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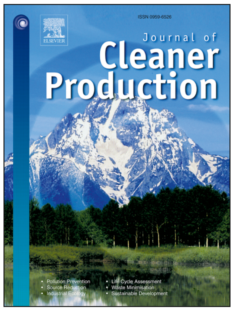

Warranty as a marketing strategy for remanufactured products

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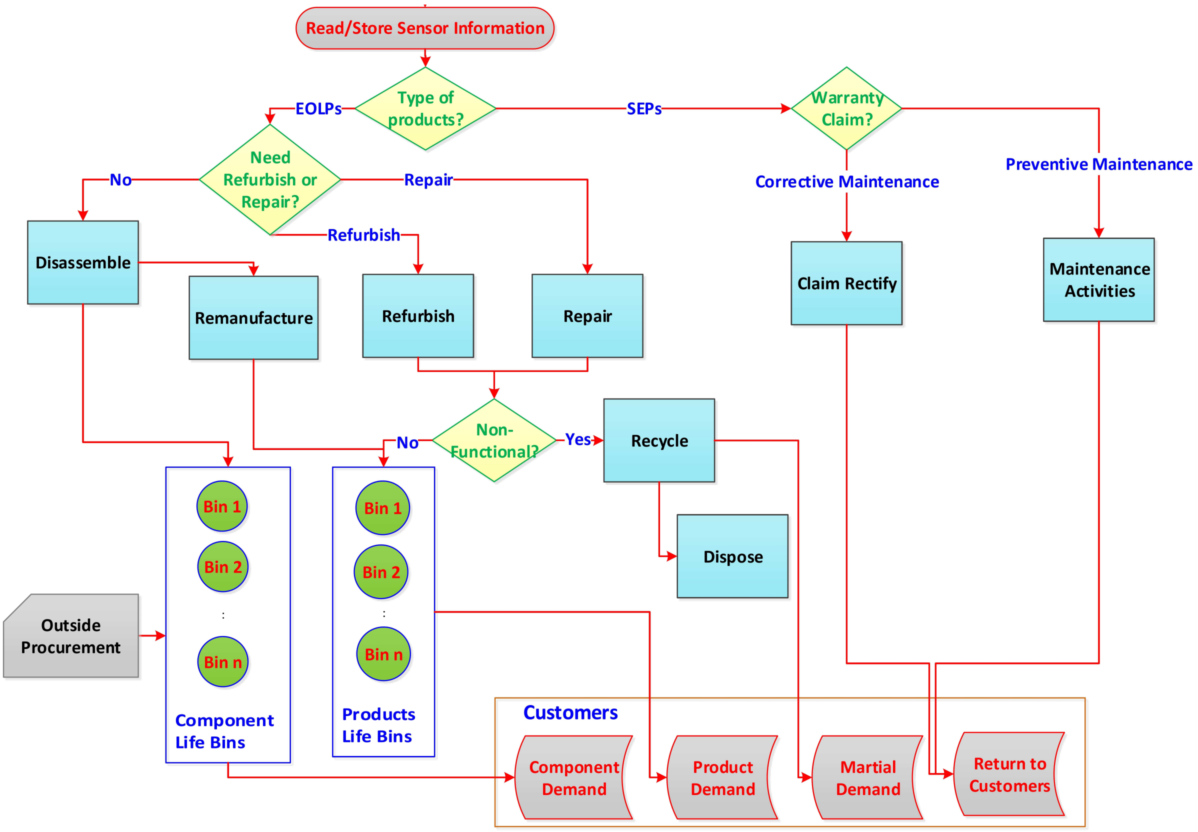
Read/Store Sensor Information
Type of products?
EOLPs
SEPs
Warranty Claim?
Need Refurbish or Repair?
No
Repair
Refurbish
Corrective Maintenance
Preventive Maintenance
Disassemble
Remanufacture
Refurbish
Repair
Claim Rectify
Maintenance Activities
Non-Functional?
No
Yes
Recycle
Dispose
Bin 1
Bin 2
:
Bin n
Component Life Bins
Bin 1
Bin 2
:
Bin n
Products Life Bins
Outside Procurement
Customers
Component Demand
Product Demand
Martial Demand
Return to Customers

Warranty as a Marketing Strategy for Remanufactured Products

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Abstract: Remanufactured products, in addition to being environment friendly, are popular with consumers because they can offer the latest technology with lower prices in comparison to brand new products. However, some consumers are hesitant to buy remanufactured products because they are skeptical about the quality of the remanufactured product and thus are unsure of the extent to which the product will render services when compared to a new product. A strategy that remanufacturers may employ to market remanufactured products and encourage customers is to offer warranties on remanufactured products. To that end, this paper studies and scrutinizes the impact of offering renewing warranties on remanufactured products. Specifically, the paper suggests a methodology which simultaneously minimizes the cost incurred by the remanufacturers and maximizes the confidence of the consumers towards buying remanufacturing products.

Keywords: Marketing, Preventive Maintenance, Extended Warranty Policies, Remanufacturing, Sensor Embedded Products, Extending product life-cycle

1. Introduction

Marketing is difficult to define because of the myriad of available interpretations and applications thereof, and the fact that there are many competing views of the role of marketing (Webster, 2002). Marketing may be perceived as the creation and management of markets. Market can be defined as the outcome of the interaction between remanufacturers and consumers. Product warranties play a key role in the creation of markets for products as well as the subsequent management of markets. The importance of warranty in a consumer product market is significant as it addresses consumer uncertainty in terms of product performance over the duration of its useful life.

Warranties, given their role in perceived value, can be employed as valuable tools in marketing. Warranties are capable of communicating value through their application as persuasive marketing tenets, whether promotional or protectionist. When deployed as a promotional tool, warranties may be used to promote the reliability and quality of the product. As a protectionist instrument, warranties provide the consumer assurance against defective products that are incapable of performing satisfactorily over the duration of the warranty period. Through the effective marketing of a warranty, the degree of risk that is associated with the purchase of a given product on behalf of the consumer is reduced, thereby increasing its value and the likelihood of purchase.

Warranties are noted for their capacity to reduce the perceived performance risk of a product through the provision of protection against product defects that lead to failures, within the scope of the warranty period. The financial risk to the consumer is also reduced through the warranty, as repair costs that fall under the scope of the warranty are realized by the remanufacturer and not the consumer.

However, the provision of warranties results in additional costs to remanufacturers. Thus it is perceived that remanufacturers would invest in reliability and quality of those remanufactured products that are offered with warranties. Given these assumptions, consumers generally perceive warranties as being positively correlated to product quality and reliability.

Because of the infinitely increasing levels of complexity and uncertainty associated with the remanufacturing process, the scope of this paper is limited to the following factors. End-Of-Life (EOL) products and demanded components arrive at the remanufacturing facilities in accordance with the Poisson distribution. The disassembly and remanufacturing time exponentially assigned to each station are distributed accordingly. Imposing a cost for backorders will be calculated based on the duration of aforementioned backorder. Excessive and unessential EOL products and components are disposed of regularly according to a stringent disposal policy. A pull control production mechanism is used in all disassembly line settings contemplated and reviewed in this research study. Comparisons of warranty costs and temporal periods are made amongst different warranty policies.

The primary contribution offered by this paper is that it presents a quantitative assessment of the effect of offering warranties on remanufactured items from a remanufacturer’s perspective by proposing an appealing price in the eyes of the buyer as well. While there are developmental studies on warranty policies for brand new products and a few on secondhand products, there exists no study that evaluates the potential benefits of warranties on remanufactured products in a quantitative and comprehensive manner. In these studies, the profit improvements achieved by the offering of warranties for different policies determine the range of how much money can be invested in a warranty while still keeping it profitable overall. To that end, this paper studies and scrutinizes the impact of offering renewing warranties on remanufactured products. Specifically, the paper suggests a methodology which simultaneously minimizes the cost incurred by the remanufacturers and maximizes the confidence of the consumers towards buying remanufacturing products.

The rest of the paper is organized as follows: section 2 list all the related work from the literature review. System descriptions and extended warranty are presented in Section 3 and Section 4 respectively. Assumptions and notations are given in Section 5. Section 6 describes the preventive maintenance analysis. The failures with Renewal Process and warranty formulation are presented in Section 7 and Section 8 respectively. Finally, results and conclusions are given in Section 9 and Section 10 respectively.

