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Optimizing Two-Dimensional Renewable Warranty Policies for Sensor Embedded Remanufactured Products

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Abstract:

Purpose: 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 entice 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.

Design/methodology/approach: This study uses discrete-event simulation to optimize the implementation of a two-dimensional renewing warranty policy for remanufactured products. The implementation is illustrated using a specific product recovery system called the Advanced Remanufacturing-To-Order (ARTO) system. The experiments used in the study were designed using Taguchi's Orthogonal Arrays to represent the entire domain of the recovery system so as to observe the system behavior under various experimental conditions. In order to determine the optimum strategy offered by the remanufacturer, various warranty and preventive maintenance scenarios were analyzed using pairwise *t*-tests along with one-way analysis of variance (ANOVA) and Tukey pairwise comparisons tests for every scenario.

Findings: The proposed methodology is able to simultaneously minimize the cost incurred by the remanufacturer, optimize the warranty price and period, and optimize the preventive maintenance strategy resulting in increased consumer confidence.

Originality/value: This is the first study that evaluates in a quantitative and comprehensive manner the potential benefits of offering warranties with preventive maintenance on remanufactured products.

Keywords: reverse supply chain, preventive maintenance, renewable warranty policies, remanufacturing, sensor embedded products, extending product life-cycle

1. Introduction

In current times, the exponential rise in technological development and the customers' desire to repeatedly purchase newer device models and technological products is the impetus which culminates into diminished product life cycles and an upturn in their rate of disposal. As a result, landfill areas and the Earth's natural resources start reaching a critical apex. Therefore, when a technological device reaches the end of its life and becomes essentially no longer useful or just antiquated, manufacturing firms repossess these same products that they had produced prior, in order to manage to meet the new regulations imposed upon them and to enlighten customers' awareness of the pertinent environmental issues regarding this matter. The manufacturers of these technological devices construct specialized facilities specifically designed for the end-of-life (EOL) product recovery process in order to minimize the amount of mechanical waste sent to landfills. This is achieved by retrieving the mechanical materials, parts, and components from the end-of-life products (EOLPs) by way of the recycling, refurbishing, and remanufacturing processes. The economic benefits from such facilities make the process of product recovery more attractive.

In product recovery, disassembly is the most vital operation because it allows for the extraction of the desired components, subassemblies and materials from EOL products. There are various ways to execute the process of disassembling EOL products. They can be effectuated at a single workstation, in a disassembly cell, or on a disassembly line. Although utilizing single workstations and disassembly cells are more flexible, the operation that produces the highest yield is the disassembly line, which is also the most efficient operation for automated disassembly (Gungor & Gupta, 2002).

The first fundamental step in the processes of remanufacturing, recycling, and disposing of EOL products is the pertinent operation of product disassembly. Disassembly is the method of deconstructing an EOL product down to its core mechanical components by utilizing either non-destructive, semi-destructive, or destructive techniques. The main and foremost intention of disassembling these EOL products is to support the foremost goal of recovery process which is to minimize the natural resource depletion.

The cardinal quandary with the product recovery process is the uncertainty it poses, in regards to the components' quality. This dilemma is due to the lack of information regarding the condition of the components prior to them being disassembled. The blatantly clear solution is to test each individual component subsequent to their disassembly. However, product disassembly puts a financial burden on remanufacturer's profits, which, in turn, allays the profit margin of remanufacturing, which is requisite upon two factors: the monetary cost of conducting the appropriate and necessary testing of the entirety of the devices, and the sheer magnitude of obligatory time required to do so. What's more, if the test reveals the component is dysfunctional, it is a sort of assault on the manufacturer upon the realization that the totality of time spent attempting to process the EOL device(s), along with the resources that were required to do so were a waste of resources which could have been otherwise, efficiently utilized.

The quality of a remanufactured product induces hesitation for many people, in regards to its efficacy and reliability. Therefore, the consumers are unsure if remanufactured products will have the capacity to render the same expected performance as that of a new device. This uncertainty regarding a remanufactured product could lead the consumer to make a determination against its purchase. With such expansive consumer apprehension, remanufacturers often employ marketing strategies in attempts to provide affirmation about product durability. One stratagem that remanufacturers often employ to encourage customer security are product warranties (Murthy & Blischke, 2006).

The use of sensor-embedded products (SEPs) is a promising approach in dealing with disassembly yield uncertainty. This is because SEPs utilize sensors implanted during the production process which work by monitoring the critical components of a product and facilitating data collection. The sensor accumulated data can aid in the prognosis of possible future product failures, as they provide an estimation of product component condition during the product's EOL stage. Moreover, the information gathered by sensors regarding any dysfunctional, replaced, or missing components prior to the disassembly of an EOL product contribute to important financial savings that would have otherwise been wasted in testing, disassembly, disposal, backorder, or holding costs processes (Ilgin & Gupta, 2010a, 2010b).

This embedded in us the motivation to study and scrutinize the impact that would be had by offering renewing warranties containing the information retrieved by the sensor-embedded remanufactured products. We will analyze quantitatively the expansion achieved by using the SEP's information in several warranty analyses models depicting a remanufacturing line under various scenarios. Moreover, we will attempt to minimize the cost associated with warranty and to maximize the profit gained by remanufacturers by unearthing a warranty with an appealing price.

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. 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 in that it proposes 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. 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 design-of-experiment study are presented in Section 3 and Section 4 respectively. Section 5 presents the renewable one-dimensional warranty. Assumptions and notations are given in Section 6. Section 7 describes the preventive maintenance analysis. The failure analysis and warranty formulation are presented in Section 8 and Section 9 respectively. Finally, results and conclusions are given in Section 10.

2. Literature Review

2.1. Environmentally Conscious Manufacturing and Product Recovery

In recent years, the number of studies dealing with environmentally conscious manufacturing and product recovery (ECMPRO) issues have gained gratuitous attention from researchers (Gungor & Gupta 1999), (Ilgin, & Gupta 2010b). This is partially due to environmental factors, government regulations, and public demands, but on the other side it is also due to economical profits obtained by implementing reverse logistics and product recycling resolutions. Manufacturers respond to consumer awareness of environmental issues and stricter environmental legislations by establishing designated facilities designed for the purpose of minimizing waste amassment by recovering materials and components derived from EOL products (Gungor & Gupta 2002). Researchers have shed light on the panoptic environmentally conscious dilemmas involved in product manufacturing. As a result, researchers have released reviews of these panoptic issues involved in environmentally conscious manufacturing and product recovery (see for example, Moyer & Gupta, 1997; Gungor & Gupta, 1999; Ilgin & Gupta, 2010c; Gupta, 2013; Ilgin, Gupta & Battaïa, 2015). Disassembly is the most apex in the remanufacturing research area, which is due to its significant role in the all recovery system. For different aspects involved in disassembly, see the book by Lambert and Gupta (2005).

2.2. Disassembly to Order Systems

The objective of the disassembly to order systems (DTOs) is the determination of the optimal lot-sizes of EOL products to disassemble in order to satisfy the demand of various components from a mix of product types that have a number of components and/or modules in common (Gupta & Lambert, 2008).

Kongar and Gupta (2002) proposed a single period integer Goal Programming (GP) model for a DTO system to determine the best combination of multiple products to selectively disassemble them to meet the demand for items and materials under a variety of physical, financial and environmental constraints and goals. Kongar and Gupta (2006) extended Kongar and Gupta (2002) study by using fuzzy GP to model the fuzzy aspiration levels of various goals. Langella (2007) developed a multi-period heuristic considering holding costs and external procurement of items. Gupta, Imtanavanich & Nakashima (2009) used neural networks (NN) to solve the DTO problem. Kongar and Gupta (2009a) proposed a LPP-based solution methodology which can satisfy tangible or intangible financial, environmental and performance related measures of DTO systems. Kongar and Gupta (2009b) developed a multi-objective tabu search (TS) algorithm by considering multiple objective functions, viz. maximizing the total profit, maximizing the resale/recycling percentage, and minimizing the disposal percentage. Inderfurth and Langella (2006) developed two heuristic procedures (i.e., one-to-one, one-to-many) to investigate the effect of stochastic yields on the DTO system. Imtanavanich and Gupta (2006) use the heuristic procedures developed by Inderfurth and Langella (2006) to deal with the stochastic elements of the DTO system. Then, they useed a GP procedure to determine the number of returned products that satisfy various goals. Ondemir, Ilgin & Gupta (2012) presented an Advanced Repair-to-Order and Disassembly-to-Order (ARTODTO) model. ARTODTO model deals with the products that are embedded with sensors and Radio-Frequency Identification (RFID) tags. The goal of the proposed model was to determine how to process each and every end-of-life product (EOLP) on hand to meet used product and component demands as well as recycled material demand. The model considered disassembly, repair, and recycling options for each EOLP in order to satisfy material and remaining-life-time-based (sophisticated) component/product demands and minimize the total cost. Outside component procurement option was also assumed to be available. Ondemir and Gupta (2012) proposed a remanufacturing-to-order (RTO) system for end-of-life sensor embedded products (SEPs). An integer programming (IP) model was proposed to determine how to process each and every end-of-life product on hand to meet the quality-based product and component demands as well as recycled material demand while fulfilling the minimum cost objective. Ondemir and Gupta (2013) proposed an ARTODTO model for EOL processing of SEPs under demand and decision uncertainty. The proposed model was formulated as a fuzzy goal programming (FGP) model to achieve a variety of financial, environmental, and physical goals. Alqahtani, Gupta & Nakashima (2014) extended Ondemir and Gupta (2013) study using simulation discrete model.

