Warranty and Maintenance

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Chapter 17

17.1 Introduction

All products are unreliable in the sense that they fail. A failure can occur early in an item's life due to manufacturing defects or late in its life due to degradation that is dependent on age and usage. Most products are sold with a warranty that offers protection to buyers against early failures over the warranty period. The warranty period offered has been getting progressively longer. For example, the warranty period for cars was 3 months in the early 1930s; this changed to 1 year in the 1960s, and currently it varies from 3 to 5 years. With extended warranties, items are covered for a significant part of their useful lives, and this implies that failures due to degradation can occur within the warranty period.

Offering a warranty implies additional costs (called "warranty servicing" costs) to the manufacturer. This warranty servicing cost is the cost of repairing item failures (through corrective maintenance (CM)) over the warranty period. For short warranty periods, the manufacturer can minimize the expected warranty servicing cost through optimal CM decision making. For long warranty periods, the degradation of an item can be controlled through preventive maintenance (PM), and this reduces the likelihood of failures. Optimal PM actions need to be viewed from a life cycle perspective (for the buyer and manufacturer), and this raises several new issues.

The literature that links warranty and maintenance is significant but small in comparison with the literature on these two topics. In this paper we review the literature dealing with warranty and maintenance and suggest areas for future research.

The outline of the paper is as follows. In Sections 17.2 and 17.3 we give brief overviews of product warranty and maintenance respectively, in order to set the background for later discussions. Following this, we review warranty and CM in Section 17.4, and warranty and PM in Section 17.5. Section 17.6 covers extended warranties and service contracts, and in Section 17.7 we state our conclusions and give a brief discussion of future research topics.

17.2 Product Warranties: An Overview

17.2.1 Role and Concept

A warranty is a contract between buyer and manufacturer associated with the sale of a product. Its purpose is basically to establish liability in the event of a premature failure of an item sold, where "failure" is meant as the inability of the item to perform its intended function. The contract specifies the promised performance and, if this is not met, the means for the buyer to be compensated. The contract also specifies the buyer's responsibilities with regards to due care and operation of the item purchased.

Warranties serve different purposes for buyers and manufacturers. For buyers, warranties serve a dual role—protectional (assurance against unsatisfactory product performance) and informational (better warranty terms indicating a more reliable product). For manufacturers, warranties also serve a dual role—promotional (to communicate information regarding product quality and to differentiate from their competitors' products) and protectional (against excessive claims from unreasonable buyers).

17.2.2 Product Categories

Products can be either new or used, and new products can be further divided into the following three categories.

1. Consumer durables, such as household appliances, computers, and automobiles bought by individual households as a single item.
2. Industrial and commercial products bought by businesses for the provision of services (*e.g.* equipment used in a restaurant, aircraft used by airlines, or copy machines used in an office). These are bought either individually (*e.g.* a single X-ray machine bought by a hospital) or as a batch, or lot, of K $(K > 1)$ items (*e.g.* tires bought by a car manufacturer). Here we differentiate between "standard" off-the-shelf products and "specialized" products that are custom built to buyer's specifications.
3. Government acquisitions, such as a new fleet of defense equipment (*e.g.* missiles, ships, *etc.*). These are usually "custom built" and are products involving new and evolving technologies. They are usually characterized by a high degree of uncertainty in the product development process.

Used products are, in general, sold individually and can be consumer durables, industrial, or commercial products.

17.2.3 Warranty Policies

Both new and used products are sold with many different types of warranty. Blischke and Murthy [1] developed a taxonomy for new product warranty and Murthy and Chatophadaya [2] developed a similar taxonomy for used products. In this section we briefly discuss the salient features of the main categories of policies for new products and then briefly touch on policies for used items.

17.2.3.1 Warranties Policies for Standard Products Sold Individually

We first consider the case of new standard products where items are sold individually. The first important characteristic of a warranty is the form of compensation to the customer on failure of an item. The most common forms for non-repairable products are (1) a lump-sum rebate (*e.g.* "money-back guarantee"), (2) a free replacement of an item identical to the failed item, (3) a replacement provided at reduced cost to the buyer, and (4) some combination of the preceding terms. Warranties of Type (2) are called Free Replacement Warranties (FRWs). For warranties of Type (3), the amount of reduction is usually a function of the amount of service received by the buyer up to the time of failure, with decreasing discount as time of service increases. The discount is a percentage of the purchase price, which can change one or more times during the warranty period, or it may be a continuous function of the time remaining in the warranty period. These are called pro rata warranties (PRWs). The most common combination warranty is one that provides for free replacements up to a specified time and a replacement at pro-rated cost during the remainder of the warranty period. This is called a combination FRW/PRW. For a repairable product under an FRW policy, the failed item is repaired at no cost to the buyer.

