mean Assembly time for station 2	Minutes	1	1	2
25	Mean Assembly time for station 3	Minutes	1	1	2
26	Mean Assembly time for station 4	Minutes	1	1	1
27	Mean Assembly time for station 5	Minutes	1	1	2
28	Mean Assembly time for station 6	Minutes	1	2	2
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	20
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	%	95	90	80
44	Mean Metals Separation Process	Hour	1	1	2
45	Mean Copper Recycle Process	Minutes	1	1	2
46	Mean Steel Recycle Process	Minutes	1	1	2
47	Mean Fiberglass Recycle Process	Minutes	1	1	2
48	Mean Dispose Process	Minutes	1	1	1
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

simulated run time. TC is the total testing cost during the simulated run time; RMC is the total remanufacturing 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.

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, $[0, W]$. 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.

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

$$E[N_i(W_1; A)] = [F_{i1}(W_1) + \int_0^{W_1} M_{iu}(W_1 - x) dF_{i1}(x)] \quad (2)$$

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

$$E[C_d(W_1; A)] = C_r[F_{i1}(W_1) + \int_0^{W_1} M_{iu}(W_1 - x) dF_{i1}(x)] \quad (3)$$

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:

$$F_W(y) = F_i1(y + W_1) - \int_0^{W_1} [1 - F_{i1}(y + W_1 - z)] dM_{iu}(z) \quad (4)$$

Let the linear refund function given by:

$$S(Y) = \begin{cases} C_s(A) \{1 - \frac{W_1 + y}{w}\}, & \text{if } 0 \leq y \leq W - W_1 \\ 0 & \text{if } Y > (W - W_1) \end{cases} \quad (5)$$

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

$$E[C_d(W - W_1; Y)] = c_s(A) \left[\left\{ \frac{W - W_1}{W} \right\} F_W(W - W_1) - \left(\frac{1}{W} \right) \int_0^{W - W_1} y dF_w(y) \right] \quad (6)$$

Table 4 List of notations

Parameters	Definition
L	Life cycle (remaining life)
A	Age at failure
W	Warranty period
W_1	Sub-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
$F_{i1}(\cdot)$	Distribution function for times to first failure
$S(Y)$	Linear refund function
$M_{iu}(\cdot)$	Renewal function
$F_w(\cdot)$	Distribution function for the first failure in the period $[W_1, W]$
$F_{i1}(x)$	First failure function
$C_b(W_1; A)$	Warranty cost to the remanufacturer in the period $[0, W_1]$ for an item with sensor embedded
$C_b(W, W_1; Y)$	Cost to the buyer in the period $[W_1, W]$ for an item of excess age Y
$C_d(W, W_1; Y)$	Warranty cost to the remanufacturer in the period $[W_1, W]$ for an item of excess age Y
$C_b(W, W_1; A)$	Cost to the buyer for an item of age A with sensor embedded
$C_d(W, W_1; A)$	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
α	Confidence interval significance level

Combining the costs over the two intervals, we have

$$E[C_d(W_1, W; A)] = C_b[F_{i1}(W_1) + \int_0^{W_1} M_{iu}(W_1 - x) dF_{i1}(x)] + C_s(A) \left[\left\{ \frac{W - W_1}{W} \right\} F_W(W - W_1) - \left(\frac{1}{W} \right) \int_0^{W - W_1} y dF_w(y) \right] \quad (7)$$

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.

Table 5 Operation costs (disassembly, assembly), sale price and repair cost for Refrigerator components

Components	C_o = Operation costs (\$ /unit)	C_s = Sale Price (\$ /unit)			C_r = Repair costs (\$ /unit)
		$L = 1$ Year	$L = 2$ Years	$L = 3$ Years	
Metal Cover	\$ 4.00	\$ 10	\$ 15	\$ 35	\$ 8.00
Control Panel	\$ 4.00	\$ 20	\$ 30	\$ 15	\$ 8.00
Agitator	\$ 2.80	\$ 5	\$ 12	\$ 15	\$ 5.60
Spin Tub	\$ 1.20	\$ 5	\$ 12	\$ 60	\$ 2.40
Motor	\$ 4.00	\$ 45	\$ 55	\$ 25	\$ 8.00
Pump	\$ 1.66	\$ 15	\$ 18	\$ 20	\$ 3.32
Water & Drain Hoses	\$ 2.34	\$ 15	\$ 18	\$ 20	\$ 4.68
Pulley	\$ 0.60	\$ 15	\$ 20	\$ 65	\$ 1.20
Transmission	\$ 3.40	\$ 50	\$ 60	\$ 35	\$ 6.80
Refrigerator	\$ 55.00	\$ 180	\$ 240	\$ 310	\$ 85.00