2.3. Sensor Embedded Products

Manufacturers are now able to build sensors in smaller sizes and at lower costs due to the expansion of technology. The use of sensor-based technologies on after-sale product condition monitoring is an active research area. Starting with the study of Scheidt and Shuqiang (1994), different methods of data acquisition from products during product usage were presented by the researchers (Karlsson, 1997, 1998; Klausner, Grimm & Horvath, 1999; Petriu, Georganas, Petriu, Makrakis & Groza, 2000; Simon, Bee, Moore, Pu & Xie, 2001). Cheng, Huang, Chen and Hung (2004), developed a generic embedded device that could be installed in different types of equipment, including manufacturing equipment, portal servers, and automated, guided vehicles. This device has the ability of retrieving, collecting, and managing equipment data with the help of an embedded real-time operating system and several software modules. Yang, Moore, Pu and Wong (2009c) and Yang, Moore and Chong (2009b) developed an intelligent product model for discovering product service systems for consumer products, such as fridge/freezer appliances and game consoles for PlayStation2. In this model, an intelligent data unit was installed in each product to acquire data during usage and the distribution stages of its life cycle. The procurement of the essential life-cycle components of a product with sensors embedded in it is presented by Vadde, Kamarthi, Gupta and Zeid (2008). Additional studies aim to further explore whether or not the use of embedded sensors increases product life-cycle management effectiveness. A comprehensive survey on the commercial sensor systems used in health management for electronic products and systems was reported by Pecht (2008). Fang, Ong and Nee (2014), who investigated the modern practices leading toward the eventual development of embedded sensors in products in two primary categories, (viz., embedding sensors in products and representing and interpreting sensor data).

Another avenue of research hinges on the life cycle data analysis obtained via the implementation of various sensor-based data acquisition methods. In this scope, Mazhar, Kara and Kaebernick (2005) presented an integrated, two-stage approach which combined the Weibull analysis and multiple linear regression to assess the component reliability in refurbished products based on their life cycle data. Mazhar, Kara and Kaebernick (2007) carried out a similar analysis by integrating Weibull analysis with neural networks. Herzog, Marwala and Heyns (2009) compared the performance of several neural network variations in the prediction of the residual life of machines and components.

Although the majority of the studies presented above focus on the development of SEP models that enable product data acquisition during their life cycle and/or in their EOL phase, only a select few number of researchers have conferred a cost-benefit analysis. Klausner, Grimm and Hendrickson (1998a) analyzed the trade-off between the higher initial manufacturing costs caused by using an electronic data log (EDL) in products and the cost savings from the reuse of used motors. Simon et al. (2001) improved the cost-benefit analysis of Klausner, Grimm and Hendrickson (1998b) by taking into consideration the limited lifespan of a product's design. It was revealed that under certain circumstances, product servicing offers more readily reusable components in contrast to EOL recovery of parts.

2.4. Warranty Analysis

A warranty is a contractual obligation incurred by a manufacturer (vendor/seller) in connection with the sale of a product. The purpose of a warranty is to establish liability in the rare event that a purchased item fails prematurely or is unable to perform its intended function. These contracts specify the promised product performance and when this expected performance level is not met, a return of compensation is available to the buyer as compensation (Blischke, 1993). Product warranties have different main functions. One of the functions is insurance and protection, permitting buyers to transfer the risk of product failure back to the sellers (Heal, 1977). Secondly, product warranties can also signal product reliability to customers (Balachander, 2001; Gal-Or, 1989; Soberman, 2003; Spence, 1977), and lastly, the sellers can use warranties to extract additional profitability (Lutz & Padmanabhan, 1995).

In contrast with massive literature on warranty policies for new items, up to now study on warranty policies for second-hand items receives less attention. Modelling the warranty cost analysis for used products is a novel field of research with a limited number of publications. The optimal upgrade strategies for second-hand items under both the virtual age along with the screening test reliability development methods are presented by Saidi-Mehrabad, Noorossana and Shafiee (2010), and Shafiee, Chukova, Yun and Akhavan-Niaki (2011a) who built a stochastic model designed to examine the optimal degree of investments for increasing the reliability of secondhand products under free repair warranty (FRW) policies. They concluded that a larger number of investments meant larger declines in the virtual age and greater reliability levels of the upgraded product. A stochastic reliability improvement model for used products with warranties and Cobb-Douglas-Type production function to reach the optimal upgrade level was presented by Shafiee, Finkelstein and Chukova (2011b). A study to determine the optimal upgrade, selling price and maximum expected profit with restrictive assumptions about the age distribution was conducted by Naini and Shafiee (2011). They built a mathematical model to implement a parametric analysis on the items' chronological ages to detect and determine the best policies. Yazdian, Shahanaghi and Makui (2014) adopted an integrated mathematical model that was not reliant on the specific age of the received item in order to determine the typically experienced remanufacturer decisions. The warranty policy and its effect on consumer behavior from the perspective of consumers has been studied by Liao, Li and Cheng (2015). A novel mathematical–statistical model was proposed where decisions involving the pricing of returned used products (cores), with the degree of their remanufacturing, selling price, and warranty period for the final remanufactured products was to investigate the joint optimization of remanufacturing, pricing and warranty decision-making for end-of-life products (Yazdia et al., 2014). Kuik, Kaihara and Fujii (2015) presented mathematical models to examine two types of the proposed extended warranty policies for manufacturers so that they could make the comparisons of their possible gained profits of remanufactured products by the manufacturers who supplied them. In contrast, the analysis of warranty costs for remanufactured products has not yet received any significant attention. However, there are few papers that consider the warranty for the remanufactured products' reverse and closed-loop supply chain management. Base and extended one-dimensional warranty can be offered for remanufacturing products using Free Replacement Warranty (FRW) and Pro-Rata Warranty (PRW) policy (Alqahtani & Gupta, 2015a, 2015b, 2015c). Also, renewable, nonrenewable, one- and two-dimensional warranty policies can be offered for EOL derived products (Alqahtani & Gupta, 2016a, 2016b, 2016c).

2.5. Maintenance Analysis

Maintenance has a significant role in product reliability and quality. In the literature, maintenance is classified into two main types viz., corrective maintenance (CM) and preventive maintenance (PM). CM occurs when item fail and it performs to restore a failure item to an operational state; PM is performed before item fail in order to reduce degeneration and failure rate. In case of short product's remaining life, the warranty is also comparatively short and only CM actions are offered. Where in a product with long remaining life, warranty could be relatively long and warranty servicing costs can be reduced by carrying out PM actions. Thus, there is a relation between warranties, CM and PM.

The literature on maintenance policies is extensive. Several review papers on maintenance policies have appeared (Wang, 2002; Garg & Deshmukh, 2006; Sharma, Yadava & Deshmukh, 2011). We refer the reader to book by Nakagawa (2006) for the detailed information on the general area of maintenance theory. An extensive review of modelling maintenance policies can be found in book by Nakagawa (2008).

Maintenance policies for second-hand products during the warranty were not receiving researchers' interest. (Shafiee & Chukova, 2013). Yeh, Lo and Yu (2011) proposed two periodical age reduction PM models to decrease the high failure rate of the second-hand products. Kim, Lim and Park (2011) studied the optimal periodic PM policies of a second-hand item following the expiration of warranty. From the manufacturer perspective, it is meaningful to carry out PM actions only when the saving of warranty servicing cost exceeds the additional cost occur by performing PM activities. Therefore, developing PM policies for remanufactured products still needs further researches (Alqahtani & Gupta, 2017).

3. System Description

This study used discrete-event simulation to optimize the implementation of a two-dimensional renewing warranty policy for remanufactured products. The implementation is illustrated using a specific product recovery system called the Advanced Remanufacturing-To-Order (ARTO) system. The experiments used in the study were designed using Taguchi's Orthogonal Arrays to represent the entire domain of the recovery system so as to observe the system behavior under various experimental conditions. In order to determine the optimum strategy offered by the remanufacturer, various warranty and preventive maintenance scenarios were analyzed using pairwise t-tests along with one-way analysis of variance (ANOVA) and Tukey pairwise comparisons tests for every scenario.

The Advanced Remanufacturing-To-Order (ARTO) system deliberated on in this study is a sort of product recovery system. A sensor embedded air conditioner (AC) is considered here as a product example. Based on the condition of EOL AC, 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.