2. Literature Review

2.1 Environmentally Conscious Manufacturing and Product Recovery

The issues of environmentally conscious manufacturing and product recovery (ECMPRO) have become increasingly prevalent in modern times, resulting in a substantial volume of research on the subject (Gungor & Gupta, 1999; Gupta & Lambert, 2008; Ilgin & Gupta, 2010). The growing importance of ECMPRO has been driven by environmental factors, public demands, and government regulation from the consumer/societal perspective. In terms of business, ECMPRO has been growing due to the potential to realize significant profits through the implementation of reverse logistics and resolutions to support product recycling (ilgin et al., 2015). Manufacturers have noted the increasing level of consumer awareness of environmental issues, and responded through the institution of stricter environmental regulations and construction of facilities to minimize the amassing of waste through the recovery of end-of-life products' (EOLPs) materials and components (Gungor & Gupta, 2002).

Researchers have begun focusing on the myriad logistical issues encountered in product manufacturing when environmentally conscious activities are being focused upon. Consequently, researchers have presented reviews of the many issues involved in environmentally conscious manufacturing and recovery (See Moyer & Gupta, 1997; Gupta, 2013; Ilgin et al., 2015). The facet of greatest focus in the discourse on ECMPRO is the area of remanufacturing research, due largely in part to the significant role played by this facet in the overall recovery process. Lambert and Gupta (2005) have presented a comprehensive exploration of the various aspects involved in disassembly.

2.2 Warranty Analysis

A warranty is a contractual obligation realized by the manufacturer when a product is sold. The warranty establishes liability on behalf of the manufacturer should the item sold prematurely fail or prove incapable of performing the intended function. Warranties define the product performance to be expected by the consumer, and should the performance definition not be met, the buyer is then afforded compensation as outlined in the warranty (Blischke, 1993). Warranties serve a variety of purposes, with Heal (1977) noting that insurance and protection are central, as it enables the buyer to transfer product risk failure to the vendor. Product warranties may also signify dependability to the consumer (Blischke, 1995; Gal-Or, 1989; Soberman, 2003; Spence, 1977). Lutz and Padmanabhan (1995) note that vendors may realize additional profitability through the provision of warranties.

A significant proportion of the extant literature on warranty policies has focused upon new items, while warranties for second-hand items have been lesser researched. An emerging facet of such research is the modeling of warranty cost analysis strategies for second-hand items. As technological progress has been realized, the potential upgrade options for second-hand items have likewise expanded. A stochastic model has been proposed to examine the ideal level of investment into second-hand products to increase their reliability within the context of free repair warranty (FRW) policies, with researchers concluding that greater investments result in declines in the virtual age of the product, although greater reliability levels of the upgraded product were realized (Saidi-Mehrabad et al., 2010; Shafiee et al., 2011a).

Shafiee et al. (2011b) presented a stochastic reliability improvement model for second-hand products with warranties incorporating a Cobb-Douglas-Type production function to identify the optimal upgrade level of the product. Naini and Shafiee (2011) conducted a study to identify the optimal upgrade, selling price, and maximum expected profit, applying restrictive assumptions concerning age distribution. A mathematical model was constructed to implement a parametric analysis on the chronological ages of the second-hand items to identify the optimal policy (Naini & Shafiee, 2011).

An integrated mathematical model was adopted by Yazdian et al. (2014) to determine typical remanufacturer decisions, delimiting the specific age of the received item. Considering the issue from an alternative perspective, Liao et al. (2015) studied the impact of warranty policies upon consumer behavior and their perspective of such policies. While such research is important and essential, the analysis of warranty costs for remanufactured products continues to be an understudied area. Despite this, there are limited studies that have explored remanufactured products' warranties within the context of reverse and closed-loop supply chain management. Remanufactured products may be adjoined by a base and extended one-dimensional warranty through the offering of FRW and Pro-Rata Warranty (PRW) policies (Alqahtani & Gupta, 2017a). Alqahtani & Gupta (2017b) found that EOL-derived products may be provided with renewable, non-renewable, one- or two-dimensional warranty policies.

2.3 Maintenance Analysis

Maintenance is central to the reliability and quality of particular product classes. Maintenance is generally split into two primary types, those of corrective maintenance (CM) and preventative maintenance (PM). PM is pursued prior to the failure of an item to reduce the rate of degeneration and rate of failure of the item. CM is undertaken upon failure of an item, and returns the item to an operational state. Should a product have a short remaining life, the adjoined warranty period is generally short with CM being the only option. When products have a long remaining life, the warranty period may likewise be long, with PM reducing overall warranty servicing costs, demonstrating the link between CM and PM policies.

Literature on maintenance policies is expansive, with many studies on maintenance policies having been published (Wang, 2002; Garg & Deshmukh, 2006; Sharma et al., 2011). Nakagawa (2006) presented a comprehensive resource on general maintenance theory, while an exhaustive review of modeling maintenance policies was presented in Nakagawa (2008).

According to Shafiee and Chukova (2013) little research has been conducted on second-hand product maintenance policies within the context of the warranty period. Optimal periodic PM policies for second-hand items have been presented by Kim et al. (2011). Alqahtani and Gupta (2017c) explored the manufacturer's perspective, noting that PM actions are economically viable insofar as the saving of warranty servicing costs exceeds the additional costs realized through PM activities, highlighting the importance of further exploring PM policies for remanufactured products. To reduce the high rate of failure experienced in second-hand products, two periodical age reduction PM models have been proposed by Yeh et al. (2011).

3. System Description

Herein, discrete-event simulation was utilized to identify an ideal implementation of a two-dimensional renewing warranty policy applied to remanufactured products. A specific product recovery system, the Advanced Remanufacturing-To-Order (ARTO) system, is deployed as an illustration to exhibit such a policy. Taguchi's Orthogonal Arrays provided the foundation for the design of the experiments in this study, representing the entirety of the recovery system to provide an opportunity to observe system behavior in varied experimental conditions. To identify the optimal strategy to be offered by the remanufacturer, a number of warranty and PM scenarios were analyzed through t-tests, Tukey pairwise comparison tests, in addition to one-way analysis of variance (ANOVA) for each scenario considered.

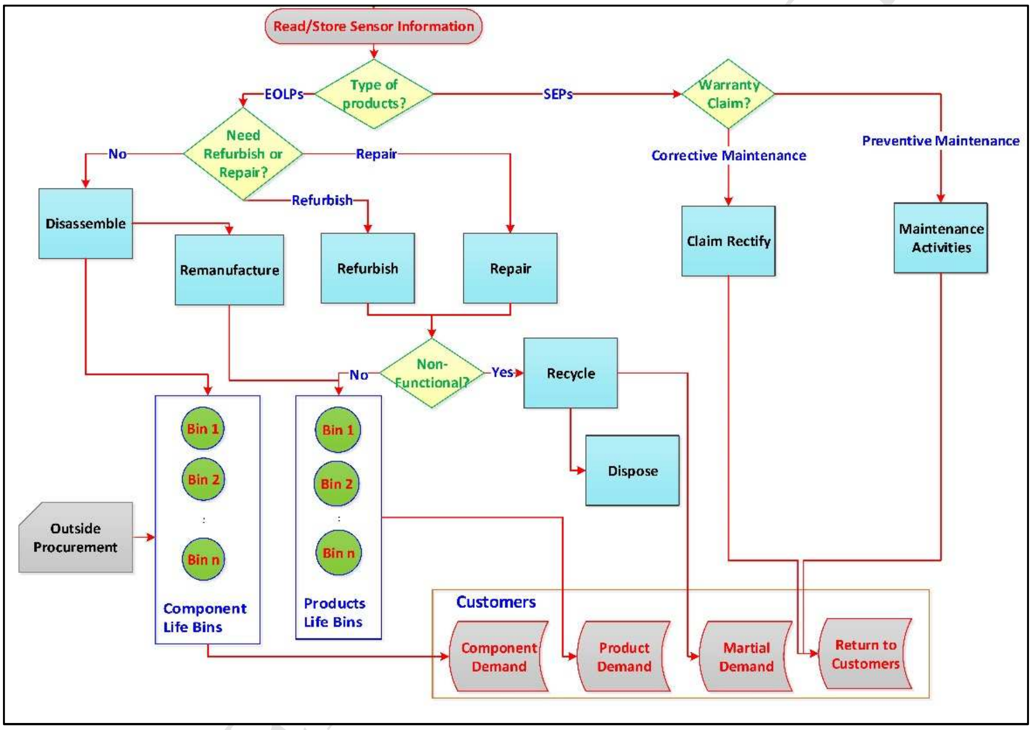

Figure 1. ARTO System's Recovery Processes

The ARTO system explored herein is a type of product recovery system, considered through the product example of a sensor-embedded washing machine (WM). A series of recovery operations are presented in Figure 1 addressing various EOL WM condition levels. Reusable components may be necessary to cover product requirements within the context of refurbishing and repairing processes, with this ideally satisfying both internal and external component needs through the disassembly of recovered components. The ARTO system may intake three different classes of items: EOL products to undergo the recovery process, failed SEPs to be refurbished, or SEPs to receive maintenance activities.