Warranties can be further divided into different sub-groups based on dimensionality (one-dimensional warranties involve only age or usage; two-dimensional warranties involve both age and usage) and whether the warranty is renewing or not. In a renewing warranty, the repaired or replacement item comes with a new warranty identical to the initial warranty.

For used products, warranty coverage may also be limited in many ways. For example, certain types of failure or certain parts may be specifically excluded from coverage. Coverage may include parts and labor or parts only, or parts and labor for a portion of the warranty period and parts only thereafter. The variations are almost endless.

17.2.3.2 Warranty Policies for Standard Products Sold in Lots

Under this type of warranty, an entire batch of items is guaranteed to provide a specified total amount of service, without specifying a guarantee on any individual item. For example, rather than guaranteeing that each item in a batch of K items will operate without failure for W hours, the batch as a whole is guaranteed to provide at least KW hours of service. If, after the last item in the batch has failed, the total service time is less than KW hours, items are provided as specified in the warranty (*e.g.* free of charge or at pro rata cost) until such time as the total of KW hours is achieved.

17.2.3.3 Warranty Policies for Specialized Products

In the procurement of complex military and industrial equipment, warranties play a very different and important role of providing incentives to the seller to increase the reliability of the items after they are put into service. This is accomplished by requiring that the contractor maintain the items in the field and make design changes as failures are observed and analyzed. The incentive is an increased fee paid to the contractor if it can be demonstrated that the reliability of the item has, in fact, been increased. Warranties of this type are called reliability improvement warranties (RIWs).

17.2.3.4 Extended Warranties

The warranty that is an integral part of a product sale is called the base warranty. It is offered by the manufacturer at no additional cost and is factored into the sale price. An extended warranty provides additional coverage over the base warranty and is obtained by the buyer through paying a premium. Extended warranties are optional warranties that are not tied to the sale process and can either be offered by the manufacturer or by a third party (*e.g.* several credit card companies offer extended warranties for products bought using their credit cards, and some large merchants offer extended warranties). The terms of the extended warranty can be either identical to the base warranty or may differ from it in the sense that they might include cost limits, deductibles, exclusions, *etc.*

Extended warranties are similar to service contracts, where an external agent agrees to maintain a product for a specified time period under a contract with the owner of the product. The terms of the contract can vary and can include CM and/or PM actions.

17.2.3.5 Warranties for Used Products

Some of the warranty policies for second-hand products are similar to those for new products, whilst others are different. Warranties for second-hand products can involve additional features, such cost limits, exclusions, and so on. The terms (*e.g.* duration and features) can vary from item to item and can depend on the condition of the item involved. They are also influenced by the negotiating skills of the buyer. Murthy and Chattopadhyay [2] proposed a taxonomy for one-dimensional warranty policies for used items sold individually. These include options such as cost limits, deductibles, cost sharing, money-back guarantees, *etc*.

17.2.4 Issues in Product Warranty

Warranties have been analyzed by researchers from many different disciplines. The various issues dealt with are given in the following list.

1. Historical: origin and use of the notion.
2. Legal: court action, dispute resolution, product liability.
3. Legislative: Magnusson–Moss Act in the USA, warranty requirements in government acquisition (particularly military) in different countries, EU legislation.
4. Economic: market equilibrium, social welfare.
5. Behavioral: buyer reaction, influence on purchase decision, perceived role of warranty, claims behavior.
6. Consumerist: product information, consumer protection, and consumer awareness.
7. Engineering: design, manufacturing, quality control, testing.
8. Statistics: data acquisition and analysis, stochastic modeling.
9. Operations research: cost modeling, optimization.
10. Accounting: tracking of costs, time of accrual, taxation implications.
11. Marketing: assessment of consumer attitudes, assessment of the marketplace, use of warranty as a marketing tool, warranty and sales.
12. Management: integration of many of the previous items, determination of warranty policy, warranty servicing.
13. Society: public policy issues.

Blischke and Murthy [3] examined several of these issues in depth. Here, we briefly discuss two issues of relevance to this chapter.

17.2.4.1 Warranty Cost Analysis

We first look at warranty cost from the manufacturer's perspective. There are a number of approaches to the costing of warranties, and costs are clearly different for buyer and seller. The following are some of the methods for calculating costs that might be considered.

1. Cost per item sold: this per unit cost may be calculated as the total cost of warranty, as determined by general principles of accounting, divided by number of items sold.
2. Cost per unit of time.