Table 6 The expected remanufacturer's warranty cost of FRW/PRW policy

Components	W	Expected Number of Failures During Warranty			Expected Cost to Remanufacturer		
		RL= 1	RL = 2	RL = 3	RL = 1	RL = 2	RL = 3
Metal Cover	0.5	0.6590	0.0042	0.0010	\$ 12.69	\$ 14.55	\$ 11.61
	1	0.1321	0.0171	0.0079	\$ 14.09	\$ 15.91	\$ 11.83
	2	0.1977	0.0382	0.0266	\$ 21.14	\$ 20.99	\$ 12.20
Solenoid Valve	0.5	0.6511	0.0041	0.0052	\$ 12.44	\$ 14.46	\$ 11.58
	1	0.1400	0.0168	0.0422	\$ 14.67	\$ 15.51	\$ 11.73
	2	0.1898	0.0380	0.1422	\$ 20.86	\$ 20.59	\$ 12.10
Temperature Controls	0.5	0.6431	0.0039	0.0274	\$ 6.22	\$ 5.82	\$ 5.94
	1	0.1243	0.0172	0.2260	\$ 8.20	\$ 10.34	\$ 6.10
	2	0.1820	0.0386	0.7599	\$ 11.33	\$ 12.72	\$ 6.32
Evaporator	0.5	0.6431	0.0018	0.1464	\$ 3.44	\$ 3.34	\$ 2.88
	1	0.0926	0.0175	1.2076	\$ 4.95	\$ 4.55	\$ 3.16
	2	0.1661	0.0334	0.4948	\$ 6.56	\$ 6.50	\$ 3.34
Motor	0.5	0.6243	0.0041	0.7825	\$ 13.00	\$ 12.44	\$ 12.17
	1	0.1353	0.0168	1.0149	\$ 14.27	\$ 13.31	\$ 12.38
	2	0.1907	0.0386	0.0212	\$ 20.06	\$ 17.24	\$ 12.51
Condenser	0.5	0.6503	0.0043	0.9727	\$ 4.06	\$ 3.47	\$ 3.37
	1	0.1266	0.0171	1.0235	\$ 5.88	\$ 4.95	\$ 3.71
	2	0.1993	0.0386	0.1130	\$ 6.81	\$ 5.73	\$ 3.90
Fan	0.5	0.6661	0.0039	1.0149	\$ 7.77	\$ 6.56	\$ 6.32
	1	0.1456	0.0170	0.2064	\$ 10.74	\$ 7.68	\$ 6.47
	2	0.1915	0.0383	0.6043	\$ 13.34	\$ 10.68	\$ 6.81
Aluminium Radiator	0.5	0.6725	0.0042	0.7231	\$ 2.04	\$ 1.61	\$ 1.15
	1	0.1243	0.0170	1.1032	\$ 3.19	\$ 2.60	\$ 1.39
	2	0.1890	0.0386	1.0191	\$ 5.57	\$ 3.75	\$ 1.49
Compressor	0.5	0.6495	0.0042	0.0216	\$ 9.01	\$ 8.45	\$ 8.08
	1	0.1313	0.0171	0.1130	\$ 11.61	\$ 10.90	\$ 8.76
	2	0.1907	0.0384	1.0235	\$ 15.82	\$ 14.27	\$ 9.04
Refrigerator	0.5	0.4890	0.0031	0.0003	\$ 78.66	\$ 75.44	\$ 74.73
	1	0.0980	0.0128	0.0019	\$ 82.07	\$ 82.96	\$ 78.23
	2	0.1468	0.0284	0.0065	\$ 96.43	\$ 95.00	\$ 81.14

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 run. As can be seen that 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 with a 0.5-year warranty has cost of the warranty \$ 78.66, which is 23.13% of sales price, $C_s = \$ 340$. 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:

$$\bar{C}(K) \mp t_{k-1} \left(1 - \frac{\alpha}{2}\right) \sqrt{\frac{s^2(k)}{k}} \quad (8)$$

$$\frac{s^2(k)}{k} = \sum \frac{[c_i - \bar{C}(k)]^2}{k-1} \quad (9)$$

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	
					L limit	U limit	L limit	U limit	L limit	U limit
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	\$ 12.39
	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	\$ 6.00
	2	4.06	4.63	5.33	\$ 2.67	\$ 10.05	\$ 2.07	\$ 10.53	\$ 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
Aluminium 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	\$ 3.45
	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	\$ 8.97	\$ 6.63	\$ 9.03
	1	1.49	2.19	2.30	\$ 9.87	\$ 12.60	\$ 8.55	\$ 12.57	\$ 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.

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A portrait of Dr. Toshiyuki Kameoka, a man with dark hair and glasses, wearing a light blue shirt and a grey jacket. He is looking directly at the camera with a neutral expression. The background is a plain, light-colored wall.

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