ORIGINAL RESEARCH

Money-back guarantee warranty policy with preventive maintenance strategy for sensor-embedded remanufactured products

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Abstract

In today's global environment, technology is constantly evolving. Being able to stay up-to-date with the very latest technological advances can be extremely hard to accomplish. As a result of these changes and developments in technology, which often come unexpectedly, consumers are frequently tempted to update their devices to the very latest model. The result is that the life cycle of a product is becoming shorter and shorter than before. Manufacturers attempt to respond to consumers' concerns involving environmental issues as well as the more governmentally stringent environmental legislations by establishing facilities which include the minimization of the totality of waste relocated to landfills by recovering materials and components from returned, or End-Of-Life products and reuse them to build a remanufactured product, and/or novel components. With the rapid growth of interest in remanufactured products' market, offering warranty for remanufactured products and components is becoming a necessity for remanufacturer in order to meet customers' requirement and as a marketing mechanism. During that process, maintenance policies are of great importance in order to reduce the warranty cost on the remanufacturer. In this paper, an optimization simulation model for remanufactured items sold with one-dimensional non-renewing money-back guarantee (MBG) warranty policy is proposed from the view of remanufacturer, in which, an End-Of-Life product is subjected to upgrade action at the end of its past life and during the warranty period, preventive maintenance actions are carried out when the remaining life of the product reaches a pre-specified value so that the remanufacturer's expected profit can be maximized. Finally, a numerical example and design of experiment analysis are provided to demonstrate the proposed approach.

Introduction

With the recent surge of technological development and consumer preference to purchase newer device models and technological products, product life cycles have diminished and disposal rates have spiked. As a result, landfills and the Earth's natural resources have begun to reach a critical apex. In response to this apex, when a technological device reaches the end of its life cycle, and it becomes obsolete, manufacturing firms now reprocess the products they produced. This practice is conducted to remain compliant with new regulations. The new regulatory regime has helped to enlighten consumer awareness of the pertinent environmental issues regarding the matter.

The manufacturers of these devices construct specialized facilities designed for the end-of-life (EOL) product recovery process. These facilities enable manufacturers to minimize the amount of mechanical waste sent to landfills by retrieving the mechanical materials from the EOL products by way of the recycling, refurbishing, and remanufacturing processes. The results of these facilities

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are significant economic benefits, which makes processing of product recovery more attractive.

In product recovery, disassembly is the most vital component of operations. 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. However, while utilizing single workstations and disassembly cells are more flexible in operation, the process that produces the highest yield is the disassembly line operation. This disassembly line operation is also the most efficient operation for automated disassembly (Sasikumar et al. 2010).

The first fundamental step in the processes of remanufacturing, recycling, and disposing of EOL products is product disassembly. This pertinent operation 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 disassembly supports the recovery processes which are necessary to minimize dependency on processes that lead to natural resource depletion.

The quandary of the product recovery process is the uncertainty it poses with regards to component quality. This dilemma is due to the lack of information on the condition of the components prior to disassembly. However, there is a simple solution: Test each individual component after disassembly (Kongar and Gupta 2006).

Of course, that is not a practical solution because product disassembly puts a financial damper on manufacturer profits. In turn, the profit margins from the remanufacturing processes are diminished. That is due to the fact that these processes are based on two factors: The monetary cost of conducting the appropriate and necessary testing of all devices, and the magnitude of obligatory time required in the testing process. Furthermore, if the test reveals that a component is dysfunctional, it is an assault on the manufacturer because of the realization that the time spent attempting to process the EOL device(s) and all the resources required to do so were wasted.

The quality of a remanufactured product induces hesitation for many people due to efficacy and reliability concerns. This causes consumers to become unsure if remanufactured products will have the capacity to render the same expected performance as new devices. This uncertainty regarding a remanufactured product could lead the consumer to make a determination against its purchase. With this level of consumer apprehension, remanufacturers often employ marketing strategies to provide affirmation about product durability. One common marketing strategy remanufacturers employ is to encourage customer security are product warranties (Murthy and Blischke 2006).

The use of sensor-embedded products (SEPs) is a promising approach in dealing with disassembly. This is because SEPs utilize sensors implanted during the production process 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 because it provides an estimation of product component condition during the product's use stage. Moreover, the information gathered by sensors regarding any dysfunctional or missing components prior to EOL product disassembly contribute to important financial savings that would have otherwise been wasted in testing, disassembly, disposal, backorder, or holding costs processes (Ilgin and Gupta 2010a, b).

This galvanized us to study the impact that would be had by offering non-renewing warranties containing the information retrieved by the sensor-embedded remanufactured products. With our study, we quantitatively analyze the expansion achieved by using the SEP's information in several warranty analyses models that depict remanufacturing lines under various scenarios. Moreover, the goals of the study are to minimize the cost associated with warranty and maximize the profit gained by remanufacturers by unearthing a warranty with an appealing price.

Due to 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 assigned to each station are then distributed accordingly. Imposing a cost for backorders will be calculated based on the duration of backorders. Then there is also the fact that excessive and non-essential EOL products and components are disposed of regularly according to a stringent disposal policy. Furthermore, a pull control production mechanism is used in all disassembly line settings to be 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 to present a quantitative assessment of the effect of offering warranties on remanufactured items from a manufacturer's perspective in that it proposes an appealing price in the eyes of the consumer as well. While there are developmental studies on warranty policies for brand new products and on secondhand products, no studies exist that evaluate the potential benefits of warranties on remanufactured products in a quantitative and comprehensive manner. In these related studies, the profit improvements are achieved through warranty offers for different policies to determine the range of how much money can be invested in a warranty while still keeping it profitable overall.

The rest of the paper is organized as follows: "Literature review" section lists all the related work from the literature review. System description and design-of-experiment study are presented in "System description" and "Design-of-experiments study" sections, respectively. "Formulation" section presents the non-renewable one-dimensional Money-back Guarantee warranty. Assumptions and notations are given in "Results" section. "Conclusion" section describes the preventive maintenance analysis. The failures' process and warranty formulation are given in Sect. 8 and Sect. 9, respectively. Finally, results and conclusions are given in Sect. 10 and Sect. 11, respectively.

Literature review

Environmentally conscious manufacturing and product recovery

Numerous studies within the last few years involved environmentally conscious manufacturing and product recovery (ECMPRO) issues have received much favorable attention from researchers (Gungor and Gupta 1999; Gupta and Lambert 2008; Ilgin and Gupta 2011a). This is partly the result of public demands, government regulations and environmental factors. But it is also due to profits earned by implementing reverse logistics and product recycling resolutions. To respond to ever increasing and stricter environmental regulations and environmental concerns, manufacturers have established designated facilities designed to minimize waste accumulation by recovering components and materials derived from end-of-life (EOL) products (Gungor and Gupta 2002).