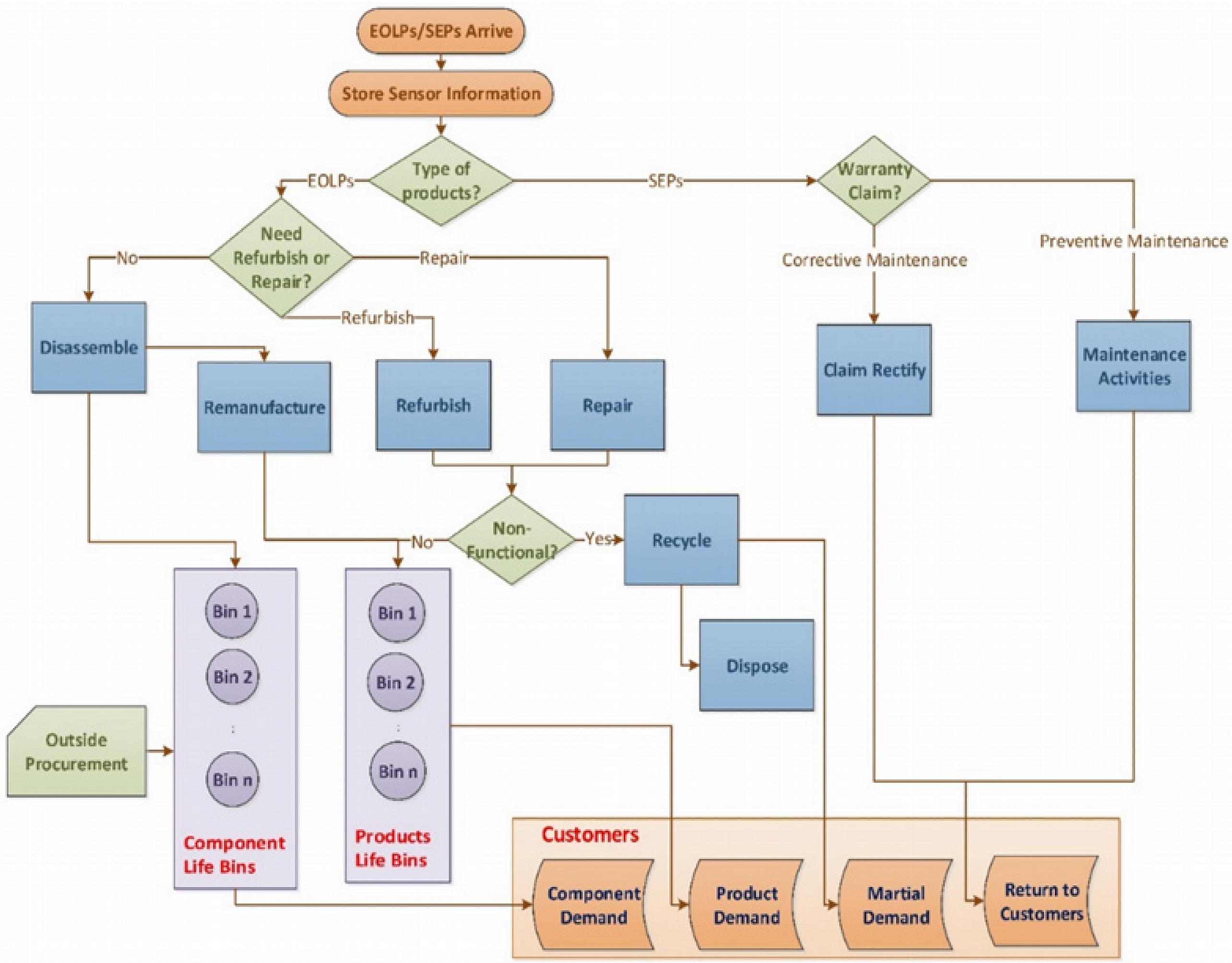

Figure 1. ARTO System's Recovery Processes

First, EOL ACs arrive at the ARTO system for information retrieval using a radio frequency data reader that is stored in the facility's database. Then the ACs 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 AC components. There are nine components in an AC: the evaporator, control box, blower, air guide, motor, condenser, fan, protector, and compressor. Exponential distributions are used to generate the station disassembly times, 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 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.

Component name	Station	Code	Preceding component
Evaporator	1	A	–
Control box	2	B	–
Blower	3	C	A, B
Air guide	3	D	A, B, C
Motor	4	E	A, B, C, D
Condenser	5	F	–
Fan	5	G	F
Protector	6	H	–
Compressor	6	I	H

Table 1. AC Components and precedence relationship

Recovery operations differ for each SEP based on their overall condition and estimated remaining life. Recovered components are used to meet spare parts demands, while recovered or refurbished products are used for consumer product demands. Also, material demands are met using recycled products and components. Recovered products and components are characterized based on their remaining lifespans and are placed in different life-bins (e.g. one year, two years, etc.) where they wait to be retrieved via a customer demand. Underutilization of any product or component can happen when it is qualified for a higher life-bin but is placed in a lower life-bin because the higher life-bin is full. Any product, component, or material inventory that is greater than the maximum inventory allowed is assumed to be of excess and is instead used for material demand or is simply disposed of.

In order to meet the product demand, repair and refurbish options could also be chosen as presented in Figure 2. EOLP may have missing or nonfunctional (broken, zero remaining life) components that need to be replaced or replenished during the repairing or refurbishing process in order to meet certain remaining life requirements. EOLP may also consist of components having lesser remaining lives than desired, and, for that reason, might also have to be replaced.

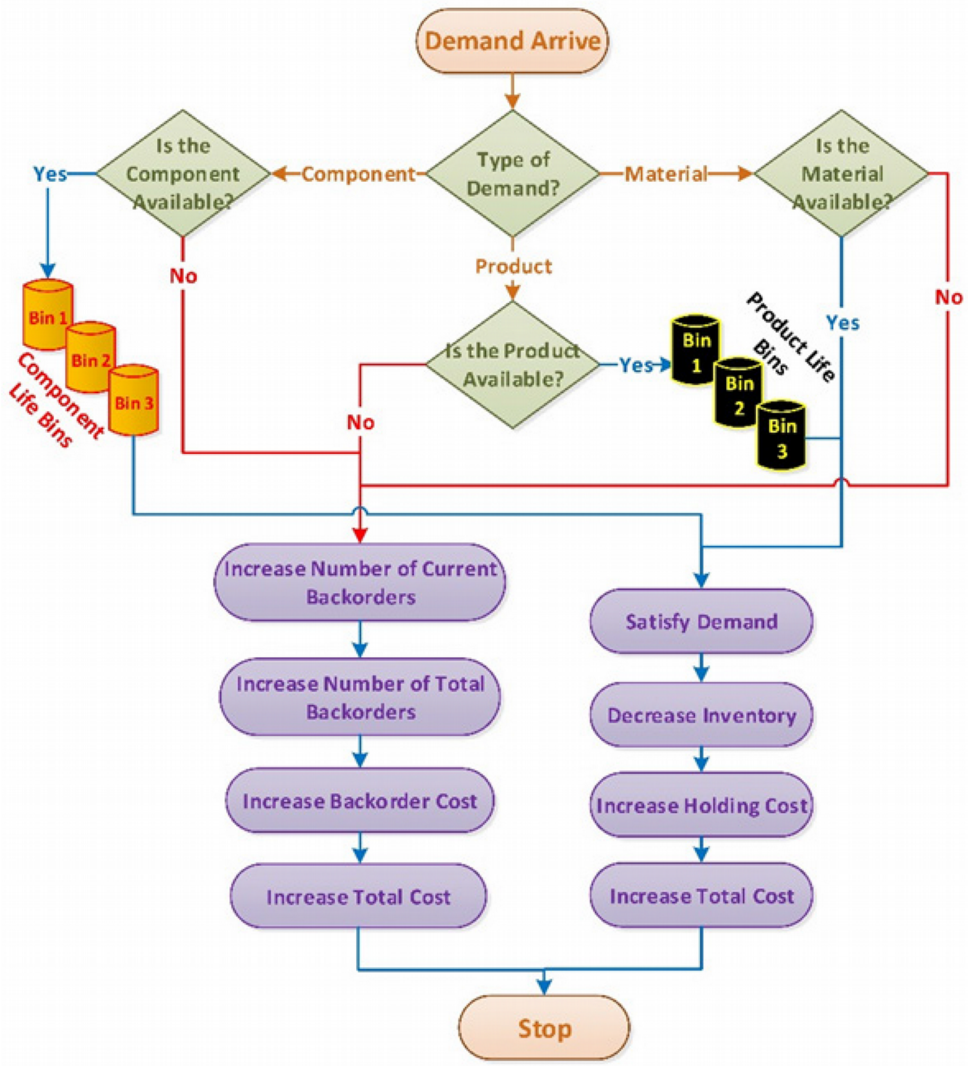

Figure 2. ARTO System Demand Process

In case of failure SEP during warranty period, The failed ACs arrive at the ARTO system for information retrieval using a radio frequency data reader that is stored in the facility's database. Then the failure ACs goes through the recovery operations explain before same as an EOLP.

Finally, in order to reduce the risk of failure, PM actions are carried out during the warranty period. Here, if the remaining life of a remanufactured AC reaches a pre-specified value the remanufactured SEPs arrive at the ARTO system for information retrieval using a radio frequency data reader that is stored in the facility's database. Then, the SEPs go through four maintenance activities based on the information from the sensor about their condition. These maintenance activities include measurements, adjustments, parts replacement, and cleaning. When PM actions are performed with degree δ, the remaining life of the remanufactured ACs will be δ units of time more than before as shown in Figure 3. Meanwhile, any failures between two successive PM actions during warranty period are rectified at no cost to the customer.

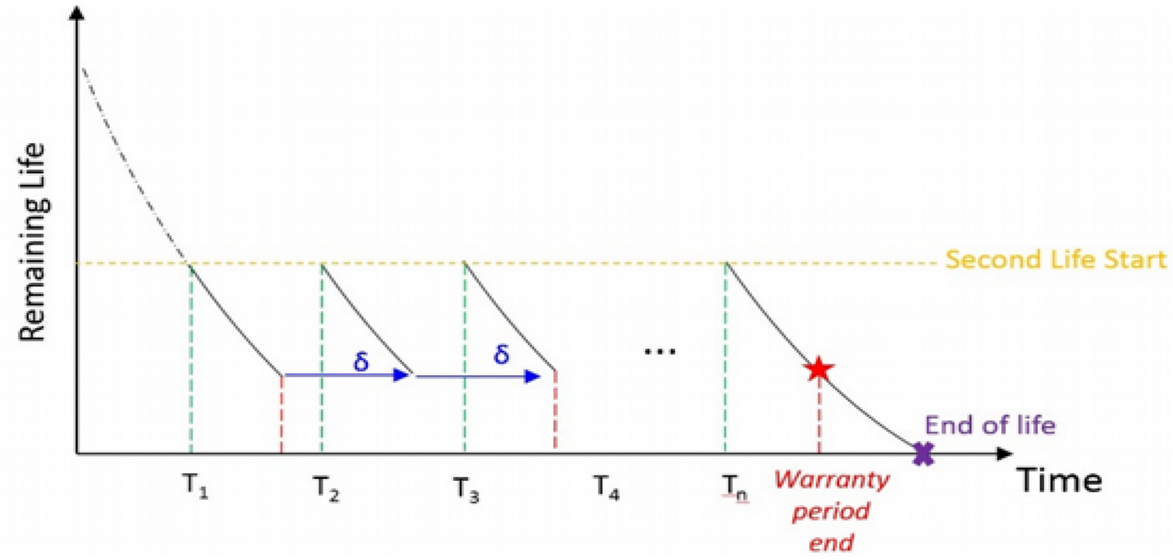

Figure 3. Scheme for PM policies for remanufactured Products

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 (2011), it was show that smart SEPs are a favorable resolution in handling remanufacturing customer uncertainty. To test this claim on ARTO, we built a simulation model to represent the full recovery system and observed its behavior under different experimental conditions. ARENA program, Version 14.5, was used to build the discrete-event simulation models. A three-level factorial design was used with 51 factors that were considered each at 3 levels. These were identified 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 have to 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.