Initially, EOL WMs enter the ARTO system for data retrieval through the use of a radio frequency data reader stored in the database of the facility, after which the WMs are processed through a 6-station disassembly line. To ensure the extraction of all components, complete disassembly is performed. Refer to Table 1 for the hierarchy of relationships amongst the components of the WM. As demonstrated in Figure 2, the WM is comprised of 9 components, the agitator, control panel, metal cover, motor, pump, pulley, spin tub, transmission, and water and drain hoses. Station disassembly times are determined by exponential distributions, inter-arrival times for the demand of each component, and the inter-arrival times of EOL WMs. Following the retrieval of information, all EOLPs are shipped to station 1 for disassembly, or, in the event the EOL only requires the repair of a particular component, it is directed to the relevant station.

Depending on the condition of the components, one of two disassembly options is chosen from the options of destructive or nondestructive disassembly. Should the disassembled component be non-functional, whether broken or having no proportion of its remaining life, destructive disassembly is employed, ensuring that the other components' functionality is not negatively impacted. Consequently, the unit disassembly costs for a functional component are greater than for a non-functional component. Following disassembly, further component testing is unnecessary as data is available to quantify component condition within the embedded sensors. Herein there are two assumptions in place, the assumption that the demand and life cycle information for EOLPs are known, and that the retrieval of information from sensors is less costly than inspection and testing operations.

The recovery options deployed vary depending upon the overall condition and estimated remaining life of each SEP. Spare parts demands are provided for through recovered components, while material demands are provided for through the use of recycled products and components. Products and components that are recovered are then distributed into bins based upon their remaining lifespans to be applied to recovery operations as appropriate. Should a product or component be classified into a lower remaining lifespan bin, the value of the higher life is lost, exhibiting the importance of accurately determining remaining life to optimize the economical return. Should a product, component, or material inventory level exceed the maximum inventory level for that particular class, it is classified as excess, and either disposed of or utilized to meet material demands.

To meet product demand, repair and refurbish options must be carefully chosen from the options, as exhibited in Figure 3. The functionality and completeness of an EOLP may be limited due to missing or nonfunctional components that would then have to be replaced or replenished during the repair or refurbishment process to align with particular remaining life requirements. EOLPs may also be comprised of components with lower remaining life than necessary, and thus may require replacement. Should SEP failure be realized during the warranty period, failed WMs arrive at the ARTO system to be analyzed for data retrieval through the facility's database. Following this the WM is processed through the recovery operations applied to an EOLP.

During the final step to support a reduction in the risk of failure, PM actions are performed during the warranty period. Within this study, should the remaining life of a remanufactured WM reach a predetermined value, the remanufactured SEPs are taken into the ARTO system for information retrieval from the radio frequency data reader of the facility. After this, the SEPs undergo four maintenance activities depending upon the data collected from the sensors, those of adjustments, cleaning, measurements, and parts replacement. PM actions are performed with degree δ, with the remaining life of the remanufactured WMs being δ units of time more than before the process, as exhibited in Figure 4. Should failures be experienced between two successive PM action during the warranty period, no costs are realized by the consumer.

The Advanced Remanufacturing-To-Order (ARTO) system deliberated on in this study is similar to a product recovery system. A sensor embedded washing machine (WM) is considered here as a product example. Based on the condition of EOL WM, it goes through a series of recovery operations as shown in Figure 1. Refurbishing and repairing processes may require reusable components in order to meet the demand of the product. This requirement satisfies both the internal and the external component demands. Thus, both will be satisfied using disassembly of recovered components. There are three different types of items arrivals in the ARTO system; either the EOL products for recovery process, failed SEP need to rectify or SEP due for maintenance activities.

Table 1. WM Components and precedence relationship

Component Name	Station	Code	Preceding Component
Metal Cover	1	A	-----
Control Panel	2	B	-----
Agitator	3	C	A, B
Spin Tub	3	D	A, B, C
Motor	4	E	A, B, C, D
Pump	5	F	A, B, C, D, F
Water & Drain Hoses	5	G	F
Pully	6	H	D, F, H
Transmission	6	I	H

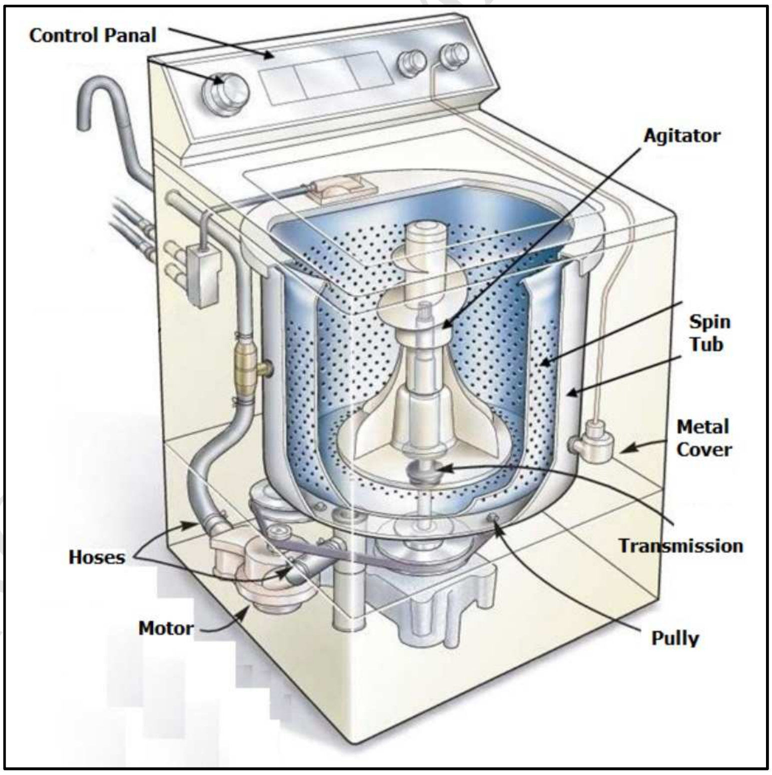

Figure 1 Washing Machine (WM) components

First, EOL WMs arrive at the ARTO system for information retrieval using a radio frequency data reader that is stored in the facility’s database. Then the WMs go through a six-station disassembly line. Complete disassembly is performed for the purpose of extracting every single component. Table 1 represents the precedence of relationships between the WM components. There are nine components in a WM: the Metal Cover, Control Panel, Agitator, Spin Tub, motor, Pump, Water & Drain Hoses, Pully, and Transmission, as shown in Figure 2. Exponential distributions are used to generate the station disassembly times, interarrival times of each component's demand, and interarrival times of EOL WM. All EOLPs after retrieval of the information are shipped either to station 1 for disassembly or, if EOLP only needs a repair for a specific component, it is instead sent to its 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 not functional (broken, zero percent of remaining life), then destructive disassembly is utilized in such a way that the other components' functionality is not damaged. Therefore, unit disassembly cost for a functional component is higher than for a nonfunctional component. After disassembly, there is no need for component testing due to the availability of information regarding components' conditions from their sensors. It is assumed that the demands and life cycle information for EOLPs are known. It is also assumed that the retrieval of information from sensors costs less than the actual inspecting and testing.

4. Extended Warranty

Within the context of the purchasing decision, buyers often compare the features of a product with competing brands offering a product of the same function. In some instances competing brands may produce products that resemble one another in terms of cost, special characteristics, credibility of the product, insurance provided to the consumer, and quality. After the influence of sale factors are experienced, discount, warranty, and the availability of parts, repairs, and other services is then factored. These elements are of significance in the purchasing decision, with the warranty allowing the buyer to further determine the level of reliability of a given product.

The warranty is an agreement between the manufacturer and the consumer through which the risk of product failure is addressed through correction or compensation on behalf of the manufacturer, insofar as the product issues are realized during the warranty period linked to the sale. Through the warranty, the product quality perception of the consumer is supported through the provision of performance guarantees. In general, the warranty cost of a product is the same for all new items insofar as the manufacturer has a well-established and effective quality control system. While warranty costs are easily measurable, EOL products vary in value due to a number of variables including age, maintenance history, and usage, and thus the warranty cost for a given remanufactured product is statistically unique.