Many academics and researchers have done much to explain the manifold of environmentally conscious dilemmas involved in manufacturing. Consequently, there exist numerous reviews of the extensive issues involved in product recovery and environmentally conscious manufacturing. (see for example, Moyer and Gupta 1997; Gupta 2013; Ilgin et al. 2015). Due to its crucial role in the recovery process, disassembly is the most important area of research. For a variety of aspects involving disassembly, see the book by Lambert and Gupta 2005.

Warranty analysis

A contractual obligation incurred by a manufacturer (seller/vendor) regarding a product's sale is called a warranty. Its purpose is to establish liability for the infrequent circumstance that the sold item either breaks down too soon or fails to work properly. These contracts detail the guaranteed performance standards. In addition, should the product fail to meet these standards, some sort of compensation is spelled out, which often involves a free replacement (Blischke 1993). Product warranties have a variety of functions, including protection and insurance. This allows the buyers to transfer the risk of product failure back to the seller (Heal 1977). Product warranties are also excellent marketing tools, as they indicate product reliability (Blischke 1995; Gal-Or, 1989; Soberman 2003; Spence 1977). Warranties can also be a means to obtain additional revenues from the purchasers (Lutz and Padmanabhan 1995).

Although there is a considerable amount of literature and attention regarding warranties on new products, that for used items received relatively little notice. A limited number of publications offer studies in the relatively new field of modeling the warranty cost analysis for used products.

For used items, the best upgrade strategies under the virtual age and the screening test reliability development methods are presented by Saidi-Mehrabad et al. 2010, and Shafiee et al. (2011a). They constructed a scholastic model designed to examine the optimal degree of investments for increasing the reliability of secondhand products under free repair warranty (FRW) policies. It was deemed that more investments meant increasing reliability and larger declines in the virtual age 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 et al. 2011b. A study conducted by Naini and Shafiee 2011 was performed to determine the maximum expected profit with restrictive assumptions about age distributions, optimal upgrade and selling price. To detect and determine the best policies, they built a mathematical model to implement a parametric analysis on the items' chronological ages. One study adopted an integrated mathematical model that was not reliant on the specific age of the received item to determine typical decisions by remanufacturers (Yazdian et al. 2014). How warranty policies effect consumer behavior from the consumer's perspective has been studied by (Liao et al. 2015). In contrast, only a small amount of attention has been paid to the analysis of warranty costs for remanufactured products. But there are some papers that delve into the warranty for the remanufactured products' reverse and closed-loop supply chain management. For remanufactured products, extended one-dimensional and base warranties can be offered using Pro-Rata Warranty (PRW) policy and Free Replacement Warranty (FRW) (Alqahtani and Gupta 2015a, b, c). Moreover, one- and two-dimensional, nonrenewable and renewable warranty policies can be offered for EOL derived products (Alqahtani and Gupta 2016a, b, c).

Maintenance analysis

With product reliability and quality, maintenance plays a significant role. Maintenance is classified into two main types in the literature; viz., preventive maintenance (PM) and corrective maintenance (CM). When an item fails and then is restored to an operational state, that's CM. To reduce degeneration and the failure rate, PM is performed before the item fails.

There is extensive literature on maintenance policies. Several review papers on maintenance policies have been published (Wang 2002; Garg and Deshmukh 2006; Sharma et al. 2011). For detailed information on the general area of maintenance theory, readers may read the book by (Nakagawa 2006). For an extensive review of modelling maintenance policies, (Nakagawa 2008) can be helpful. Only a little interest has been generated by researchers for maintenance policies for second-hand products that fail while still under warranty (Shafiee and Chukova 2013). One researcher proposed two periodical age reduction PM models to reduce the high failure rate of the second-hand products (Yeh et al. 2011). For a study that examines the optimal periodic PM policies of a second-hand item following the expiration of warranty, refer to (Kim et al. 2011). Manufacturers should only perform PM actions when the cost savings of warranty servicing exceeds the additional cost incurred by performing PM activities. Thus, more research is required to develop effective PM policies for remanufactured products (Alqahtani and Gupta 2017a, b).

System description

In this study, discrete-event simulation was used to optimize the implementation of a one-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 study's experiments were designed using Taguchi's orthogonal arrays to represent the entire domain of the recovery system. This was done to observe the system behavior under various experimental conditions. To figure out the best strategy offered by the remanufacturer, for every scenario various preventive maintenance and warranty scenarios were analyzed using Tukey pairwise comparisons tests, pairwise t tests and one-way analysis of variance (ANOVA).

The ARTO system discussed in this study is like a product recovery system. In this paper, a sensor-embedded microwave oven (MO) is a product example. Based on the condition of EOL MO, it goes through a series of recovery operations as shown in Fig. 1. To meet the sales demand of the product, repairing and refurbishing processes may require reusable components. This requirement satisfies the internal and external component demands. Consequently, each will be properly built using the recovered components from the disassembly of old devices. In the ARTO system, there are three types of items that arrive for disassembly: failed SEP that needs to be rectified; EOL products for recovery; or SEP due for maintenance activities.