Parameters	Unit	Value	Parameters	Unit	Value
Backorder cost rate	%	40	Price for 3 Years Air Guide	$	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 Evaporator	$	10	Price for 3 Years Protector	$	20
Price for 1 Year Control Box	$	20	Price for 3 Years Compressor	$	65
Price for 1 Year Blower	$	5	Weight for Evaporator	lbs.	8
Price for 1 Year Air Guide	$	5	Weight for Control Box	lbs.	4
Price for 1 Year Motor	$	45	Weight for Blower	lbs.	2
Price for 1 Year Condenser	$	15	Weight for Air Guide	lbs.	2
Price for 1 Year Fan	$	15	Weight for Motor	lbs.	6
Price for 1 Year Protector	$	15	Weight for Condenser	lbs.	12
Price for 1 Year Compressor	$	50	Weight for Fan	lbs.	3
Price for 2 Years Evaporator	$	15	Weight for Protector	lbs.	3
Price for 2 Years Control Box	$	30	Weight for Compressor	lbs.	6
Price for 2 Years Blower	$	12	Unit copper scrap revenue	$/lbs	0.6
Price for 2 Years Air Guide	$	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 Protector	$	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 Evaporator	$	20	Price of 1 Year AC	$	180
Price for 3 Years Control Box	$	35	Price of 2 Years AC	$	240
Price for 3 Years Blower	$	15	Price of 3 Years AC	$	275
Operation costs for Evaporator	$	4	Operation costs for Condenser	$	1.66
Operation costs for Control Box	$	4	Operation costs for Fan	$	2.34
Operation costs for Blower	$	2.8	Operation costs for Protector	$	0.6
Operation costs for Air Guide	$	1.2	Operation costs for Compressor	$	3.4
Operation costs for Motor	$	4	Operation costs for AC	$	55

Table 2. Parameters used in the ARTO system

No	Factor	Unit	Levels		
			1	2	3
1	Mean arrival rate of EOL ACs	Products/hour	10	20	30
2	Probability of Repair EOLPs	%	5	10	15
3	Probability of a nonfunctional control box	%	10	20	30
4	Probability of a nonfunctional motor	%	10	20	30
5	Probability of a nonfunctional fan	%	10	20	30
6	Probability of a nonfunctional compressor	%	10	20	30
7	Probability of a missing control box	%	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 Evaporator	Parts/hour	10	15	20
30	Mean demand rate for Control Box	Parts/hour	10	15	20
31	Mean demand rate for Blower	Parts/hour	10	15	20
32	Mean demand rate for Air Guide	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 Protector	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

No	Factor	Unit	Levels		
			1	2	3
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 AC	Products/hour	10	15	20
51	Maximum inventory level for AC 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

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

So, the number of experiments must be greater than or equal to a system's degrees-of-freedom. The Precisely, $L_{109}(3^{54})$ (i.e., 109= [(Number of levels -1) x 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:

$$\text{Profit} = SR+CR+SCR-HC-BC-DC-DPC-TC-RMC-TPC-PMC-WC \tag{1}$$

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 ACs 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 ACs 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 ACs during the 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; *PMC* is the total preventive maintenance cost during the simulated run time and *WC* is the total warranty cost.

In each EOL AC, there are three types of scraps that need to be recovered and sold. The evaporator and condenser are sold as copper scrap, Chassis and metal covers are sold as steel scraps and blowers, fan and air guides are sold as fiberglass. All the other components are considered to be waste components. Scrap revenue from steel, copper, and fiberglass components is calculated by multiplying their weight in pounds by the units of scrap revenue produced by each metal type. Disposal cost is calculated as well by multiplying the waste weight by the unit disposal cost. The time of retrieving information from smart sensors is assumed to be 20 seconds per AC. The transportation cost is assumed to be $50 for each trip taken by the truck. There are different prices in the secondary market of recovery product due to different level of quality.

5. Renewable Two-Dimensional Warranty

During the process of deciding to purchase a product, the buyer usually compare features of a product with other competing brands that are selling the same product. In some cases, the competing brands produce similar products bearing similar features such as the costs, special characteristics, quality, credibility of the product, and even insurance from the provider. In these cases, after sale factors come into effect, such as the discount, warranty, availability of parts, repairs, and other services. These factors will be very significant to the buyer in such a situation. So will the warranty since it further assures the buyer of the reliability of the product.

A warranty is an agreement that requires the manufacturer to correct any product failures or to compensate the buyer for any problems that may occur with the product during the warranty period in relevance to its sale. The objective of the warranty is to promote the product's quality and guarantee its performance in order to assure productivity for both the manufacturer and the buyer. For a given product, the warranty cost (in a statistical sense) is the same for all new items if the manufacturer has good quality control. In contrast, each EOL product is different due to factors such as age, usage, and maintenance history. This makes the warranty cost for each remanufactured product derived from an EOL item statistically different.

The importance of warranties for remanufactured products is increasing because consumers are becoming more demanding of product quality and the increase in customer's awareness of the environment will increase the demand for remanufactured products and future costs of replacement/repair in case of product failures. Therefore, warranty management has become very important to remanufacturers of remanufactured products. They need to estimate the warranty cost in order to factor it into the pricing structure. Failure to do so can result in the remanufacturers incurring loss, as opposed to profit, with the sale of remanufactured items. Analyses of warranty costs for remanufactured products are more complex when compared to new products because of the uncertainties in usage and maintenance history. Moreover, warranty policies similar to new and secondhand products may not be economically acceptable from the remanufacturer's point of view. Therefore, there is a need to test and compare these warranty policies for remanufactured products and estimate the expected warranty cost associated with these policies. There are other related issues such as the servicing strategies involving remanufactured spare parts in the replacement/repair of failures during the warranty period.

In the two-dimensional warranty, a policy is defined by a region in a two-dimensional plane, typically with one axis representing time or age and the other axis representing the usage. For renewing policies, the warranty period begins anew with each replacement or repair. Therefore, the warranty period is uncertain as the warranty expires only when an item does not fail for a period W, as shown in Figure 4. There are many different available two-dimensional consumer warranty policies which most products are sold with. The most famous renewing consumer warranties are the Renewing Free Replacement Warranty (FRW) and Renewing Pro-Rata Warranty (PRW), or a combination of the both FRW/PRW.

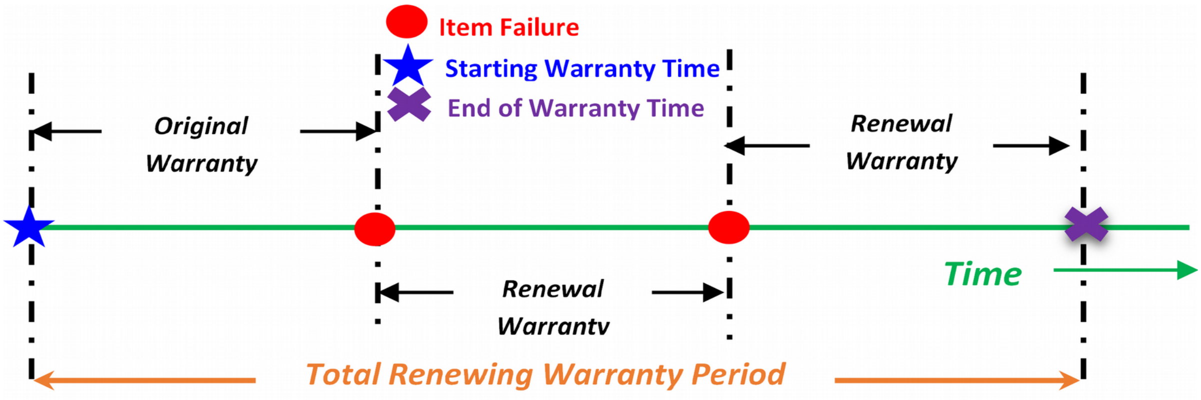

Figure 4. Parameters used in the ARTO system

6. Assumptions and Notations

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

6.1. 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 components) is a random variable.