Consumer are increasingly aware and in demand of warranties for remanufactured products due to a growing concern with product quality, and an increasing level of environmental awareness on behalf of consumer. This awareness is anticipated to increase the demand for remanufactured products in concert with the future costs of replacement/repair in the event product failure is experienced. This highlights the importance of warranty management to remanufacturers of remanufactured products. Such manufacturers must effectively estimate the warranty costs to then be incorporated into the pricing structure, with failure to accomplish this potentially resulting in loss rather than profit through the sale of remanufactured items.

The analysis of warranty costs for remanufactured products is complex in comparison to new products due to the variable levels of usage and maintenance history. Further, warranty policies similar to new and second-hand products may not be economically viable for the manufacturer. To determine the prospective profitability of the chosen warranty format, it is necessary to test and compare warranty policies for remanufactured products to estimate the anticipated warranty cost that is associated with the policies. According to Murthy and Blischke (2006), remanufacturers confront further issues including the servicing strategies concerning remanufactured spare parts within the context of repair or replacement to address failures within the context of the warranty period.

A base warranty (BW) is a predetermined agreement entered into between the remanufacturer and buyer at the time of purchase, and is generally associated with products. Should the product fail to perform as defined, the warranty contract defines the options available to the buyer. The BW is an element of the sale, with the cost thereof incorporated into the product price. The extended warranty (EW) by contrast is purchased separately with the buyer having a choice of terms in some instances (Murthy, 2014).

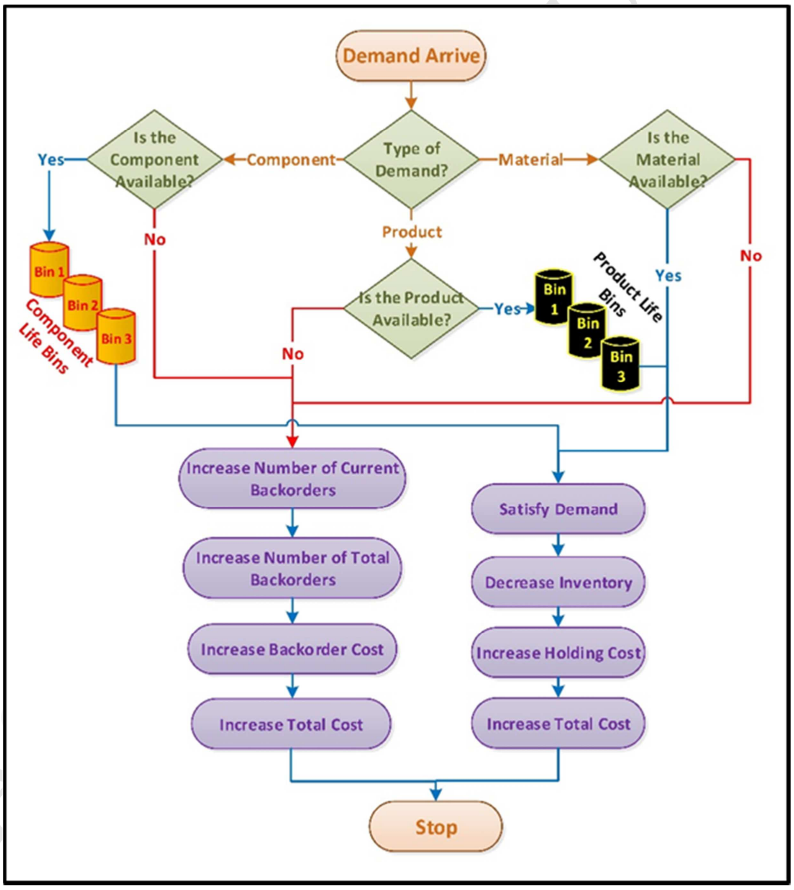

Figure 3. ARTO System Demand Process

In the modern environment, EWs are offered with a variety of products, including appliances, automobiles, electronics, and many more. In general the buyer must purchase the EW at the time of purchase for the product. The EW costs the buyer an extra amount beyond the price, determined by the duration and terms therein. By contrast, the BW is an essential element of the product sale, while the consumer does not pay a premium for it.

There are various types of EW policies that manufacturers generally offer to their buyers. The main expense realized by the EW is the cost of servicing an item that fails during the warranty period, added atop the purchase price. Of the EW options, the most popular is the Free Replacement Warranty (FRW). The warranty cost realized by the vendor is the cost of servicing all warranty claims for a product during the full warranty period, whether base or extended.

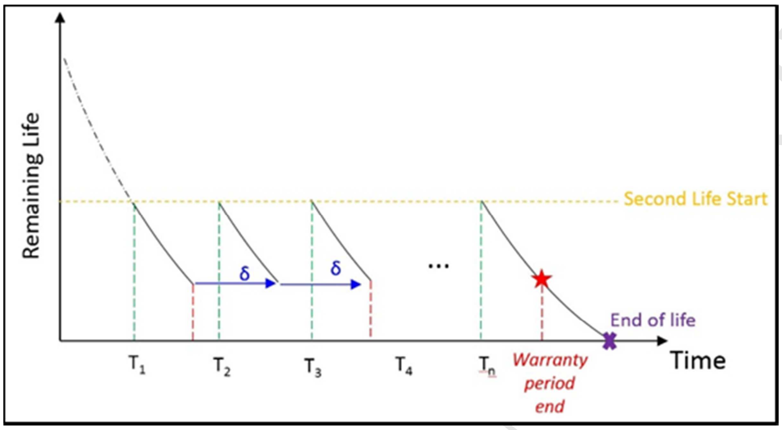

Figure 4. Scheme for PM policies for remanufactured products

5. Assumptions and Notations

This section starts with the model assumptions. Then, the notation of all the parameters used in this paper.

5.1 Assumptions

The following assumptions have been considered to simplify the analysis:

i. The failures are statistically independent.

ii. Every item failure under warranty period results in a claim.

iii. All claims are valid.

iv. The failure of a remanufactured item is only a function of its age.

v. The time to carry out the replacement/repair action is relatively small compared to the mean time between failures.

vi. The cost to service warranty claim (for repair/replacement of failed component) is a random variable.

5.2 Notations

W: Warranty period
W_1: Sub-interval of warranty period
C_o: Operating cost of item

C_S:	Sale price of item
C_p:	Cost of remanufacturing an item
n:	Number of components in an item
RL:	Remaining life of item at sale
RL_i:	Remaining life of component i ($1 \leq i \leq n$)
$U_{i,}\, L_i$:	Upper and Lower range of replacement component's remaining life
j:	Number of preventive maintenance;
v:	Virtual remaining life;
v_j:	Virtual remaining life after performing the jth PM activity;
m:	Level of PM effort;
$\delta(m)$:	Remaining life increment factor of PM with effort m;
t:	Remaining life of remanufactured item at failure;
$\Lambda(RL)$:	Intensity function for system failure;
Λ_i:	Intensity function of non-stationary Poisson process
M_{iu}:	Renewal function associated with $F_{iu}\,(x)$
$E\,[.]$:	Expected value of expression within [.]
$F_i\,(x)$:	Failure distribution of a remanufactured component i
$F_{i1}\,(x)$:	Distribution function for times to first failure of component i
$F_{i2}\,(x)$:	Distribution function for times to subsequent failures of component i
$F_{iu}\,(x)$:	Distribution function for times to failure of remanufactured component used in replacement
$H\,(rl)$:	Distribution function for a remanufactured item
$H_i\,(rl)$:	Distribution function for a remanufactured components
$N\,(W;\, RL)$:	Number of failures over the warranty period with remaining life, RL
$N_i(W;\, RL_i)$:	Number of failures for component, i, over the warranty period
$\Lambda(t)$:	Intensity function for system failure
$F_w(x)$:	Distribution function for the first failure in the period $[W_1,\, W)$ given by the excess remaining life of renewal process associated with failures in the period $[0,\, W_1)$
$C_d(W;\, RL)$:	Total warranty cost to remanufacturer
$C(m)$	Cost of performing a Preventive maintenance with effort m
C_j:	Cost of replacement/repair j^{th} failure, $j \geq 1$

6. Preventive Maintenance Analysis

Usually, PM activities involve a set of maintenance tasks, such as, cleaning, systematic inspection, lubricating, adjusting and calibrating, replacing different components, etc. (Ben Mabrouk et. al., 2016). The right PM activities can be able to reduce the number of failures efficiently, as a result reduce the warranty cost and increased the customer satisfaction. This study, adopt the modelling framework proposed by Kim et al., 2004 to model the effect of PM activities.