Initially, EOL MOs arrive at the ARTO system for information retrieval using a radio frequency data reader and is stored in the facility's database. Then the MOs are processed through a six-station disassembly line. To extract every component, a complete disassembly is performed. Nine components exist within a MO: the cooking cavity, control panel, metal mesh window, wave stirrer, high voltage transformer, microwave emitter, cooling fan, wave guide and magnetron and capacitor, as shown in Fig. 2. Exponential distributions are used to generate the interarrival times, interarrival times of each component's demand and disassembly times of EOL MO. Once the information is retrieved, all EOLPs are shipped either to station 1 for disassembly or, if it only needs one component, it is sent to its corresponding station. Destructive and nondestructive are the two types of disassembly operations that are used depending on the component's condition. Consequently, for a functional component, the disassembly cost is higher than for a nonfunctional component. Following disassembly, component testing is not needed due to the availability of information provided by the sensors regarding the component's conditions. It is assumed the retrieval of information from the sensors is less expensive than the actual testing and inspecting. For each SEP, recovery operations vary, depending on their estimated remaining life and overall condition. To meet the demands of spare parts, recovered components are used. Refurbished or recovered products are used for consumer product demands. Moreover, recycled components and products are used to meet material demands. Components and products that have been recovered are characterized based on their remaining lifespan. They are then placed in separate life-bins (e.g. 1, 2 years, etc.) where they wait to be retrieved via a customer demand. Underutilization of components or products can happen when it should be placed in a higher life-bin but is placed in a lower life-bin because the higher life-bin is full. Any component or product inventory that is greater than the maximum inventory allowed is assumed to be excess. It is instead disposed of or used for material demand. To meet product demand, refurbish and repair options can also be chosen as presented in Fig. 3. End-of-life products (EOLP) may have nonfunctional (broken, zero remaining life) or missing components that need to be replenished or replaced during the refurbishing or repairing
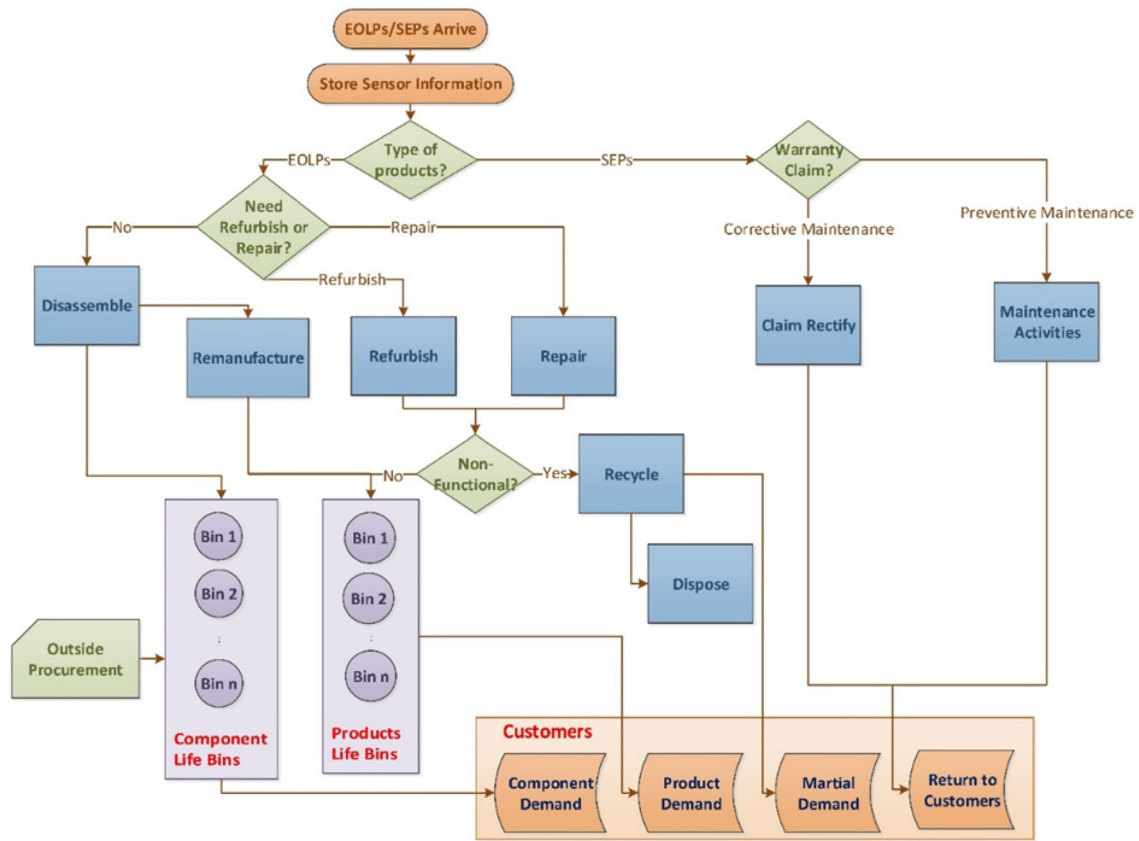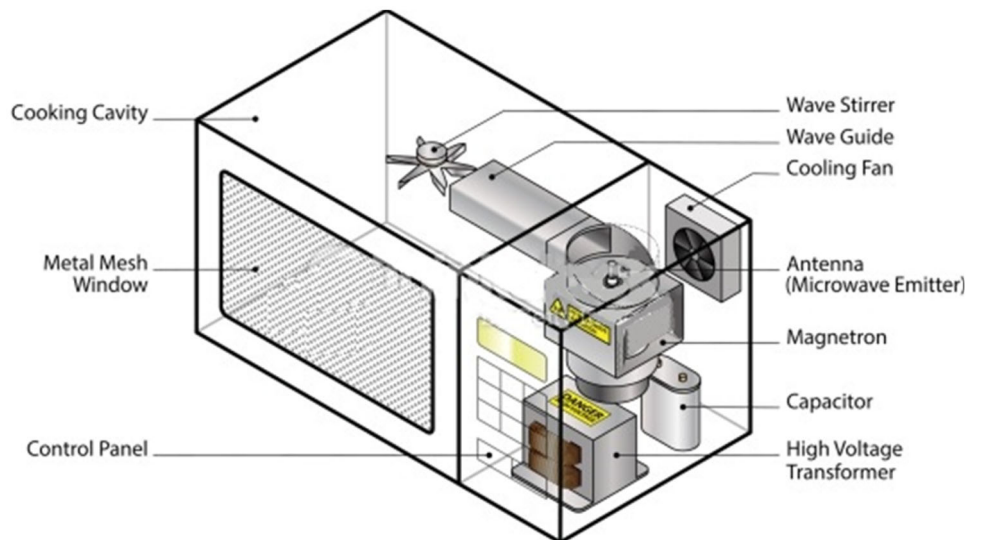
Fig. 1 ARTO system's recovery processes

Fig. 2 MO components

process to meet remaining life requirements. End-of-life products may also consist of components having shorter remaining lives than desired. For that reason, they might also have to be replaced.