6.2. Notations

W: Warranty period;

W_{i}: Limits of warranty period;

U: Warranty usage;

U_{i}: Limits of warranty usage;

Ω: Warranty region;

Ω_i: Warranty sub-region i;

C_o: Operating cost of item;

C_S: Sale price of item;

C_p: Cost of remanufacturing a remanufactured item;

n: Number of components in a remanufactured item;

RL: Remaining life of remanufactured item at sale;

RL_i: Remaining life of component i $(1 \leq i \leq n)$;

j: Number of preventive maintenance;

v: Virtual remaining life;

v_j: Virtual remaining life after performing the j^{th} 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;

x: Usage of remanufactured item at failure;

$\Lambda(RL)$: Intensity function for system failure;

$F_i(\,.\,)$: Marginal distribution function of $F(\,.\,,\,.\,)$;

$F(\,.\,,\,.\,)$: Bivariate distribution function;

$F(\,.\,|\,.\,)$: Conditional distribution function;

$R(\,.\,,\,.\,)$: Refund function for two-dimensional warranty;

$N(\,.\,)$: Number of replacements under warranty;

$N(\,.\,,\,.\,)$: Tow-Dimensional renewal function associated with $F(\,.\,,\,.\,)$;

$N(W; RL)$: Number of failures over the warranty period with remaining life, RL;

τ_{ri}: Time at which warranty expires;

$G(\,.\,)$: Distribution function of usage rate;

$E[.]$: Expected value of expression within [.];

$C_d(W; RL)$: Total warranty cost to remanufacturer;

7. Preventive Maintenance Analysis

Usually, a PM activities involve a set of maintenance tasks, such as, cleaning, systematic inspection, lubricating, adjusting and calibrating, replacing different components, etc. (Ben-Mabrouk, Chelbi & Radhoui, 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, Djamaludin and Murthy (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, Morimura and Suzuki, 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, Sanchez & Serradell 1999). Therefore, the virtual remaining life after performing the j^{th} PM activity, i.e. RL_j, is then given by

$$v_j = v_{j-1} + \delta(m)(RL_j - RL_{j-1}) \tag{2}$$

where m is the level of PM effort, and $\delta(m)$, $m = 0, 1, \ldots, M$, 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.

8. 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 products 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.

In two-dimensional warranty policies, remanufactured item failures can be viewed as random points occurring over a two-dimensional region. 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 $\Lambda(RL)$ where RL represents the remaining life of the item. $\Lambda(RL)$ 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

$$P\{N\ (W\,; RL) =\ n\} = \left\{\int_{v}^{v+W} \Lambda(RL)\, dRL\right\} \mathrm{e}^{-\int_{v}^{v+W} \Lambda(RL) dRL} /n! \tag{3}$$

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

$$E\ [N\ (W;\ RL)] = \int_{v}^{v+W} \Lambda(RL) dRL \tag{4}$$

The expected number of renewals over the warranty period is given by the two-dimensional renewal function

$$N\ (t, x) = F(t, x) + \int_{0}^{x} \int_{0}^{t} N(t, x) dF(t, x) \tag{5}$$

ARENA 14.5 is used to generate the remaining life and usage of remanufactured item at failure; (ti, xi), 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 and usage 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.

9. Warranty Formulation

9.1. Renewing 2D Free Replacement Warranty Policy

Under this policy whenever a remanufactured item fails in the warranty region; Ω, the remanufacturer replaced all failures with a remanufactured one at no cost to the buyer. The replacement comes with a new warranty identical to the original one. There are four different warranty regions under FRW policy as shown in Figure 5.

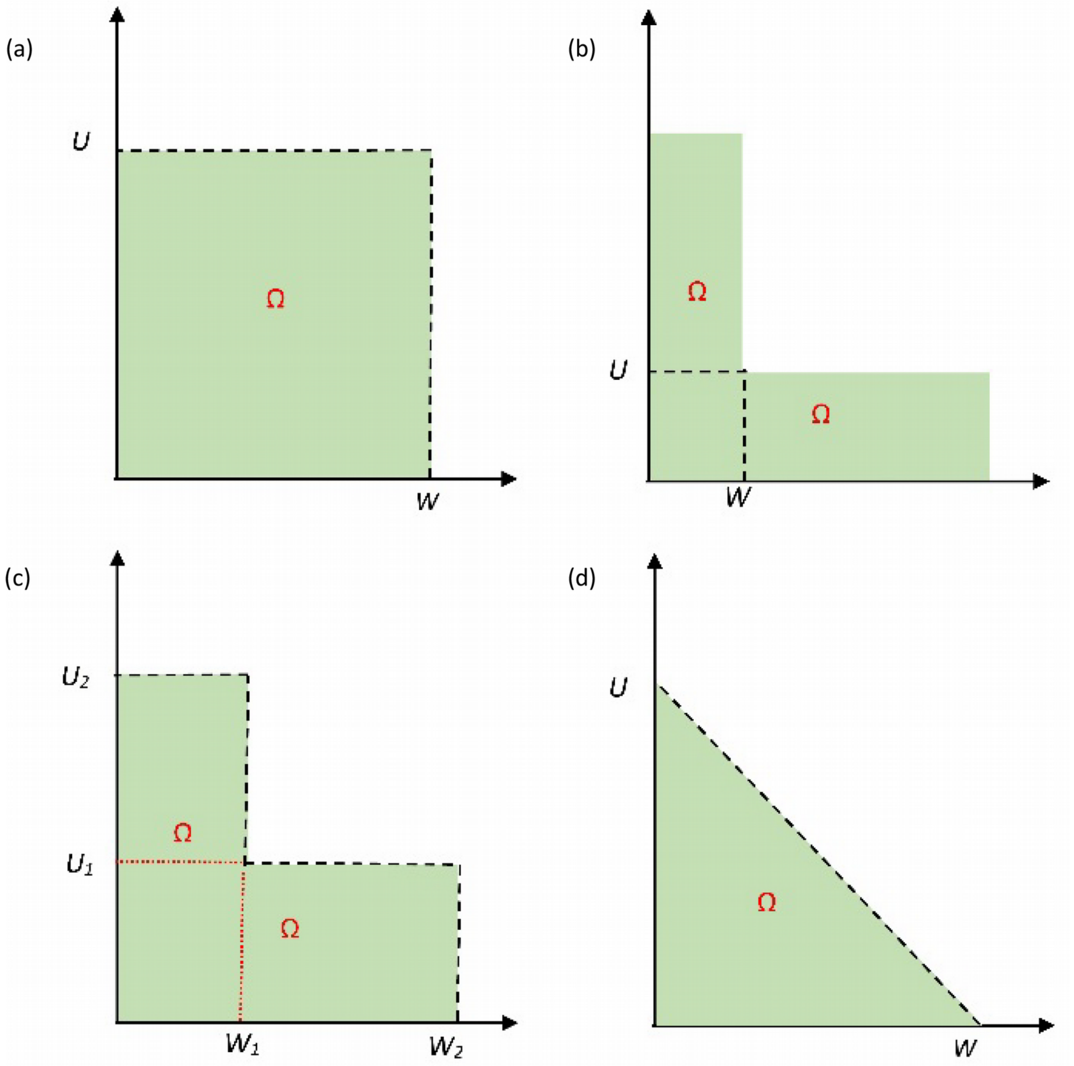

Figure 5. Warranty Regions for Renewing FRW

9.1.1. Renewing FRW with Rectangle Region

The warranty region is characterized by a rectangle shape as shown in Figure 5(a). The warranty expires the first time a failure occurs outside the rectangle. The policy assures the buyer a maximum cover for W unit of time and/or U unit of usage. As a result the number of replacements under warranty, $N(RL)$, is a random variable distributed according to a geometric distribution function with $E[N(RL)]$ given by

$$E\,[N(RL)] = \frac{1}{1 - F(W,\ U)} \tag{6}$$

The expected warranty cost per remanufactured item is given by

$$E\,[C_d(W;\, RL)] = \frac{C_S\,(RL)}{1 - F(W, U)} \tag{7}$$

9.1.2. Renewing FRW with Infinite Strips Region

The warranty region is characterized by two infinite dimensional strips as shown in Figure 5(b). Under this warranty region, the policy assures the buyer is guaranteed a minimum coverage for W units of time after sale and for U units of usage. The warranty expires the first time instant both time and usage exceeds the limits W and U respectively. As a result, the number of replacements under warranty is given by

$$E\,[N(RL)] = \frac{1}{1 - [F_1(W) + F_2\,(U) - F(W, U)]} \tag{8}$$

As a result, the expected warranty cost per remanufactured item is given by

$$E\,[C_d(W;\, RL)] = \frac{C_S\,(RL)}{1 - [F_1(W) + F_2(U) - F(W, U)]} \tag{9}$$

9.1.3. Renewing FRW with Four Parameters Region

The warranty region is characterized by four parameters (W_1, W_2, U_1 and U_2) as shown in Figure 5(c). Under this policy, a buyer is assured of warranty coverage for a minimum time period W_1 and for a minimum usage U_1 and for a maximum cover for W_2 unit of time and U_2 unit of usage. As a result the number of replacements under warranty is given by

$$E\,[N(RL)] = \frac{1}{1 - [F(W_1,\ U_2) + F(W_2,\ U_1) - F(W_1, U_1)} \tag{10}$$

As a result, the expected warranty cost per remanufactured item is given by

$$E\ [C_d(W;\ RL)] = \frac{C_S\ (RL)}{1 - [F(W_1,\ U_2) + F(W_2,\ U_1) - F(W_1, U_1)} \tag{11}$$

9.1.4. Renewing FRW with Triangle Region

The warranty region is characterized by a triangle shape as shown in Figure 5(d). The number of replacements under warranty is given by

$$E\ [N(RL)] = \frac{1}{1 - F(U)} \tag{12}$$

As a result, the expected warranty cost per remanufactured item is given by

$$E\ [C_d(W;\ RL)] = \frac{C_S\ (RL)}{1 - F(U)} \tag{13}$$

9.2. Renewing 2D Pro-Rata Warranty Policy

Under this policy, if the remanufactured item fails in the warranty region, *Ω*, a remanufactured replacement is supplied at reduced price. This can be viewed as a conditional refund since the refund is tied to a remanufactured replacement purchase. Similar to FRW policy, two different forms for warranty region and refund function, *R*(*t*, *x*) are been consider for PRW.