A series of PM activities of a remanufactured item are performed at remaining life RL_1, RL_2,… RL_j,…, with $RL_0 = 0$. Here, the effect of PM results in a restoration of the item so that the item's virtual remaining life is effectively increase. The concept of virtual age is introduced in Kijima et al., 1988; and then extended in Kijima (1989). In this study, the j^{th} PM only reimburses the damage accrued during the time between the $(j-1)^{th}$ and the j^{th} PM activities, as a result an arithmetic reduction of virtual remaining life can be obtain (Martorell et al., 1999). Therefore, the virtual remaining life after performing the j^{th} PM activity, i.e. RL_j, is then given by

$$v_j = v_{j-1} + \delta(m)(RL_j - RL_{j-1}) \tag{1}$$

where m is the level of PM effort, and $\delta(m)$, $m = 0, 1, …, M$, is the remaining life increment factor of PM with effort m. Note that, the effect of PM depends on its level m, $0 \le m \le M$, and its relationship with the remaining life is characterized by the age-incremental factor $\delta(m)$. Larger value of m represents greater PM effort, hence $\delta(m)$ is a increasing function of m with $\delta(0) = 0$ and $\delta(M) = 1$. More specifically, if $m = 0$, then $v_j = RL_j$, $j \ge 1$, which means that the item is restored to as bad as old (ABAO);if $m = M$, the item is restored back to as good as new (AGAN); while in a more general case $m \in (0, M)$, the item is partially restored, i.e. the PM activity is imperfect. This concept will be used in the next section to derive the expected.

7. Failures and Renewal Process

Most products are complex and multipart so that an item can be viewed as a system consisting of several components. The failure of an item occurs due to the failure of one or more components. A remanufactured product or component is categorized in terms of two states viz., working or failed. The time intervals between consecutive failures are random variables and modelled by proper distribution functions. Interchangeably, the number of failures over time can model by a suitable counting process.

The actions to make a failed item operational depend on whether the failed component (s) are repairable or not. In the case of a repairable component, the remanufacturer has the option of repairing or replacing it by a remanufactured working component if available. If not a new component will be used to rectify the claim. In case of repairable components, the characterization of subsequent failures depends on the type of repair (e.g., minimal repair, imperfect repair and so on). Similarly, in the case of a non-repairable component, the remanufacturer can use a remanufactured working component in the replacement to make the item operational.

Time to first failure of a remanufactured component depends on the mean remaining lifetime (MRL) and the PM of the component at the time of sale of the remanufactured product. If the sensor information about EOL component indicates that it has never failed, or was always minimally repaired, then the remaining life of the component at sale is the same as that of the item. Usually, the MRL of remanufactured component at sale differs due to the replacement or repair and maintenance actions. Therefore, the time to first failure under warranty needs to be defined. Let RL_i denote the remaining life of remanufactured component, *i*. There are two cases: either RL_i is known because of embedded sensor or RL_i is unknown because it is a conventional product.

The sensor embedded in the item provides the remanufacturer with the MRL of the item at sale and the virtual remaining life due to upgrades and maintenances information. The item failure is modelled by a point process with intensity function Λ (RL) where RL represents the remaining life of the item. Λ (RL) is a decreasing function of RL indicating that the number of failures increases with remaining life decrease. The failures over the warranty period occur according to a non-stationary Poisson process with intensity function Λ (RL). This implies that N (W; RL), the number of failures over the warranty period W for an item of remaining life RL at the time of sale and virtual remaining life v, is a random variable with

$$P\{N\,(W\,;RL) = \; n\} = \left\{\int_{v}^{v+W} \Lambda(RL)\, dRL\right\} \mathrm{e}^{-\int_{v}^{v+W} \Lambda(RL) dRL}/n! \tag{2}$$

The expected number of failures over the warranty period is given by

$$E\;[N\;(W;\; RL)] = \int_{v}^{v+W} \Lambda(RL) dRL \tag{3}$$

ARENA 14.7 is used to generate the remaining life of remanufactured item at failure; (t_i), using a bivariate random number generator and time history of replacements under warranty and repeat sales over the simulation time interval. The ARENA simulation program yields the remaining life at failures under warranty; the virtual remaining life after preventive maintenance activities, the number of replacements under warranty for each purchase and the time between repeat purchases.

8. Warranty Formulation

In this paper, the component remaining life RL_i is known from sensor information and components which fail during the warranty period will be replaced by remanufactured components.

8.1 First Failure

Since a sensor embedded is used to determent the remaining life of the component, the distribution for the first failure, $F_{i1}(x)$ is given by:

$$F_{i1}(x) = [F_i(v_i + x) - F_i(v_i)]/[1 - F_i(L_i)] \tag{4}$$

8.2 Succeeding Failures

In the meantime, distribution for succeeding failures, $F_{i2}(x)$, is given by:

$$F_{i2}(x) = \; p\, F_i(x) + (1 - p)\, F_{iu}(x) \tag{5}$$

Accordingly, the expected number of failures over the warranty period is given by:

$$E[N_i(W; v_i)] = [F_{i1}(W) + \int_0^W M_{i2}(W - x) dF_{i1}(x)] \tag{6}$$

8.3 Analysis of Extended Free Replacement Warranty Policy

This section carries out an analysis of Extended Free Replacement Warranty (FRW) Policy to determine the expected warranty costs.

Under this policy the remanufacturer resolves all failures over the warranty period at no cost to the buyer. The replacement/repair can involve either repair or replacement of failed items or components. The warranty expires after time *W* from the time of sale.

If an item of remaining life *RL* fails at time (X_1) (where $X_1 < W$ and $RL > W$). Then the replaced or repaired item is warranted for the remaining period (W-X_1) until the total operating time of the original item and its replacements/ repaired items exceeds the warranty period *W*. Under this policy, there is no cost to the buyer.

Since the cost is completely carried by the remanufacturer then cost to remanufacturer for replacement/repair jth failure is equal to cost of replacement/repair jth failure:

$$C_{pj} = C_{dj} \tag{7}$$

The number of failures over the warranty period for an item with sensor embedded is given by:

$$C_d\,(W;\ v\,) = \sum_{j=1}^{N(W;RL)} C_{pj} \tag{8}$$

$$E[C_d(w;v)|N(W;v) = n] = n\,E[C_{pj}] \tag{9}$$

$$E\,[C_d(W;\ v)] = E\,[N\,(W;v)].E\big[C_{pj}\big] = E[N\,(W;\ v)].E[C_{dj}\,] = \ E[N\,(W;v)]\,\overline{c_d} \tag{10}$$

$$E\,[C_d(W;\ v)]\ =\ \overline{c_d}\int_v^{v+W} \Lambda(t)\,dt \tag{11}$$

8.4 Analysis of Extended Pro-Rata Warranty Policy

This section carries out an analysis of Extended Pro-Rata Warranty (PRW) Policy to determine expected warranty costs.

Under this policy the remanufacturer refunds a fraction of sale price if an item fails before warranty period. The buyer is not constrained to buy a replacement item. This paper consider linear refund function given by

$$S(X) = \begin{cases} C_S\,(v)\left\{1 - \frac{W_1+Y}{W}\right\} & for\ 0 \le\ X \le (W - W_1) \\ \quad 0 & for\ X > (W - W_1) \end{cases} \tag{12}$$

The time to failure, F_{i1} given by (4). As a result, the expected warranty cost to the remanufacturer, $E\,[C_d\,(W;\ v)]$ is given by

$$E[C_d(W;\ v)]\ = \int_0^W S(x)dF_{i1}\,(x) = c_S\,(v)[F_{i1}\,(W) - \left(\frac{1}{W}\right)\int_0^W x\ dF_{i1}\,(x)] \tag{13}$$

8.5 Analysis of FRW-PRW Combination Policy

This section carries out an analysis of Extended FRW-PRW Policy to determine expected warranty costs.

Under this policy the remanufacturer replaces failed items at no cost to the buyer up to W_1 ($W_1 < W$). If a failure occurs in the interval [W_1, W) the remanufacturer refunds a fraction of the sale price and the warranty terminates.