In case of failure of SEP during the warranty period, the SEP will go through the same recovery operations as an EOLP. Lastly, to reduce the risk of failure, PM actions are performed during the warranty period. At this point, if the remaining life of a remanufactured MO reaches a pre-specified value, the SEPs are processed through four maintenance activities. These maintenance activities include cleaning, parts replacement, adjustments and measurements. The maintenance activities increase the remaining life of the MOs by δ time units, as shown in Fig. 4. Any failures

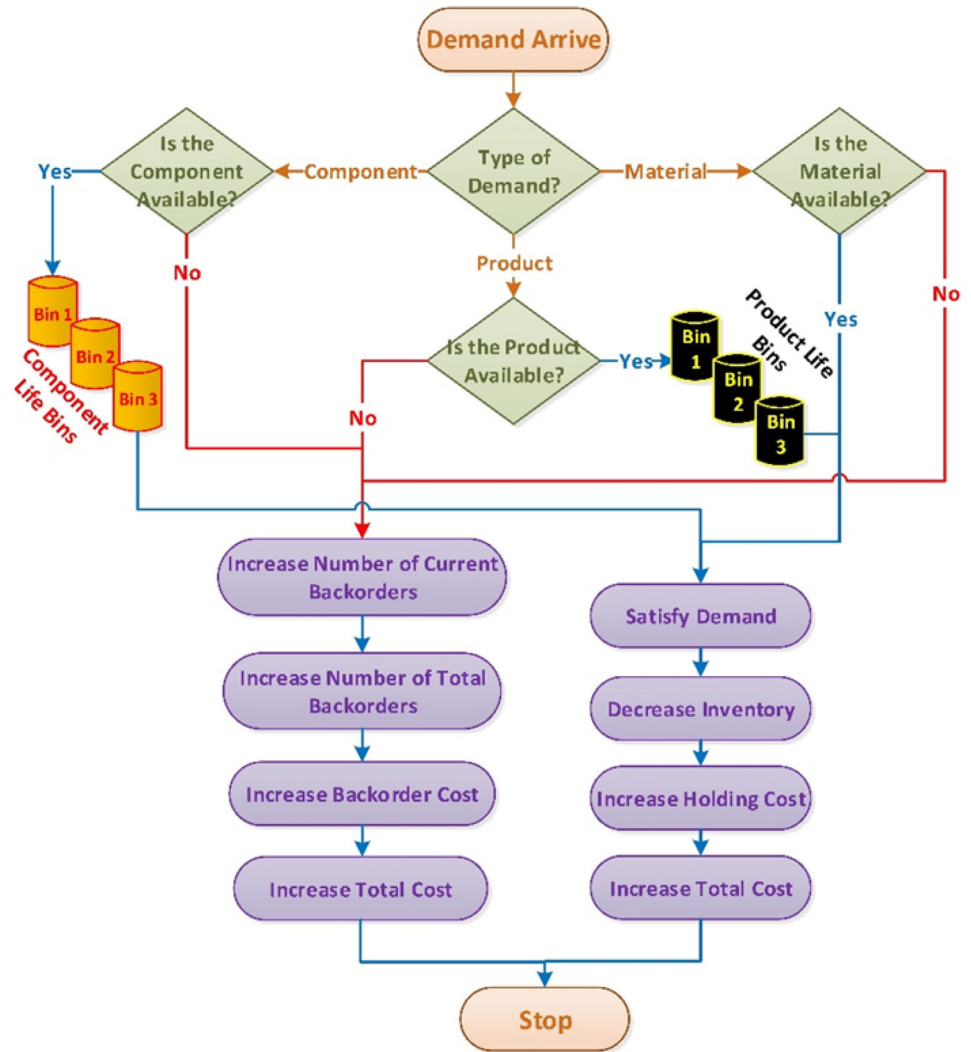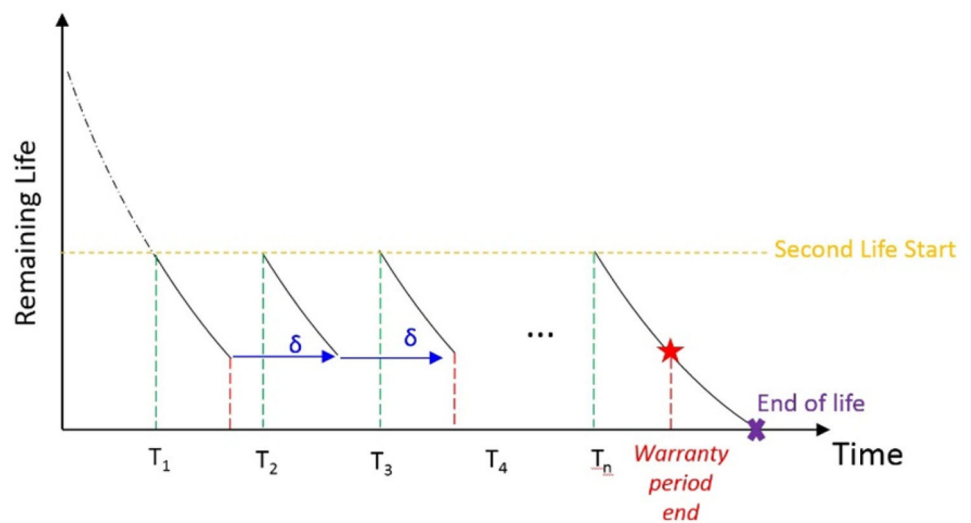**Fig. 3** ARTO system demand process

Fig. 4 Scheme for PM policies for remanufactured products

between two successive PM actions during the warranty period are rectified without cost to the customer.

Design-of-experiments study

In a comprehensive study for the quantitative evaluation of the SEPs on the performance of a disassembly line conducted by (Ilgin and Gupta 2011b), it was shown that smart SEPs are a favorable resolution in handling remanufacturing customer uncertainty. To test this claim on ARTO, we built a simulation model to represent the full recovery system and observed its behavior under different experimental conditions. The ARENA program, Version 14.5, was used to build the discrete-event simulation models. A factorial design was used with 54 factors that were considered each at 3 levels. These were identified as high, intermediate and low 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 Tables 1 and 2. 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 are a means to only have to conduct a minimal number of experiments. In most cases, orthogonal