9.2.1. Renewing PRW with Rectangle Region

The warranty region is characterized by a rectangle shape as shown in Figure 5(a) and the refund function is given by

$$R(t,x) = \begin{cases} C_S\ (RL) \times \left[1 - \frac{t}{W}\right] \times \left[1 - \frac{x}{U}\right] & if(t,x) \in \Omega \\ 0 & if(t,x) \notin \Omega \end{cases} \tag{14}$$

As a result, the expected warranty cost per remanufactured item is given by

$$E\ [C_d(W;\ RL)] = C_S\ (RL) \times [F(W,U) - \frac{\int_0^U \int_0^W [t_1 U + (W - t_1)x_1] dF(t_1,x_1)}{W\ U\ [1 - F(W,U)]} \tag{15}$$

9.2.2. Renewing PRW with Infinite Strips Region

The warranty region is characterized by two infinite dimensional strips as shown in Figure 5(b) and the refund function is given by

$$R(t,x) = \begin{cases} C_S\,(RL) \times \left[1 - Min\left\{\frac{t_1}{W}, \frac{x_1}{U}\right\}\right] & if(t,x) \in \Omega \\ 0 & if(t,x) \notin \Omega \end{cases} \tag{16}$$

As a result, the expected warranty cost per remanufactured item is given by

$$E\;[C_d(W;\,RL)] = C_S\,(RL) \times \left\{F(W,U) - \frac{\iint_{\Omega}^{0}[1 - \text{Min}(\frac{t}{k}, \frac{x}{L})]\;dF(t_1,x_1)}{1 - [\,F_1(W) + F_2\,(U) - F(W,U)]}\right\} \tag{17}$$

9.3. Renewing FRW-PRW Combination Policy

In combination warranty, the warranty region, *Ω*, consists of two disjoint sub-regions Ω_1 and Ω_2 where the warranty terms are different for each region. If a failure occurs in Ω_1, the buyer is entitle to FRW policy. While, if a failure occurs in Ω_2, the buyer is entitle to PRW policy. The replacement is covered with a new warranty identical to that of the original item. Similar to PRW policy, two different forms for warranty region and refund function, *R*(*t*, *x*) are been consider for FRW-PRW combination policy as shown in Figure 6.

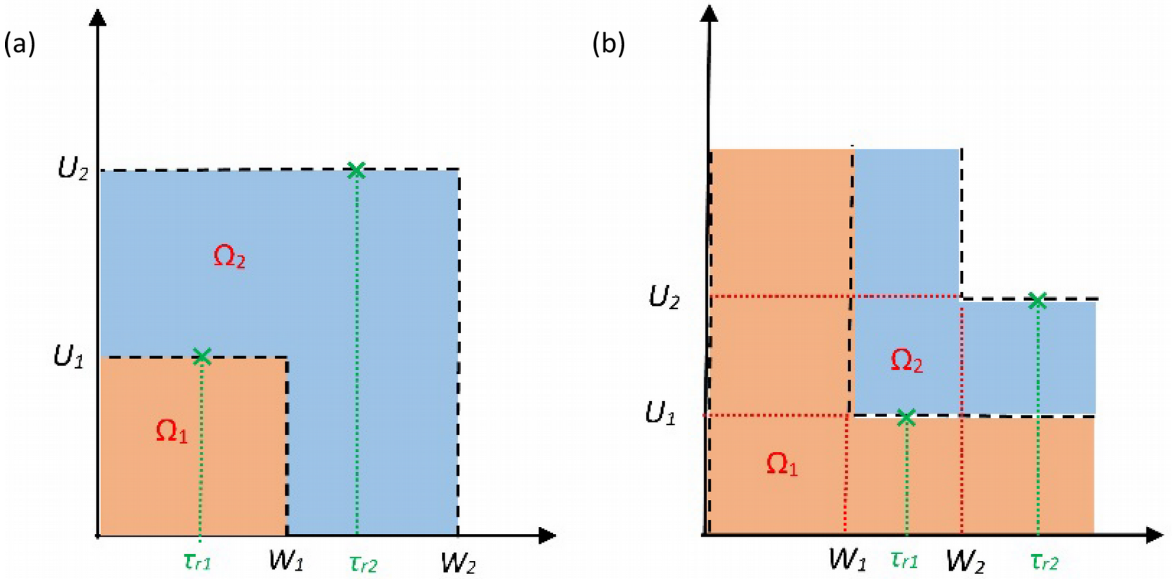

Figure 6. Warranty Regions for Combination Warranty Policy

9.3.1. Renewing FRW-PRW Combination with Rectangle Region

The warranty region is characterized by two rectangle shape sub-region as shown in Figure 6(a). The warranty expires the first time a failure occurs outside the rectangle. The refund function is given by

$$R(t,x) = \begin{cases} C_S\,(RL) \times \left[1 - \dfrac{t}{W_2}\right] \times \left[1 - \dfrac{x - U_1}{U_2 - U_1}\right] & if\; 0 < t \leq W_1; U_1 < x \leq U_2 \\ C_S\,(RL) \times \left[1 - \dfrac{t - W_1}{W_2 - W_1}\right] \times \left[1 - \dfrac{x - U_1}{U_2 - U_1}\right] & if\; W_1 < t \leq W_2; U_1 < x \leq U_2 \\ C_S\,(RL) \times \left[1 - \dfrac{t - W_1}{W_2 - W_1}\right] \times \left[1 - \dfrac{x}{U_2}\right] & if\; W_1 < t \leq W_2; 0 < x \leq U_1 \end{cases} \tag{18}$$

The expected warranty cost per remanufactured item is given by

$$\begin{aligned} \mathrm{E}\,[C_d(W;\,RL)] = & \iint_{\Omega_1} [EC(W_1 - t, U_1 - x, W_2 - t, U_2 - x) + C_S\,(RL)]\; dF\,(t,x) \\ & + \iint_{\Omega_2} R(t,x)\; dF\,(t,x) \end{aligned} \tag{19}$$

9.3.2. Renewing FRW-PRW Combination with Infinite Strips Regions

The warranty region is characterized by two infinite dimensional strips regions as shown in Figure 6(b). As a result the refund function is given by

$$R(t,x) = \begin{cases} C_S\,(RL) \times \left[1 - Min\left\{\dfrac{t - W_1}{W_2 - W_1}, \dfrac{x - U_1}{U - U_1}\right\}\right] & if(t,x) \in\; \Omega_2 \\ 0 & if(t,x) \notin \Omega \end{cases} \tag{20}$$

As a result, the expected warranty cost per remanufactured item is given by

$$\begin{aligned} E\,[C_d(W;\,RL)] = & \int_0^{r_1} [C_S\,(RL) \times F(\tau_{r1}|r) \\ & + \frac{\int_{\tau_{r1}}^{\tau_{r2}} [C_S\,(RL) - C_p\,(RL) - R(t,rt)]\; dF(t|r)]}{1 - F(\tau_{r2}|r)}]\; dG(r) \\ & + \int_{r_1}^{\infty} [C_S\,(RL) \times F(W_1|r) \\ & + \frac{\int_{W_1}^{W_2} [\,C_S\,(RL) - C_p\,(RL) - R(t,rt)]\; dF(t|r)]}{1 - F(W_2|r)}]\; dG(r) \end{aligned} \tag{21}$$

10. Results

The results are divided into four sections. Section 10.1 deals with the evaluation of the effect of offering different warranty policies to help the decision maker choose the best warranty policy to offer. Section 10.2, shows a quantitative assessment of offering PM on warranty policies. Section 10.3 presents a quantitative assessment of the impact of SEPs on the warranty and maintenance costs and policies to the remanufacturer. Finally, section 10.4 presents a discussion about how to price remanufactured items using warranty and maintenance information.

10.1. Remanufacturing Warranty Policies Evaluation

In this section, the results to compute the expected number of failures and expected cost to the remanufacturer were obtained using the ARENA 14.5 program. We evaluate different warranty period with offering a preventive maintenance policy during each period.

10.1.1. Renewable Free Replacement Warranty (FRW) Policy

Table 4 presents the expected number of failures and cost for remanufactured AC and components for renewable FRW, PRW and Combination Policies. In Table 4, 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, Cs. Thus, the expected cost of warranty is calculated by subtracting Cs from the expected cost to remanufacturer. For example, from Table 4, for $W = 0.5$ and $RL = 1$, the warranty cost for AC is \$61.10 - Cs =\$61.10 - \$55.00 = \$6.10 which is ([\$6.10 / \$ 55.00] x 100) = 11.09% of the cost of supplying the item, Cs, which is significantly less than that \$55.00, Cs. This saving might 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 ([|\$74.92 - \$55.00| / \$ 55.00] x 100) = 36.22%.

10.1.2. Renewable Pro-Rata Warranty (PRW) Policy

The results for PRW are also given in Table 4. Here too, the expected cost of warranty can be calculated as above. For example, the cost of warranty for 3 years remaining life AC with $W = 2$ years will cost \$121.27 - Cs = \$121.27 - \$55.00 = \$66.27 which is 120.49% of the cost of supplying the item, Cs.