Since the item has no sensor embedded to retrieve all the data needed, the remaining life *RL* is known. The failures over [0, W_1) are given by a modified renewal process. Therefore, the expected warranty cost to the remanufacturer for failures in [0, W_1), *E* [C_d(W_1; *RL*)], is given by:

In this model, the failure distribution of the component i, at the time of sale, is given by F_{iu}. Then, failures over [0, W_1) are given by an ordinary renewal process. The cost over [W_1, *W*) is given by

$$E[C_d(W_1, W;\ L)] = C_S[\ F_{i1}(W_1) + \int_0^{W_1} M_{iu}(W_1 - x)\, dF_{i1}\,(x)] \\ + c_S\ [\left\{\frac{W - W_1}{W}\right\} F_W(W - W_1) - \left(\frac{1}{W}\right) \int_0^{(W-W_1)} X dF_W(X) \qquad (14)$$

8.6 Pricing of a Remanufactured Item

A remanufactured item with small remaining life indicates a higher expected warranty cost where a younger item with large remaining life implies a smaller expected warranty cost. Remanufacturers sell remanufactured items of different remaining life. If a remanufacturer were to price each item so as to recover the warranty and preventive maintenance costs associated with the item, then the sale price, C_S (*v*), of a remanufactured item of virtual remaining life *v* needs to satisfy the inequality given below and failure to do so would imply a loss (rather than profit) in an expected sense.

$$C_S(v) > C_p(v) + C(m) + C_d(W; v) \qquad (15)$$

If the remanufacturer were to price an item based on a fixed expected warranty cost, then the warranty duration (*W*) must decrease as the virtual remaining life (*v*) decrease. This indicates a shorter warranty period for a remanufactured item with low remaining life. An alternative strategy for overcoming this problem is to determine the sale price based on a warranty cost averaged over the different remaining lives. That will make higher warranty costs for less remaining life. Remanufactured items are balanced by lower warranty costs for higher remaining life items. This lowers the sale price of lower remaining life items at the expense of higher sale price for higher remaining life items. From a marketing point of view, this is a more attractive and better strategy for the remanufacturer.

9. Results

The results are divided into two parts. The first part deals with evaluating the effect of offering different warranty policies to help the decision maker choose the best warranty policy to offer, and the second part presents a quantitative assessment of the impact of SEPs on the warranty costs and policies to the remanufacturer.

9.1 Remanufacturing Warranty Policies Evaluation

In this part, the results to compute the expected number of failures and expected cost to the remanufacturer were obtained using the ARENA 14.7 program.

- 9.1.1 Extended Free Replacement Warranty (FRW) Policy:

Table 2a-2b present the expected number of failures and cost for remanufactured WM and components for extended FRW, PRW and Combination Policies. In Table 2-a and

Table 2-b, the expected number of failures represents the expected number of failed items per unit of sale. In other words, it is the average number of free replacements that the remanufacturer would have to provide during the warranty period per unit sold. Expected cost to the remanufacturer includes the cost of supplying the original item, C_s. Thus, the expected cost of warranty is calculated by subtracting C_s from the expected cost to remanufacturer. For example, from Table 2-b, for $W = 0.5$ and $RL = 1$, the warranty cost for WM is \$113.74 - C_s = \$113.74 - \$110.00 = \$3.74 which is ([\$3.74 / \$ 110.00] x 100) = 3.40% of the cost of supplying the item, C_s, which is significantly less than that \$110.00, C_s. This may be acceptable, but the corresponding values for longer warranties are much higher. For example, for $W = 2$ years and $RL = 1$, the corresponding percentage is ([\$131.52 - \$110.00 / \$ 110.00] x 100) = 19.59%.

- 9.1.2 Extended Pro-Rata Warranty (PRW) Policy:

The results for PRW are also given in Table 2-b. Here too, the expected cost of warranty can be calculated as above. For example, the cost of warranty for 3 years remaining life WM with $W = 2$ years will cost \$170.44 - C_s = \$170.44 - \$110.00 = \$60.44 which is 54.96% of the cost of supplying the item, C_s.

- 9.1.3 Combination Free Replacement Warranty (FRW) Policy:

Here too the results given in Table 2-b and the expected cost of warranty can be calculated in a similar manner as above. For example, the cost of warranty for 3 years remaining life WM with $W = 2.0$ years will cost \$111.26 - \$110.00 = \$1.26 which is 1.15% of the cost of supplying the item, C_s.

9.2 Impact of SEPs on Warranty Analysis

In order to assess the impact of SEPs on warranty cost, pairwise t tests were carried out for each performance measure. Table 3 presents ninety-five percent confidence interval, t value and p value for each test. According to these tables, SEPs achieve statistically significant savings in holding, backorder, disassembly, disposal, testing, remanufacturing and transportation costs. In addition, SEPs provide statistically significant improvements in total revenue and profit. According to Table 3, the lowest average value of warranty costs, the number of warranty claims and PM during the warranty period for remanufactured WMs across all policies are \$18,051.70, 23,962 claims and \$3,462.48 respectively for the extended FRW warranty policy.

10. Conclusion

Sensors are implanted into sensor-embedded products during the initial production process. The value of sensors is realized through their ability to determine the best warranty policy and warranty period to present to consumers when selling remanufactured components and products. The remaining life and condition of components and products may be estimated prior to presenting a warranty, based upon the data collected through the sensors. Such information allows the remanufacturer to avoid unnecessary costs by enabling the remanufacturer to control the number of claims during warranty periods, and to determine the appropriate PM policy to employ. Herein, the costs of extended FRW, PRW, and combination FRW/PRW policies were explored through the offering of PM for different periods. The impact of offering the consumer FRW, PRW, or combination FRW/PRW policies to each disassembled component and SEP was also analyzed to identify the impact of SEPs on warranty costs. To further examine the issue, a case study was constructed in addition to a number of simulation scenarios to illustrate the prospective value of the model proposed herein.

Table 3. Results of performance measures for different models with warranty and PM

Performance Measure	Mean Value with Warranty (PM offered)			
	Conventional Model	Sensor Embedded Model with FRW	Sensor Embedded Model with PRW	Sensor Embedded Model FRW/PRW
Holding Cost	\$375,385.55	\$301,548.74	\$317,111.26	\$318,392.24
Backorder Cost	\$69,633.45	\$60,654.40	\$63,784.70	\$64,042.36
Disassembly Cost	\$810,570.05	\$643,094.96	\$676,284.22	\$679,016.10
Disposal Cost	\$131,308.02	\$121,768.44	\$128,052.74	\$128,570.00
Testing Cost	\$241,762.49	N/A	N/A	N/A
Remanufacturing Cost	\$2,786,743.91	\$1,797,936.76	\$1,890,725.80	\$1,898,363.46
Transportation Cost	\$70,316.93	\$63,212.98	\$66,475.32	\$66,743.84
Warranty Cost	\$176,556.98	\$18,051.70	\$43,487.68	\$31,771.64
Number of Claims	83,583	23,962	30,974	29,586
Preventive Maintenance Cost	\$13,630.88	\$3,462.48	\$6,363.96	\$5,543.46
Total Cost	\$4,759,491.23	\$3,033,692.46	\$3,223,259.68	\$3,222,029.10
Total Revenue	\$6,693,569.22	\$7,452,158.07	\$6,933,609.46	\$7,677,871.58
Profit	\$1,934,078.00	\$4,418,465.61	\$3,710,349.78	\$4,455,842.48

Table 4. ANOVA Table and Tukey Pairwise Comparisons for Warranty Cost

ANOVA: Warranty Cost					
Null hypothesis	All means are equal				
Alternative hypothesis	At least one mean is different				
Significance level	α = 0.05				
SUMMARY					
Models	***Count***	***Sum***	***Average***	***StDev***	***95% CI***
Conventional Model	2000	353,113,950	176,556.98	675.40	(157977.3, 179653.8)
SEP Model FRW	2000	36,103,400	18,051.70	669.48	(14086.7, 21037.3)
SEP Model PRW	2000	86,975,360	43,487.68	681.49	(29522.2,46473.6)
SEP Model FRW/PRW	2000	63,543,280	31,771.64	668.45	(27806.6, 34757.4)
ANOVA					
Source of Variation	***SS***	***df***	***MS***	***F-Value***	***P-value***
Model	2.42E+13	3	5.25E+12	62499126	0
Error	1.032E+09	7996	83999		
Total	2.42E+13	7999			
Tukey Pairwise Comparisons					

Grouping Information Using the Tukey Method and 95% Confidence

Model	N	Mean	Grouping
SEP Model FRW	2000	18,051.70	A
SEP Model FRW/PRW	2000	31,771.64	B
SEP Model PRW	2000	43,487.68	C
Conventional Model	2000	176,556.98	D

Means that do not share a letter are significantly different.