Table 1 Parameters used in the ARTO system

Parameters	Unit	Value	Parameters	Unit	Value
Backorder cost rate	%	40	Sale price of 3-year wave stirrer	$	15
Holding cost rate	$/hour	10	Sale price of 3-year high voltage transformer	$	60
Remanufacturing cost	$	1.5	Sale price of 3-year microwave emitter	$	25
Disassembly cost per minute	$	1	Sale price of 3-year cooling fan	$	20
Sale price of 1-year cooking cavity	$	10	Sale price of 3-year wave guide	$	20
Sale price of 1-year control panel	$	20	Sale price of 3-year magnetron and capacitor	$	65
Sale price of 1-year metal mesh window	$	5	Weight of cooking cavity	kg	3.63
Sale price of 1-year wave stirrer	$	5	Weight of control panel	kg	1.81
Sale price of 1-year high voltage transformer	$	45	Weight of metal mesh window	kg	0.91
Sale price of 1 year microwave emitter	$	15	Weight of wave stirrer	kg	0.91
Sale price of 1 year cooling fan	$	15	Weight of high voltage transformer	kg	2.72
Sale price of 1 year wave guide	$	15	Weight of microwave emitter	kg	5.44
Sale price of 1 year magnetron and capacitor	$	50	Weight of cooling fan	kg	1.36
Sale price of 2-year cooking cavity	$	15	Weight of wave guide	kg	1.36
Sale price of 2-year control panel	$	30	Weight of magnetron and capacitor	kg	2.72
Sale price of 2-year metal mesh window	$	12	Unit copper scrap revenue	$/kg	0.6
Sale price of 2-year wave stirrer	$	12	Unit fiberglass scrap revenue	$/kg	0.9
Sale price of 2-year high voltage transformer	$	55	Unit steel scrap revenue	$/kg	0.2
Sale price of 2-year microwave emitter	$	18	Unit disposal cost	$/kg	0.3
Sale price of 2-year cooling fan	$	18	Unit copper scrap cost	$/kg	0.3
Sale price of 2-year wave guide	$	20	Unit fiberglass scrap cost	$/kg	0.45
Sale price of 2-year magnetron and capacitor	$	60	Unit steel scrap cost	$/kg	0.1
Sale price of 3-year cooking cavity	$	20	Sale price of 1 year MO	$	180
Sale price of 3-year control panel	$	35	Sale price of 2-years MO	$	240
Sale price of 3-year metal mesh window	$	15	Sale price of 3-year MO	$	275
Cost of supplying cooking cavity	$	4	Cost of supplying microwave emitter	$	1.66
Cost of supplying control panel	$	4	Cost of supplying cooling fan	$	2.34
Cost of supplying metal mesh window	$	2.8	Cost of supplying wave guide	$	0.6
Cost of supplying wave stirrer	$	1.2	Cost of supplying magnetron and capacitor	$	3.4
Cost of supplying high voltage transformer	$	4	Cost of supplying MO	$	55

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

No.	Factor	Unit	Levels			No.	Factor	Unit	Levels		
			1	2	3				1	2	3
1	Mean arrival rate of EOL MOs	Products/hour	10	20	30	28	Mean assembly time for station 6	Minutes	1	2	2
2	Probability of repair EOLPs	%	5	10	15	29	Mean demand rate for cooking cavity	Parts/hour	10	15	20
3	Probability of a nonfunctional control panel	%	10	20	30	30	Mean demand rate for control panel	Parts/hour	10	15	20
4	Probability of a nonfunctional high voltage transformer	%	10	20	30	31	Mean demand rate for metal mesh window	Parts/hour	10	15	20
5	Probability of a nonfunctional cooling fan	%	10	20	30	32	Mean demand rate for wave stirrer	Parts/hour	10	15	20
6	Probability of a nonfunctional magnetron and capacitor	%	10	20	30	33	Mean demand rate for high voltage transformer	Parts/hour	10	15	20
7	Probability of a missing control panel	%	5	10	15	34	Mean demand rate for microwave emitter	Parts/hour	10	15	20
8	Probability of a missing high voltage transformer	%	5	10	15	35	Mean demand rate for cooling fan	Parts/hour	10	15	20
9	Probability of a missing cooling fan	%	5	10	15	36	Mean demand rate for wave guide	Parts/hour	10	15	20
10	Probability of a missing magnetron and capacitor	%	5	10	15	37	Mean demand rate for magnetron and capacitor	Parts/hour	10	12	20
11	Mean non-destructive disassembly time for station 1	Minutes	1	1	1	38	Mean demand rate for 1 year MO	Products/hour	5	10	15
12	Mean non-destructive disassembly time for station 2	Minutes	1	1	1	39	Mean demand rate for 2-year MO	Products/hour	5	10	15
13	Mean non-destructive disassembly time for station 3	Minutes	1	1	1	40	Mean demand rate for 3-year MO	Products/hour	5	10	15
14	Mean non-destructive disassembly time for station 4	Minutes	1	1	1	41	Mean demand rate for refurbished MO	Products/hour	5	10	15
15	Mean non-destructive disassembly time for station 5	Minutes	1	1	1	42	Mean demand rate for material	Products/hour	5	10	15
16	Mean non-destructive disassembly time for station 6	Minutes	1	2	2	43	Percentage of good parts to recycling	%	95	90	80
17	Mean destructive disassembly time for station 1	Minutes	0	1	1	44	Mean metals separation process	Hour	1	1	2
18	Mean destructive disassembly time for station 2	Minutes	0	1	1	45	Mean copper recycle process	Minutes	1	1	2
19	Mean destructive disassembly time for station 3	Minutes	0	1	1	46	Mean steel recycle process	Minutes	1	1	2
20	Mean destructive disassembly time for station 4	Minutes	0	1	1	47	Mean fiberglass recycle process	Minutes	1	1	2
21	Mean destructive disassembly time for station 5	Minutes	0	1	1	48	Mean dispose process	Minutes	1	1	1
22	Mean destructive disassembly time for station 6	Minutes	1	1	1	49	Maximum inventory level for MO	Products/hour	10	15	20
23	Mean assembly time for station 1	Minutes	1	1	2	50	Maximum inventory level for refurbished MO	Products/hour	10	15	20
24	Mean assembly time for station 2	Minutes	1	1	2	51	Maximum inventory level for MO component	Products/hour	10	15	20
25	Mean assembly time for station 3	Minutes	1	1	2	52	Level of preventive maintenance effort	–	0.5	0.6	0.7
26	Mean assembly time for station 4	Minutes	1	1	1	53	Number of preventive maintenance to perform	#	2	3	4
27	Mean assembly time for station 5	Minutes	1	1	2	54	Time between each preventive maintenance	Months	1	2	3

arrays are more efficient when compared to many other statistical designs. The minimum number of experiments that are required to conduct the Taguchi method can be calculated based on the degrees of freedom approach. So, the number of experiments must be greater than or equal to a system's degrees-of-freedom. Precisely, $L_{109}(3^{54})$ (i.e., $109 = [(\text{number of levels} - 1) \times \text{number of factors}] + 1$) orthogonal arrays were chosen, meaning it requires 109 experiments to accommodate 54 factors upon three different levels. Additionally, orthogonal array assumes 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. Two thousand replications with 6 months (8 h a shift, one shift a day and 5 days a week) were used to run each experiment. Arena models calculate the profit using the following equation:

$$\begin{aligned} \text{Profit} = &\text{SR} + \text{CR} + \text{SCR} - \text{HC} - \text{BC} - \text{DC} - \text{DPC} \\ &- \text{TC} - \text{RMC} - \text{TPC} - \text{PMC} - \text{WC} \end{aligned} \quad (1)$$

where SR is the total revenue generated by the products; components and material sales during the simulated run time; CR is the total revenue generated by the collection of EOL MOs 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 MOs 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 MOs 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.