		Renewable Free Replacement Warranty (FRW)					
		Expected frequancy of Failures			Expected Cost to Remanufacturer		
Components	W^*	$RL^* = 1$	$RL = 2$	$RL = 3$	$RL = 1$	$RL = 2$	$RL = 3$
Evaporator	0.5	0.5188	0.0034	0.0008	$4.40	$5.04	$4.01
	1	0.104	0.0135	0.0061	$4.89	$5.52	$4.11
	2	0.1557	0.03	0.021	$7.32	$7.28	$4.23
Control Box	0.5	0.5125	0.0032	0.0041	$4.32	$5.01	$4.01
	1	0.1102	0.0133	0.0332	$5.09	$5.38	$4.08
	2	0.1494	0.0299	0.1118	$7.23	$7.14	$4.20
Blower	0.5	0.5062	0.0031	0.0216	$2.16	$2.02	$2.07
	1	0.0978	0.0136	0.1779	$2.85	$3.59	$2.10
	2	0.1433	0.0303	0.5981	$3.92	$4.41	$2.19
Air Guide	0.5	0.5062	0.0014	0.1152	$1.18	$1.16	$1.00
	1	0.0729	0.0138	0.9505	$1.72	$1.58	$1.09
	2	0.1307	0.0264	0.3895	$2.28	$2.25	$1.16
Motor	0.5	0.4914	0.0032	0.6159	$4.50	$4.32	$4.23
	1	0.1065	0.0133	0.7989	$4.95	$4.61	$4.29
	2	0.15	0.0303	0.0167	$6.96	$5.98	$4.34
Condenser	0.5	0.5119	0.0034	0.7656	$1.41	$1.20	$1.18
	1	0.0996	0.0135	0.8056	$2.04	$1.72	$1.29
	2	0.1569	0.0303	0.0889	$2.36	$1.98	$1.36
Fan	0.5	0.5243	0.0031	0.7989	$2.70	$2.28	$2.19
	1	0.1146	0.0133	0.1624	$3.72	$2.67	$2.24
	2	0.1508	0.0302	0.4756	$4.63	$3.69	$2.36
Protector	0.5	0.5294	0.0034	0.5692	$0.72	$0.55	$0.40
	1	0.0978	0.0133	0.8683	$1.10	$0.90	$0.47
	2	0.1488	0.0303	0.8022	$1.93	$1.30	$0.51
Compressor	0.5	0.5113	0.0034	0.017	$3.13	$2.93	$2.80
	1	0.1034	0.0135	0.0889	$4.01	$3.78	$3.03
	2	0.15	0.0302	0.8056	$5.49	$4.95	$3.13
AC	0.5	0.608	0.0044	0.0003	$61.10	$58.63	$58.10
	1	0.1563	0.0179	0.0028	$63.77	$64.47	$60.83
	2	0.2048	0.0398	0.009	$74.92	$73.82	$63.08

Components	W^*	Renewable Pro-Rata Warranty (PRW)					
		Expected frequancy of Failures			Expected Cost to Remanufacturer		
		$RL^* = 1$	$RL = 2$	$RL = 3$	$RL = 1$	$RL = 2$	$RL = 3$
Evaporator	0.5	1.0029	0.0065	0.0014	$7.54	$8.63	$6.90
	1	0.2011	0.0261	0.012	$8.37	$9.47	$7.03
	2	0.301	0.0581	0.0404	$12.55	$12.47	$7.25
Control Box	0.5	0.9909	0.0062	0.0079	$7.39	$8.58	$6.89
	1	0.2131	0.0256	0.0643	$8.72	$9.21	$6.97
	2	0.2889	0.0578	0.2163	$12.40	$12.24	$7.20
Blower	0.5	0.9788	0.006	0.0416	$3.70	$3.47	$3.53
	1	0.189	0.0263	0.3437	$4.86	$6.14	$3.61
	2	0.2769	0.0587	1.1563	$6.73	$7.57	$3.75
Air Guide	0.5	0.9788	0.0027	0.2227	$2.04	$1.99	$1.69
	1	0.1409	0.0266	1.8377	$2.94	$2.71	$1.87
	2	0.2528	0.0508	0.7529	$3.89	$3.88	$1.99
Motor	0.5	0.9499	0.0062	1.1908	$7.73	$7.39	$7.23
	1	0.2058	0.0255	1.5445	$8.49	$7.92	$7.36
	2	0.2902	0.0587	0.0321	$11.92	$10.24	$7.42
Condenser	0.5	0.9895	0.0066	1.4802	$2.41	$2.06	$2.01
	1	0.1927	0.026	1.5573	$3.50	$2.94	$2.22
	2	0.3035	0.0586	0.1721	$4.05	$3.40	$2.33
Fan	0.5	1.0137	0.006	1.5445	$4.62	$3.89	$3.75
	1	0.2215	0.0258	0.3139	$6.36	$4.56	$3.85
	2	0.2915	0.0583	0.9195	$7.93	$6.35	$4.05
Protector	0.5	1.0233	0.0065	1.1004	$1.22	$0.95	$0.68
	1	0.189	0.026	1.6787	$1.90	$1.55	$0.82
	2	0.2877	0.0587	1.551	$3.31	$2.22	$0.89
Compressor	0.5	0.9883	0.0065	0.0328	$5.35	$5.02	$4.80
	1	0.1998	0.026	0.1721	$6.90	$6.47	$5.21
	2	0.2902	0.0584	1.5573	$9.39	$8.49	$5.38
AC	0.5	1.1753	0.0087	0.0008	$92.04	$87.50	$111.67
	1	0.3022	0.0347	0.0054	$96.05	$96.22	$116.90
	2	0.3961	0.0773	0.0176	$112.84	$110.19	$121.27

Components	**W^***	**Renewable Combination FRW/PRW**					
		Expected frequancy of Failures			**Expected Cost to Remanufacturer**		
		$RL^* = 1$	**$RL = 2$**	**$RL = 3$**	**$RL = 1$**	**$RL = 2$**	**$RL = 3$**
Evaporator	0.5	0.4407	0.0028	0.0007	$12.35	$14.14	$11.31
	1	0.0883	0.0115	0.0052	$13.72	$15.51	$11.52
	2	0.1322	0.0256	0.0179	$20.57	$20.44	$11.88
Control Box	0.5	0.4355	0.0028	0.0034	$12.11	$14.06	$11.28
	1	0.0937	0.0113	0.0282	$14.29	$15.10	$11.41
	2	0.127	0.0254	0.095	$20.31	$20.05	$11.80
Blower	0.5	0.4301	0.0026	0.0183	$6.07	$5.68	$5.78
	1	0.0831	0.0115	0.1511	$7.96	$10.06	$5.91
	2	0.1217	0.0257	0.5082	$11.02	$12.40	$6.15
Air Guide	0.5	0.4301	0.0011	0.098	$3.35	$3.27	$2.78
	1	0.0619	0.0118	0.8077	$4.82	$4.44	$3.06
	2	0.1111	0.0223	0.3309	$6.38	$6.35	$3.27
Motor	0.5	0.4174	0.0028	0.5233	$12.66	$12.11	$11.85
	1	0.0904	0.0113	0.6788	$13.90	$12.97	$12.06
	2	0.1275	0.0257	0.0141	$19.53	$16.78	$12.16
Condenser	0.5	0.435	0.0029	0.6506	$3.94	$3.37	$3.29
	1	0.0847	0.0115	0.6845	$5.73	$4.82	$3.63
	2	0.1334	0.0257	0.0755	$6.64	$5.58	$3.81
Fan	0.5	0.4455	0.0026	0.6788	$7.57	$6.38	$6.15
	1	0.0973	0.0113	0.1381	$10.43	$7.47	$6.30
	2	0.1281	0.0256	0.4042	$12.99	$10.40	$6.64
Protector	0.5	0.4497	0.0028	0.4836	$2.00	$1.56	$1.12
	1	0.0831	0.0113	0.7379	$3.11	$2.54	$1.35
	2	0.1265	0.0257	0.6815	$5.42	$3.63	$1.45
Compressor	0.5	0.4345	0.0028	0.0144	$8.77	$8.22	$7.86
	1	0.0878	0.0115	0.0755	$11.31	$10.61	$8.53
	2	0.1275	0.0257	0.6845	$15.38	$13.90	$8.82
AC	0.5	0.3037	0.002	0.0002	$150.79	$143.35	$182.96
	1	0.0614	0.008	0.0011	$157.36	$157.64	$191.51
	2	0.0891	0.018	0.0041	$184.87	$180.52	$198.67

Table 4. Expected number of failures and cost for remanufactured AC and components
for 2D Renewable FRW, PRW and Combination Policies

10.1.3. Combination Warranty (FRW-PRW) Policy

Here too the results given in Table 4 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 AC with $W = 2.0$ years will cost \$198.67 - \$55.00 = \$143.67 which is 261.23% saving in the cost of supplying the item, Cs.

10.2. Preventive Maintenance Evaluation

In order to assess the impact of PM on warranty cost, pairwise t tests were carried out for each performance measure. Table 5 and Table 6 present all models costs for conventional, warranty models with/ without PM respectively. According to these tables, PM achieves significant savings in holding, backorder, disassembly, disposal, remanufacturing, transportation, warranty, PM costs and number of warranty claims. In addition, SEPs provide significant improvements in total revenue and profit. According to Table 5 and Table 6, offering PM helps remanufacturer achieve saving 18%, 21%, 19% and 18% in total cost for Conventional, SEM with FRW, SEM with FRW, and SEM with FRW respectively.

	Mean Value with Warranty (PM offered)			
Performance Measure	**Conventional Model**	**Sensor Embedded Model with FRW**	**Sensor Embedded Model with PRW**	**Sensor Embedded Model FRW/PRW**
Holding Cost	\$250,257.03	\$150,774.37	\$158,555.63	\$159,196.12
Backorder Cost	\$46,422.30	\$30,327.20	\$31,892.35	\$32,021.18
Disassembly Cost	\$540,380.03	\$321,547.48	\$338,142.11	\$339,508.05
Disposal Cost	\$87,538.68	\$60,884.22	\$64,026.37	\$64,285.00
Testing Cost	\$161,174.99	N/A	N/A	N/A
Remanufacturing Cost	\$1,857,829.27	\$898,968.38	\$945,362.90	\$949,181.73
Transportation Cost	\$46,877.95	\$31,606.49	\$33,237.66	\$33,371.92
Warranty Cost	\$117,704.65	\$9,025.85	\$21,743.84	\$15,885.82
Number of Claims	55,722	11,981	15,487	14,793
Preventive Maintenance Cost	\$9,087.25	\$1,731.24	\$3,181.98	\$2,771.73
Total Cost	\$3,117,272.15	\$1,504,865.22	\$1,596,142.83	\$1,596,221.55
Total Revenue	\$4,693,569.22	\$6,452,158.07	\$4,933,609.46	\$6,677,871.58
Profit	\$1,576,297.06	\$4,947,292.85	\$3,337,466.64	\$5,081,650.03

Table 5. Results of performance measures for different models with warranty and preventive maintenance

The lowest average value of warranty, PM costs and the number of warranty claims during the warranty period for remanufactured ACs across all policies are \$7,094.30, \$1,724.32 and 9,339 claims respectively for the Sensor Embedded Model with FRW warranty policy. Whereas the conventional AC has the worst values for the warranty, PM costs and the number of warranty claims during the warranty period.