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Table 2.a Expected number of failures and cost for remanufactured WM's components for extended FRW, PRW and Combination Policies

Components	***W***	**Extended Free Replacement Warranty (FRW)**						**Extended Pro-Rata Warranty (PRW)**						**Extended Combination FRW/PRW**					
		Expected probability of Failures			**Expected Cost**			**Expected Probability of Failures**			**Expected Cost**			**Expected probability of Failures**			**Expected Cost**		
		***RL* = 1**	***RL* = 2**	***RL* = 3**	***RL* = 1**	***RL* = 2**	***RL* = 3**	***RL* = 1**	***RL* = 2**	***RL* = 3**	***RL* = 1**	***RL* = 2**	***RL* = 3**	***RL* = 1**	***RL* = 2**	***RL* = 3**	***RL* = 1**	***RL* = 2**	***RL* = 3**
Metal Cover	**0.5**	0.5316	0.0035	0.0007	$7.48	$8.58	$6.86	0.6688	0.0044	0.0009	$10.78	$12.36	$9.86	0.4518	0.0029	0.0007	$8.20	$9.40	$7.50
	1	0.1066	0.0139	0.0064	$8.30	$9.40	$6.98	0.1341	0.0174	0.0080	$11.98	$13.54	$10.04	0.0905	0.0117	0.0054	$9.12	$10.30	$7.66
	2	0.1596	0.0309	0.0214	$12.46	$12.38	$7.18	0.2007	0.0387	0.0269	$17.94	$17.84	$10.36	0.1356	0.0262	0.0183	$13.68	$13.60	$7.90
Control Panel	**0.5**	0.5253	0.0033	0.0041	$7.34	$8.52	$6.84	0.6607	0.0041	0.0052	$10.58	$12.28	$9.84	0.4464	0.0028	0.0035	$8.06	$9.36	$7.50
	1	0.1130	0.0135	0.0340	$8.66	$9.14	$6.94	0.1421	0.0171	0.0428	$12.48	$13.18	$9.98	0.0959	0.0116	0.0289	$9.50	$10.04	$7.60
	2	0.1532	0.0306	0.1147	$12.32	$12.16	$7.14	0.1926	0.0386	0.1443	$17.74	$17.50	$10.30	0.1302	0.0261	0.0974	$13.52	$13.34	$7.84
Agitator	**0.5**	0.5189	0.0032	0.0221	$3.68	$3.44	$3.52	0.6527	0.0040	0.0278	$5.30	$4.96	$5.06	0.4409	0.0027	0.0188	$4.04	$3.78	$3.86
	1	0.1002	0.0140	0.1823	$4.84	$6.10	$3.60	0.1261	0.0175	0.2292	$6.96	$8.80	$5.16	0.0851	0.0118	0.1549	$5.32	$6.68	$3.94
	2	0.1469	0.0311	0.6130	$6.68	$7.50	$3.72	0.1846	0.0392	0.7711	$9.62	$10.82	$5.38	0.1248	0.0265	0.5210	$7.32	$8.24	$4.10
Spin Tub	**0.5**	0.5189	0.0014	0.1180	$2.02	$1.98	$1.68	0.6527	0.0018	0.1485	$2.92	$2.84	$2.44	0.4409	0.0012	0.1003	$2.22	$2.18	$1.86
	1	0.0747	0.0141	0.9742	$2.92	$2.70	$1.86	0.0940	0.0177	1.2254	$4.22	$3.88	$2.68	0.0635	0.0120	0.8278	$3.22	$2.96	$2.04
	2	0.1340	0.0269	0.3992	$3.88	$3.84	$1.98	0.1686	0.0339	0.5021	$5.58	$5.54	$2.84	0.1139	0.0229	0.3392	$4.26	$4.22	$2.18
Pump	**0.5**	0.5036	0.0033	0.6313	$7.66	$7.34	$7.18	0.6334	0.0041	0.7941	$11.04	$10.58	$10.34	0.4279	0.0028	0.5364	$8.40	$8.06	$7.88
	1	0.1092	0.0135	0.8189	$8.42	$7.86	$7.30	0.1373	0.0170	1.0300	$12.14	$11.32	$10.54	0.0927	0.0116	0.6958	$9.24	$8.62	$8.02
	2	0.1539	0.0311	0.0171	$11.84	$10.16	$7.38	0.1935	0.0392	0.0214	$17.04	$14.66	$10.64	0.1307	0.0265	0.0145	$13.00	$11.16	$8.10
Water & Drain Hoses	**0.5**	0.5246	0.0035	0.7848	$2.40	$2.04	$1.98	0.6599	0.0045	0.9871	$3.44	$2.94	$2.88	0.4458	0.0030	0.6668	$2.64	$2.24	$2.20
	1	0.1021	0.0138	0.8257	$3.48	$2.92	$2.18	0.1284	0.0173	1.0386	$5.00	$4.22	$3.16	0.0867	0.0117	0.7017	$3.82	$3.22	$2.42
	2	0.1608	0.0311	0.0912	$4.02	$3.38	$2.30	0.2023	0.0391	0.1147	$5.80	$4.86	$3.34	0.1367	0.0265	0.0775	$4.42	$3.70	$2.54
Pully	**0.5**	0.5374	0.0032	0.8189	$4.58	$3.88	$3.72	0.6759	0.0040	1.0300	$6.60	$5.58	$5.38	0.4566	0.0027	0.6958	$5.04	$4.26	$4.10
	1	0.1174	0.0136	0.1665	$6.34	$4.52	$3.82	0.1477	0.0172	0.2094	$9.12	$6.54	$5.50	0.0998	0.0117	0.1415	$6.94	$4.98	$4.20
	2	0.1544	0.0309	0.4875	$7.88	$6.30	$4.02	0.1943	0.0388	0.6132	$11.34	$9.08	$5.80	0.1313	0.0263	0.4143	$8.64	$6.90	$4.42
Transmission	**0.5**	0.5425	0.0035	0.5834	$1.22	$0.96	$0.68	0.6824	0.0044	0.7339	$1.74	$1.36	$0.98	0.4610	0.0029	0.4957	$1.34	$1.04	$0.74
	1	0.1002	0.0137	0.8900	$1.88	$1.52	$0.82	0.1261	0.0173	1.1195	$2.72	$2.20	$1.18	0.0851	0.0117	0.7563	$2.06	$1.68	$0.90
	2	0.1525	0.0311	0.8222	$3.30	$2.20	$0.88	0.1919	0.0392	1.0343	$4.74	$3.18	$1.28	0.1296	0.0265	0.6987	$3.62	$2.44	$0.96
Compressor	**0.5**	0.5240	0.0035	0.0173	$5.32	$4.98	$4.76	0.6592	0.0044	0.0219	$7.66	$7.18	$6.86	0.4452	0.0029	0.0148	$5.84	$5.48	$5.24
	1	0.1060	0.0138	0.0912	$6.86	$6.44	$5.16	0.1332	0.0173	0.1147	$9.86	$9.26	$7.44	0.0900	0.0117	0.0775	$7.50	$7.06	$5.68
	2	0.1539	0.0310	0.8257	$9.32	$8.42	$5.34	0.1935	0.0389	1.0386	$13.44	$12.14	$7.70	0.1307	0.0264	0.7017	$10.24	$9.24	$5.86

Table 2.b Expected number of failures and cost for remanufactured WM for extended FRW, PRW and Combination Policies

Components	***W***	**Extended Free Replacement Warranty (FRW)**						**Extended Pro-Rata Warranty (PRW)**						**Extended Combination FRW/PRW**					
		Expected probability of Failures			**Expected Cost**			**Expected Probability of Failures**			**Expected Cost**			**Expected probability of Failures**			**Expected Cost**		
		***RL* = 1**	***RL* = 2**	***RL* = 3**	***RL* = 1**	***RL* = 2**	***RL* = 3**	***RL* = 1**	***RL* = 2**	***RL* = 3**	***RL* = 1**	***RL* = 2**	***RL* = 3**	***RL* = 1**	***RL* = 2**	***RL* = 3**	***RL* = 1**	***RL* = 2**	***RL* = 3**
WM	**0.5**	0.6232	0.0045	0.0004	$113.74	$107.78	$106.84	0.7838	0.0058	0.0006	$131.66	$125.16	$159.74	0.3114	0.0021	0.0002	$110.02	$105.90	$104.98
	1	0.1602	0.0184	0.0029	$116.52	$117.70	$111.46	0.2016	0.0231	0.0035	$137.38	$137.62	$167.22	0.0629	0.0082	0.0012	$114.44	$115.56	$109.50
	2	0.2100	0.0409	0.0092	$131.52	$133.62	$115.30	0.2641	0.0515	0.0117	$161.42	$157.60	$170.44	0.0914	0.0185	0.0042	$132.92	$131.06	$111.26

Appendix: Design-of-Experiments Study

Ilgin and Gupta (2011) conducted a quantitative evaluation of SEPs in the context of disassembly line performance, and demonstrated that smart SEPs are a viable solution to handling customer uncertainty pertaining to remanufactured products. Herein, this claim was tested on ARTO through the construction of a simulation model representing the full recovery system and the observed behavior therein under varying experimental conditions. Discrete-event simulation models were constructed through the ARENA program, Version 14.5. 51 factors were employed in a three-level factorial design, with the levels defined as low, intermediate, or high. The three-level designs were employed to model possible curvature in the response function, while also addressing the case of nominal factors that are realized at all three levels. Refer to Appendix A, Table A.1 and Table A.2 for the parameters, factors, and factor levels.