For each EOL MO, there are three types of scraps that need to be recovered and sold. Disposal cost is calculated by multiplying the unit disposal cost by the waste weight. The time of retrieving information from smart sensors is assumed to be 20 s per MO. The transportation cost is assumed to be $50 for each delivery by truck. There are varying prices in the secondary market of recovery product due to varying levels of quality.

Formulation

Under a buyback warranty policy, the buyer could return the remanufactured product during the warranty period and get a refund of the sale price from the remanufacturer. There are two types of a refund, either unconditional (money-back guarantee) or conditional on predetermine events such as if the number of failures over the warranty period exceed some specified limit.

Under the money-back guarantee policy, all failures during warranty period are replaced/repaired free of charge to the buyer. In case the number of failures during warranty period exceed a predetermine value, k, then the buyer has the option of returning the item for 100% money back. The warranty ceases either when the buyer returns the remanufactured product or the product reaches the end of the warranty period.

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.

Notations

W: Warranty period.

k: Number of claim.

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 jth PM activity.

m: Level of PM effort.

$\delta(m)$: Remaining life increment factor of PM with effort m.

α: Cost sharing parameter.

$\Lambda(\text{RL})$: Intensity function for system failure.

$N(W; \text{RL})$ Number of failures over the warranty period W for an item of remaining life RL.

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

$C_d(W; \text{RL})$: Total warranty cost to remanufacturer.

$Jd(W; \text{RL})$: Total warranty cost to remanufacturer.

n: Number of failures.

$\overline{c}_{bb}$: Expected cost of buyback to remanufacturer (may be full sale price if the item has to be scrapped and the difference between sale price and salvage value otherwise).

Pn(RL, RL + W): Probability of n failures over [0,W] given the remaining life of the item is RL.

ϒ Probability that buyer will execute money-back option.

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 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 increase 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 increased. The concept of virtual age is introduced in Kijima et al. 1988; and then extended in Kijima (1989). In this study, the jth PM only reimburses the damage accrued during the time between the $(j − 1)$th and the jth 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 jth 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 $\delta(m)$, $m = 0, 1, …,$ M, is the remaining life increment factor of PM with effort m. Note that, the effect of PM depends on its level m, $0 \leq m \leq M$, 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 $v_j = RL_j$, $j \geq 1$, 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.

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 one-dimensional warranty policies, remanufactured item failures can be viewed as random points occurring over a one-dimensional horizon. 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 maintenance 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,

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

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

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

Table 3 Expected cost to remanufacturer and buyer for remanufactured MO and components for money-back guarantee warranty (MBG) Policies

Components	W	Money-back guarantee warranty (MBG)					
		Expected probability of failures			Expected cost to remanufacturer		
		RL = 1	RL = 2	RL = 3	RL = 1	RL = 2	RL = 3
Cooking cavity	0.5	$0.73	$0.00	$0.00	$4.15	$4.76	$3.80
	1	$0.15	$0.02	$0.01	$4.62	$5.21	$3.88
	2	$0.22	$0.04	$0.03	$6.92	$6.88	$4.00
Control panel	0.5	$0.72	$0.00	$0.01	$4.08	$4.74	$3.80
	1	$0.15	$0.02	$0.05	$4.81	$5.08	$3.85
	2	$0.21	$0.04	$0.16	$6.84	$6.75	$3.97
Metal mesh window	0.5	$0.71	$0.00	$0.03	$2.04	$1.91	$1.95
	1	$0.14	$0.02	$0.25	$2.69	$3.38	$1.99
	2	$0.20	$0.04	$0.84	$3.71	$4.17	$2.08
Wave stirrer	0.5	$0.71	$0.00	$0.16	$1.12	$1.10	$0.94
	1	$0.10	$0.02	$1.33	$1.63	$1.50	$1.03
	2	$0.18	$0.04	$0.55	$2.16	$2.14	$1.10
High voltage transformer	0.5	$0.69	$0.00	$0.86	$4.25	$4.08	$3.99
	1	$0.15	$0.02	$1.12	$4.68	$4.36	$4.06
	2	$0.21	$0.04	$0.02	$6.58	$5.65	$4.10
Microwave emitter	0.5	$0.72	$0.00	$1.07	$1.34	$1.13	$1.11
	1	$0.14	$0.02	$1.13	$1.93	$1.63	$1.22
	2	$0.22	$0.04	$0.12	$2.24	$1.87	$1.29
Cooling fan	0.5	$0.73	$0.00	$1.12	$2.55	$2.16	$2.08
	1	$0.16	$0.02	$0.23	$3.51	$2.52	$2.13
	2	$0.21	$0.04	$0.67	$4.37	$3.49	$2.24
Wave guide	0.5	$0.74	$0.00	$0.80	$0.68	$0.53	$0.37
	1	$0.14	$0.02	$1.22	$1.04	$0.85	$0.46
	2	$0.21	$0.04	$1.12	$1.83	$1.24	$0.49
Magnetron and capacitor	0.5	$0.72	$0.00	$0.02	$2.96	$2.77	$2.65
	1	$0.14	$0.02	$0.12	$3.80	$3.57	$2.88
	2	$0.21	$0.04	$1.13	$5.18	$4.68	$2.97
MO	0.5	$0.85	$0.01	$0.00	$55.69	$53.60	$53.14
	1	$0.22	$0.03	$0.00	$57.93	$58.49	$55.43
	2	$23.98	$23.65	$20.43	$61.97	$61.65	$68.50

ARENA 14.5 is used to generate the remaining life and usage of remanufactured item at failure, 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.

All failures over warranty period [0, W) are replaced/repaired at no cost to the buyer. If the number of failures over [0, W) exceed a specified value k (k > 1), then at the (k + 1)^{st} failure, the buyer has the option of returning the item for 100% money-back and the warranty ceases when the buyer exercises this option. If the number of failures over [0, W) is either k or the buyer does not exercise the buyback option when the (k + 1)^{st} failure occurs, then the item is covered for all failures till W.