Performance Measure	Mean Value with Warranty (No PM offered)			
	Conventional Model	Sensor Embedded Model with FRW	Sensor Embedded Model with PRW	Sensor Embedded Model FRW/PRW
Holding Cost	$295,303.30	$182,436.99	$188,681.20	$187,851.42
Backorder Cost	$54,778.31	$36,695.91	$37,951.90	$37,784.99
Disassembly Cost	$637,648.44	$389,072.45	$402,389.11	$400,619.50
Disposal Cost	$103,295.64	$73,669.91	$76,191.38	$75,856.30
Testing Cost	$190,186.49	N/A	N/A	N/A
Remanufacturing Cost	$2,192,238.54	$1,087,751.74	$1,124,981.85	$1,120,034.44
Transportation Cost	$55,315.98	$38,243.85	$39,552.82	$39,378.87
Warranty Cost	$138,891.49	$10,921.28	$25,875.17	$18,745.27
Number of Claims	65,752	24,497	28,429.53	27,456
Total Cost	$3,667,658.18	$1,818,792.13	$1,895,623.42	$1,880,270.79
Total Revenue	$3,754,855.38	$5,548,855.94	$4,094,895.85	$5,409,075.98
Profit	$87,197.19	$3,730,063.81	$2,199,272.43	$3,528,805.19

Table 6. Results of performance measures for different models with warranty

10.3. Sensor Embedded Evaluation

10.3.1. Effect of SEPs on Warranty Cost

In order to assess the impact of SEPs on warranty cost, pairwise *t* tests were carried out for each performance measure. Table 5 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 6, the lowest average value of warranty costs and the number of warranty claims during the warranty period for remanufactured ACs across all policies are $9,025.85 and 11,981 claims respectively for the FRW warranty policy. If a comparison made between the conventional product model and SEPs with PRW warranty (worst policy case in term of cost). The SEPs model saved around 81.37% and 71.97% in warranty cost and number of claim respectively for SEPs model without PM and 81.53% and 72.21% for SEPs model with PM.

10.3.2. Renewable Pro-Rata Warranty (PRW) Policy

MINITAB-17 program was used to carry out one-way analyses of variance (ANOVA) and Tukey pairwise comparisons for all the results in this section. ANOVA was used in order to determine whether there are any significant differences between the warranty costs, number of claims and PM costs for the four different models viz., conventional model, SEPs with FRW, SEPs with PRW and SEPs with FRW/PRW, while the Tukey pairwise comparisons was conducted to identify which models are similar and which models are not. Table 7 shows that there is a significant difference in warranty costs between different warranty policies. Tukey test shows that all the models are different and the SEP model with FRW policy has the lowest warranty cost. In addition, there is a significant difference in the number of warranty claims between different warranty policies (see Table 8). The FRW policy has the lowest number of claims. Finally, Table 9 shows that there is a significant difference in PM costs between different warranty policies. Tukey test shows that all models are different and the SEP model with FRW policy has the lowest costs. These results can be useful in the determining the economical warranty policy associated with embedding sensors in Acs.

<table>
<tr><th colspan="6">ANOVA: Warranty Cost</th></tr>
<tr><td colspan="6">Null hypothesis All means are equal.
Alternative hypothesis At least one mean is different.
Significance level α = 0.05.</td></tr>
<tr><th colspan="6">SUMMARY</th></tr>
<tr><th>Models</th><th>Count</th><th>Sum</th><th>Average</th><th>StDev</th><th>95% CI</th></tr>
<tr><td>Conventional Model</td><td>2000</td><td>234,999,053</td><td>117,704.65</td><td>290.55</td><td>(117487, 117512)</td></tr>
<tr><td>SEP Model FRW</td><td>2000</td><td>19,012,894</td><td>9,025.85</td><td>288.00</td><td>(9493.74, 9519.15)</td></tr>
<tr><td>SEP Model PRW</td><td>2000</td><td>42,991,749</td><td>21,743.84</td><td>293.17</td><td>(21483.2, 21508.6)</td></tr>
<tr><td>SEP Model FRW/PRW</td><td>2000</td><td>30,995,719</td><td>15,885.82</td><td>287.56</td><td>(15485.2, 15510.6)</td></tr>
<tr><th colspan="6">ANOVA</th></tr>
<tr><th>Source of Variation</th><th>SS</th><th>df</th><th>MS</th><th>F-Value</th><th>P-value</th></tr>
<tr><td>Model</td><td>1.57496E+13</td><td>3</td><td>5.24986E+12</td><td>62499126.07</td><td>0.000</td></tr>
<tr><td>Error</td><td>671655610</td><td>7996</td><td>83999</td><td></td><td></td></tr>
<tr><td>Total</td><td>1.57503E+13</td><td>7999</td><td></td><td></td><td></td></tr>
<tr><td colspan="6">Tukey Pairwise Comparisons.
Grouping Information Using the Tukey Method and 95% Confidence.</td></tr>
<tr><th colspan="2">Model</th><th>N</th><th>Mean</th><th>Grouping</th><td></td></tr>
<tr><td colspan="2">Conventional Model</td><td>2000</td><td>117,704.65</td><td>A</td><td></td></tr>
<tr><td colspan="2">SEP Model FRW</td><td>2000</td><td>9,025.85</td><td>B</td><td></td></tr>
<tr><td colspan="2">SEP Model PRW</td><td>2000</td><td>21,743.84</td><td>C</td><td></td></tr>
<tr><td colspan="2">SEP Model FRW/PRW</td><td>2000</td><td>15,885.82</td><td>D</td><td></td></tr>
<tr><td colspan="6">Means that do not share a letter are significantly different.</td></tr>
</table>

Table 7. ANOVA Table and Tukey Pairwise Comparisons for Warranty Cost

ANOVA: Warranty Claims					
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	111,000,028	55,722	284.38	(55491.8, 55508.3)
SEP Model FRW	2000	23,503,224	11,981	140.92	(11743.4, 11759.9)
SEP Model PRW	2000	31,506,965	15,487	144.38	(15745.2, 15761.7)
SEP Model FRW/PRW	2000	29,503,360	14,793	143.00	(14743.4, 14759.9)
ANOVA					
Source of Variation	**SS**	**df**	**MS**	**F-Value**	**P-value**
Model	2.59008E+12	3	8.63359E+11	24316482.90	0.000
Error	283898791	7996	35505		
Total	2.59036E+12	7999			
Tukey Pairwise Comparisons. Grouping Information Using the Tukey Method and 95% Confidence.					
Model		**N**	**Mean**	**Grouping**	
Conventional Model		2000	55,722	A	
SEP Model FRW		2000	11,981	B	
SEP Model PRW		2000	15,487	C	
SEP Model FRW/PRW		2000	14,793	D	
Means that do not share a letter are significantly different.					

Table 8. ANOVA Table and Tukey Pairwise Comparisons for Number of Claims

ANOVA: Preventive Maintenance					
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	18,500,571	9,087.25	146.15	(9244.74, 9255.83)
SEP Model FRW	2000	3,500,607	1,731.24	29.59	(1744.76, 1755.85)
SEP Model PRW	2000	6,498,581	3,181.98	144.12	(3243.74, 3254.84)
SEP Model FRW/PRW	2000	5,502,922	2,771.73	145.07	(2745.91, 2757.01)
ANOVA					
Source of Variation	**SS**	**df**	**MS**	**F-Value**	**P-value**
Model	68996751725	3	22998917242	1436256.82	0.000
Error	128040710	7996	16013		
Total	69124792435	7999			
Tukey Pairwise Comparisons. Grouping Information Using the Tukey Method and 95% Confidence.					
Model		**N**	**Mean**	**Grouping**	
Conventional Model		2000	9,087.25	A	
SEP Model FRW		2000	1,731.24	B	
SEP Model PRW		2000	3,181.98	C	
SEP Model FRW/PRW		2000	2,771.73	D	
Means that do not share a letter are significantly different.					

Table 9. ANOVA Table and Tukey Pairwise Comparisons for Preventive Maintenance

11. Conclusions

Sensor embedded products utilize sensors implanted into products during their production process. Sensors are useful in predicting the best warranty policy and warranty period to offer a customer for the remanufactured components and products. The conditions and remaining lives of components and products can be estimated prior to offering a warranty based on the data provided by the sensors. This helps reduce the number of claims during warranty periods, determines the right preventive maintenance (PM) policy and eliminates unnecessary costs inflicted on the remanufacturer. The renewing, one-dimensional Free Replacement Warranty (FRW), Pro-Rata Warranty (PRW) and combination FRW/PRW policies' costs for remanufactured products and components were evaluated with/without offering PM for different periods in this paper. To that end, the effect of offering renewable, two-dimensional, Free Replacement Warranty (FRW) or Pro-Rata Warranty (PRW) or Combination FRW/PRW warranty policies to each disassembled component and sensor embedded remanufactured product was examined and the impact of sensor embedded products on warranty costs was assessed. A case study and varying simulation scenarios were examined and presented to illustrate the model's applicability.

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