A significant number of experiments (viz., 5.185E+25) to present a full-factorial design with 54 factors over three levels. Such a number would not be viable within the confines of this study, and thus to reduce the number of experiments to a practical quantity, a relatively small set of possible variable combinations were employed in the study. Partial fraction experiments were employed, the selection method of an experiment's number, to yield the greatest amount of information possible concerning all factors that impact the performance parameter within the minimum number of experiments possible. Taguchi (1986) when engaging in such experiments employed particular guidelines and options, with a new means of conducting the experimental design presented in the form of using a special set of arrays named orthogonal arrays (OAs). OAs provided a means through which only minimal number of experiments to be conducted are identified. The minimum quantity of experiments required to conduct the Taguchi method may be calculated through the application of the degrees of freedom approach. Generally, OA is more efficient than other statistical designs.

Thus, the quantity of experiments must be greater than or equal to the system's degree-of-freedom. Specifically, $L_{109}(3^{54})$ (i.e., 109= [(Number of levels -1) x Number of Factors] +1) Orthogonal Arrays were selected due to the degree of freedom in the ARTO system being 101, which means 101 experiments are necessary to address the 54 factors upon three different levels incorporated herein. OA assumes that there is no interaction between any two factors amongst the 54 studied. Additionally, to support verification and validation, animations of the simulation models were constructed in concert with multiple dynamic and counters plots. Some 2,000 replications over 6 months were utilized to run each experiment (at 8 hours a shift, one shift per day, and 5 days per week). Arena models were deployed to calculate the profit through the application of this equation:

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:

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

SR is defined as the total revenue generated by the product; component and material sales during the run time of the simulation; CR is the total revenue produced through the collection of EOL WMs during simulation run time; SCR is the total revenue produced through selling scrap components during the simulated run time; HC is defined as the total holding cost of components, materials, products, and EOL WMs within the run time of the simulation; BC is the total backorder cost associated with products, materials, and components within the simulation run time; DC is the total disassembly cost realized during the run time of the simulation; DPC represents the total disposal cost of components, materials, and EOL WMs during the simulations run time. TC is the total testing cost realized during the simulation's run time; RMC is the total remanufacturing cost of products during the simulation run time; TPC represents the total transportation cost during the run time of the simulation; PMC is the total preventive maintenance cost that is realized during the simulation's run time, with WC representing the total cost of the warranty.

Table A.1. Parameters used in the ARTO system

Parameters	**Unit**	**Value**	**Parameters**	**Unit**	**Value**
Backorder cost rate	%	40	Price for 3 Years Spin Tub	$	30
Holding cost rate	$/hour	10	Price for 3 Years Motor	$	120
Remanufacturing cost	$	1.5	Price for 3 Years Pump	$	50
Disassembly cost per minute	$	1	Price for 3 Years Water & Drain Hoses	$	40
Price for 1 Year Metal Cover	$	20	Price for 3 Years Pully	$	40
Price for 1 Year Control Panel	$	40	Price for 3 Years Transmission	$	130
Price for 1 Year Agitator	$	10	Weight for Metal Cover	lbs.	8
Price for 1 Year Spin Tub	$	10	Weight for Control Panel	lbs.	4
Price for 1 Year Motor	$	85	Weight for Agitator	lbs.	2
Price for 1 Year Pump	$	30	Weight for Spin Tub	lbs.	2
Price for 1 Year Water & Drain Hoses	$	30	Weight for Motor	lbs.	6
Price for 1 Year Pully	$	30	Weight for Pump	lbs.	12
Price for 1 Year Transmission	$	10	Weight for Water & Drain Hoses	lbs.	3
Price for 2 Years Metal Cover	$	30	Weight for Pully	lbs.	3
Price for 2 Years Control Panel	$	60	Weight for Transmission	lbs.	6
Price for 2 Years Agitator	$	24	Unit copper scrap revenue	$/lbs	0.6
Price for 2 Years Spin Tub	$	24	Unit Fiberglass scrap revenue	$/lbs	0.9
Price for 2 Years Motor	$	110	Unit steel scrap revenue	$/lbs	0.2
Price for 2 Years Pump	$	36	Unit disposal cost	$/lbs	0.3
Price for 2 Years Water & Drain Hoses	$	36	Unit copper scrap Cost	$/lbs	0.3
Price for 2 Years Pully	$	40	Unit Fiberglass Scrap Cost	$/lbs	0.45
Price for 2 Years Transmission	$	120	Unit steel scrap Cost	$/lbs	0.1
Price for 3 Years Metal Cover	$	40	Price of 1 Year WM	$	360
Price for 3 Years Control Panel	$	70	Price of 2 Years WM	$	480
Price for 3 Years Agitator	$	30	Price of 3 Years WM	$	550
Operation costs for Metal Cover	$	4	Operation costs for Pump	$	1.66
Operation costs for Control Panel	$	4	Operation costs for Water & Drain Hoses	$	2.34

Operation costs for Agitator	$	2.8	Operation costs for Pully	$	0.6
Operation costs for Spin Tub	$	1.2	Operation costs for Transmission	$	3.4
Operation costs for Motor	$	4	Operation costs for AC	$	55

Within each EOL WM in the study, there are three types of scrap to be recovered and ideally sold. Steel scraps are recovered from chassis and metal covers. Fiberglass is recovered from agitators, water and drain hoses, and spin tubs. Copper scrap is provided by metal covers and pumps. The revenue that is generated from copper, fiberglass, and steel components is determined by multiplying the weight in pounds of the scrap by the units of scrap revenue that are produced through each recovered material type. Retrieving information from the smart sensors is assumed to consume some 20 seconds per WM. The disposal cost is likewise determined through the multiplication of waste weight by the unit disposal cost. Transportation costs associated with a truck are assumed to be $50 per trip. While such estimates are of value, it must be noted that there is price variation in the secondary market of recovered products and materials due to varying levels of quality.

Table A.2. Factors and factor levels used in design-of-experiments study

No	**Factor**	**Unit**	**Levels**		
			1	**2**	**3**
1	Mean arrival rate of EOL WMs	Products/hour	10	20	30
2	Probability of Repair EOLPs	%	5	10	15
3	Probability of a nonfunctional Control Panel	%	10	20	30
4	Probability of a nonfunctional motor	%	10	20	30
5	Probability of a nonfunctional Water & Drain Hoses	%	10	20	30
6	Probability of a nonfunctional Transmission	%	10	20	30
7	Probability of a missing Control Panel	%	5	10	15
8	Probability of a missing motor	%	5	10	15
9	Probability of a missing Water & Drain Hoses	%	5	10	15
10	Probability of a missing Transmission	%	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 Control Panel	Parts/hour	10	15	20
31	Mean demand rate for Agitator	Parts/hour	10	15	20

32	Mean demand rate for Spin Tub	Parts/hour	10	15	20
33	Mean demand rate for Motor	Parts/hour	10	15	20
34	Mean demand rate for Pump	Parts/hour	10	15	20
35	Mean demand rate for Water & Drain Hoses	Parts/hour	10	15	20
36	Mean demand rate for Pully	Parts/hour	10	15	20
37	Mean demand rate for Transmission	Parts/hour	10	12	20
38	Mean demand rate for 1 Year WM	Products/hour	5	10	15
39	Mean demand rate for 2 Years WM	Products/hour	5	10	15
40	Mean demand rate for 3 Years WM	Products/hour	5	10	15
41	Mean demand rate for Refurbished WM	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 WM	Products/hour	10	15	20
50	Maximum inventory level for Refurbished WM	Products/hour	10	15	20
51	Maximum inventory level for WM 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

Highlights

- This is the first adaptation of warranty policies for sensor embedded remanufactured products.
- The proposed model is very easy to implement.
- The model was thoroughly tested by using different warranty policies.
- The proposed approach helps remanufacturer and consumers as a decision support tools to choose which warranty to offer or buy.