In this model, the buyer has the option of returning the item at the (k + 1)^{st} failure, should this occur within the warranty period, the warranty can cease before the item reaches a remaining life (RL − W).

Let N be the number of item failures over [RL − W, RL). Since failures are replaced/repaired minimally, then:

$$P_n(\text{RL} - W, \text{RL}) = \text{Prob}\{N = n\}$$
$$= \frac{\left\{\int_{\text{RL}-W}^{\text{RL}} \Lambda(t)dt\right\}^n e^{-\left\{\int_{\text{RL}-W}^{\text{RL}} \Lambda(t)dt\right\}}}{n!}. \quad (5)$$

The expected warranty cost to the remanufacturer is given by:

$$E[J_{\mathrm{d}}(W;\mathrm{RL})|N=n] = (k\overline{c}+\overline{c}_{dd})\gamma + n\overline{c}(1-\gamma). \quad (6)$$

On removing the conditioning, the expected warranty cost to the remanufacturer is given by:

$$E[J_d(W;\mathrm{RL})] = \sum_{n=0}^{k} n\overline{c}P_n(\mathrm{RL}-W,\mathrm{RL}) + \sum_{n=k+1}^{\infty} \{(k\overline{c} + \overline{c}_{dd})\gamma + n\overline{c}(1-\gamma)\}P_n(\mathrm{RL}-W). \quad (7)$$

Results

The results are divided into four sections. Section 9.1 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 9.2 shows a quantitative assessment of offering PM on warranty policies. Finally, Sect. 9.3 presents a quantitative assessment of the impact of SEPs on the warranty and maintenance costs and policies to the remanufacturer.

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 and without offering a preventive maintenance policy during each period.

Table 3 presents the expected number of failures and cost for remanufactured MO and components for MBG policies. In Tables 3, the expected cost to the remanufacturer not includes the cost of supplying the original item, C_s. Thus, the percentage of expected cost of warranty from

the cost of supplying the original item is calculated by subtracting C_s from the expected cost to remanufacturer. For example, from Table 3, for $W = 0.5$ and RL $= 1$, the warranty cost to remanufactured for MO is $55.69 - C_s = |\$55.69 - \$55.00| = \$0.69$ which is ($[\$0.69/\$55.00] \times 100$) = 1.25% of the cost of supplying the item, C_s, which is significantly less than that \$55.00, C_s. This saving might be acceptable, but the corresponding values for longer warranties are lower. For example, for $W = 2$ years and RL $= 1$, the corresponding percentage is ($[|\$61.97 - \$55.00|/\$55.00] \times 100$) = 12.67%.

Sensor-embedded evaluation

In order to assess the impact of SEPs on warranty cost, one-way analyses of variance (ANOVA) were carried out for total warranty cost, number of claims and PM cost as performance measures. Table 4 presents 95% confidence interval and p value for each test. According to Table 4, SEPs achieve statistically significant savings in these performance measures.

Warranty effect evaluation

In order to assess the impact of MBG on total cost, Table 5 presents the average values of all the cost with and without offering MBG for the conventional product model and SEPs product model. According to this table, offering warranty achieves statistically significant savings in holding, backorder, disassembly, disposal, remanufacturing, transportation, warranty and number of warranty claims. In addition, warranty without PM provide statistically significant improvements in total cost and profit with saving

Table 4 Results of models without warranty

Performance measure	Mean value		95% confidence interval	p value
	Conventional model ($\mu1$)	SEPs model ($\mu2$)		
Holding cost	$281,152.96	$150,774.37	$130316.59 < \mu1-\mu2 < 130440.59$	0.00
Backorder cost	$52,153.45	$30,327.20	$21764.25 < \mu1-\mu2 < 21888.25$	0.00
Disassembly cost	$607,093.61	$321,547.48	$285484.13 < \mu1-\mu2 < 285608.13$	0.00
Disposal cost	$98,345.93	$60,884.22	$37399.71 < \mu1-\mu2 < 37523.71$	0.00
Testing cost	$2,087,190.90	$0.00	$2087147.06 < \mu1-\mu2 < 2087234.74$	0.00
Remanufacturing cost	$52,665.35	$898,968.38	$-846365.03 < \mu1-\mu2 < -846241.03$	0.00
Transportation cost	$46,877.95	$31,606.49	$15209.462 < \mu1-\mu2 < 15333.458$	0.00
Warranty cost	$0.00	$0.00	$0.00 < \mu1-\mu2 < 0.00$	0.00
Number of claims	35,722	11,981	$23679.00 < \mu1-\mu2 < 23803.00$	0.00
PM cost	$0.00	$0.00	$0.00 < \mu1-\mu2 < 0.00$	0.00
Total cost	$3,225,480.16	$1,494,108.14	$1730752.04 < \mu1-\mu2 < 1731992.00$	0.00
Total revenue	$3,541,081.33	$4,026,506.99	$-486045.64 < \mu1-\mu2 < -484805.68$	0.00
Profit	$315,601.17	$2,532,398.85	$-2217417.66 < \mu1-\mu2 < -2216177.7$	0.00

Table 5 Results of warranty models with warranty and without preventive maintenance

Performance measure	Mean value for warranty model without PM		95% confidence interval	p value
	Conventional model (μ1)	SEPs with MBG policy (μ2)		
Holding cost	$255,502.10	$137,018.54	118421.56 < μ1–μ2 < 118545.56	0.00
Backorder cost	$47,395.25	$27,560.31	19772.94 < μ1–μ2 < 19896.94	0.00
Disassembly cost	$551,705.69	$292,211.24	259432.45 < μ1–μ2 < 259556.45	0.00
Disposal cost	$89,373.38	$55,329.47	37399.71 < μ1–μ2 < 37523.71	0.00
Testing cost	$1,896,766.94	$0.00	1896723.10 < μ1–μ2 < 1896810.78	0.00
Remanufacturing cost	$47,860.45	$816,951.39	− 769152.94 < μ1–μ2 < − 769028.94	0.00
Transportation cost	$42,601.06	$28,722.88	13816.18 < μ1–μ2 < 13940.18	0.00
Warranty cost	$29,463.75	$16,543.11	12858.64 < μ1–μ2 < 12982.64	0.00
Number of claims	32463	10888	21513.00 < μ1–μ2 < 21637.00	0.00
PM cost	$0.00	$0.00	0.00 < μ1–μ2 < 0.00	0.00
Total cost	$2,960,668.62	$1,374,336.94	1580131.85 < μ1–μ2 < 1592531.51	0.00
Total revenue	$3,978,251.86	$4,523,606.61	− 551554.58 < μ1–μ2 < − 539154.92	0.00
Profit	$1,017,583.24	$3,149,269.68	− 2137886.27 < μ1–μ2 < − 2125486.61	0.00

8.94% in total cost and increase 68.99% in total profit for conventional product model where in SEPs 24.36% in total cost and 19.59% in total profit for MBG model.

Preventive maintenance evaluation

According to Table 6, offering MBG warranty with PM during the warranty period for remanufactured MOs helps achieves statistically significant savings in holding, backorder, disassembly, disposal, remanufacturing, transportation, warranty, PM costs and number of warranty claims. In addition, warranty PM provide statistically significant improvements in total cost and profit with saving 11.23% in total cost and increase 32.27% in total profit compare to

not offering warranty nor PM where 18.72% saving in total cost and 10.99% increase in total profit for compare to offering just warranty without PM.

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 six different models viz., conventional model, SEPs model, conventional model with warranty, SEPs with MBG, conventional model with warranty and PM and SEPs with MBG and PM, while the Tukey pairwise comparisons was conducted to identify which models are similar and which models are not. Table 7 shows that

Table 6 Results of warranty models with warranty and preventive maintenance

Performance measure	Mean value for warranty model with PM		95% confidence interval	p value
	Conventional model (μ1)	SEPs with MBG policy (μ2)		
Holding cost	$243,071.10	$130,352.14	112656.96 < μ1–μ2 < 112780.96	0.00
Backorder cost	$45,089.32	$26,219.41	18807.91 < μ1–μ2 < 18931.91	0.00
Disassembly cost	$524,863.44	$277,994.22	246807.222 < μ1–μ2 < 246931.22	0.00
Disposal cost	$85,025.08	$52,637.52	32325.56 < μ1–μ2 < 32449.56	0.00
Testing cost	$1,804,483.14	$0.00	1804044.75 < μ1–μ2 < 1804921.53	0.00
Remanufacturing cost	$45,531.89	$777,204.08	− 731734.19 < μ1–μ2 < − 731610.19	0.00
Transportation cost	$40,528.38	$27,325.42	13140.96 < μ1–μ2 < 13264.96	0.00
Warranty cost	$28,030.24	$15,738.23	12230.01 < μ1–μ2 < 12354.01	0.00
Number of claims	30884	10358	20464.00 < μ1–μ2 < 20588.00	0.00
PM cost	$89,357.46	$35,842.36	53453.10 < μ1–μ2 < 53577.10	0.00
Total cost	$2,905,980.05	$1,343,313.39	1556466.83 < μ1–μ2 < 1568866.45	0.00
Total revenue	$4,469,394.06	$5,082,076.56	− 618882.33 < μ1–μ2 < − 606482.67	0.00
Profit	$1,563,414.02	$3,738,763.17	− 2181548.98 < μ1–μ2 < − 2169149.32	0.00

Table 7 ANOVA table and Tukey pairwise comparisons for warranty cost

ANOVA: Profit

Null hypothesis: All means are equal

Alternative hypothesis: At least one mean is different

Significance level $\alpha = 0.05$

Models	Count	Sum	Average	SD	95% CI
Conventional model	2000	631202343.9	315601.1719	28696.00	(38480.3, 38501.8)
SEPs model	2000	5064797709	2532398.854	14639.36	(18741.1, 18762.6)
Conventional model with warranty	2000	2035166483	1017583.241	29093.20	(23492.5, 23514.0
SEP model MBG	2000	6298539357	3149269.678	28781.24	(20481.4, 20502.9)
Conventional model with warranty and PM	2000	3126828034	1563414.017	14614.77	(17743.2, 17764.7)
SEP model MBG and PM	2000	7477526341	3738763.17	28840.79	(19494.6, 19516.1)

ANOVA

Source of variation	SS	df	MS	F value	p value
Model	1.72E+16	5	3.44E+15	82514.48	0.00
Error	7.51E+12	11994	626319452.1		
Total	1.72E+16	11999			

Tukey pairwise comparisons

Grouping information using the Tukey method and 95% confidence

Model		N	Mean	Grouping
Conventional model		2000	315601.17	A
Conventional model with warranty		2000	1017583.24	B
Conventional model with warranty and PM		2000	1563414.02	C
SEPs model		2000	2532398.85	D
SEP model MBG		2000	3149269.68	E
SEP model MBG and PM		2000	3738763.17	F

Means that do not share a letter are significantly different

there is a significant difference in warranty costs between different warranty policies. Tukey test shows that all the models are different and the SEPs model with MBG policy and PM strategy has the highest total profit. In addition, there is a significant difference in the number of warranty claims between different models. These results can be useful in determining the economical warranty policy associated with embedding sensors in MOs.

Conclusions

Remanufactured products are very popular with consumers due to their appeal in offering the latest technology with lower prices as compared to brand new products. A remanufactured product induces hesitation for many consumers regarding its efficacy and reliability. Therefore, the consumers are unsure if the remanufactured products will have the capacity to render the same expected performance as that of new products. 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 an attempt to provide affirmation about product durability. One strategy that remanufacturers employ to increase consumer confidence is product warranty. To that end, this paper studied and scrutinized the impact that would be had by offering money-back warranty on remanufactured products.

The advanced remanufacturing-to-order (ARTO) system deliberated on in this study is a product recovery system. A discrete-event simulation model was developed from the view of remanufacturer for remanufactured items sold with one-dimensional non-renewing Money-back Guarantee warranty policy, in which, an End-Of-Life product is subjected to preventive maintenance action when the remaining life of the product reaches a pre-specified value so that the remanufacturer's expected profit can be maximized. Experiments were designed using Taguchi's Orthogonal Arrays to represent the full recovery system and observe their behavior under different experimental conditions. In order to assess the impact of warranty and

preventive maintenance on remanufacturer total cost, pairwise t tests were carried out along with one-way analyses of variance (ANOVA) and Tukey pairwise comparisons test for each performance measure of the ARTO system.

This study was able to determine the optimal costs of warranty and preventive maintenance for one-dimensional non-renewable money-back warranty offered on remanufactured products using simulation model and design of experiments analysis. Moreover, the optimum prices were determined for remanufactured products to make them competitive in the eyes of the buyer. This is the first study that maximizes the remanufacturer's profit, minimizes the warranty and preventive maintenance costs, maximizes the confidence of the consumers toward buying a remanufactured product and maximizes the attractiveness of the remanufactured product's price.

The future study will be designed to determine the optimal preventive maintenance policy with the corresponding warranty period and cost.

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