These costs are random variables, since claims under warranty and the cost to rectify each claim are uncertain. The selection of an appropriate cost basis depends on the product, the context and perspective. The type of customer—individual, corporation, or government—is also important, as are many other factors.

From the buyer's perspective, the time interval of interest is from the instant an item is purchased to the instant when it is disposed or replaced. This includes the warranty period and the post-warranty period. The cost of rectification over the warranty period depends on the type of warranty. It can vary from no cost (in the case of an FRW) to cost sharing (in the case of a PRW). The cost of rectification during the post-warranty period is borne completely by the buyer. As such, the variable of interest to the buyer is the cost of maintaining an item over its useful life. Hence, the following cost estimates are of interest.

1. Cost per item averaging over all items purchased plus those obtained free or at reduced price under warranty.

2. Life cycle cost of ownership of an item with or without warranty, including purchase price, operating and maintenance cost, *etc.*, and finally the cost of disposal.
3. Life cycle cost of an item and its replacements, whether purchased at full price or replaced under warranty, over a fixed time horizon.

The warranty costs depend on the nature of the maintenance actions (corrective and/or preventive) used and we discuss this further later in the chapter.

17.2.4.2 Warranty Servicing

Warranty servicing costs can be minimized by using optimal servicing strategies. In the case where only CM actions are used, two possible strategies are as follows.

1. Replace versus repair. The manufacturer has the option of either repairing or replacing a failed item by a new one.
2. Cost repair limit strategy. Here, an estimate of the cost to repair a failed item is made and, by comparing it with some specified limit, the failed item is either repaired or replaced by a new one.

17.2.5 Review of Warranty Literature

Review papers on warranties include a three-part paper in the *European Journal of Operational Research*: Blischke and Murthy [1] deal with concepts and taxonomy, Murthy and Blischke [4] deal with a framework for the study of warranties, and Murthy and Blischke [5] deal with warranty cost analysis. Papers by Blischke [6] and Chukova *et al.* [7] deal mainly with warranty cost analysis. Two recent review papers are by Thomas and Rao [8] and Murthy and Djamaludin [9], with the latter dealing with warranty from a broader perspective.

Over the last 6 years, four books have appeared on the subject. Blischke and Murthy [10] deal with cost analysis of over 40 different warranty policies for new products. Blischke and Murthy [3] provide a collection of review papers dealing with warranty from many different perspectives. Sahin and Polotoglu [11] deal with the cost analysis of some basic one-dimensional warranty policies. Brennan [12] deals with warranty administration in the context of defense products.

Finally, Djamaludin *et al.* [13] list over 1500 papers on warranties, dividing these into different categories. This list does not include papers that have appeared in the law journals.

17.3 Maintenance: An Overview

As indicated earlier, maintenance can be defined as actions (i) to control the deterioration process leading to failure of a system, and (ii) to restore the system to its operational state through corrective actions after a failure. The former is called PM and the latter CM.

CM actions are unscheduled actions intended to restore a system from a failed state into a working state. These involve either repair or replacement of failed components. In contrast, PM actions are scheduled actions carried out either to reduce the likelihood of a failure or prolong the life of the system.

17.3.1 Corrective Maintenance

In the case of a repairable product, the behavior of an item after a repair depends on the type of repair carried out. Various types of repair action can be defined.

- *Good as new repair*. Here, the failure time distribution of repaired items is identical to that of a new item, and we model successive failures using an ordinary renewal process. In real life this type of repair would seldom occur.
- *Minimal repair*. A failed item is returned to operation with the same effective age as it possessed immediately prior to failure. Failures then occur according to a non-homogeneous Poisson process with an intensity function having the same form as the hazard rate of the time to first failure distribution. This type of

rectification model is appropriate when item failure is caused by one of many components failing and the failed component being replaced by a new one (see Murthy [14] and Nakagawa and Kowada [15]).

- *Different from new repair (I)*. Sometimes when an item fails, not only the failed components are replaced but also others that have deteriorated sufficiently. These major overhauls result in $F_1(x)$, the failure time distribution function of all repaired items, being different from $F(x)$, the failure time distribution function of a new item. The mean time to failure of a repaired item is assumed to be smaller than that of a new item. In this case, successive failures are modeled by a modified renewal process.
- *Different from new repair (II)*. In some instances, the failure distribution of a repaired item depends on the number of times the item has been repaired. This situation can be modeled by assuming that the distribution function after the jth repair ($j \geq 1$) is $F_j(x)$ with the mean time to failure μ_j decreasing as j increases.

17.3.2 Preventive Maintenance

PM actions can be divided into the following categories.

- *Clock-based maintenance*. PM actions are carried out at set times. An example of this is the "block replacement" policy.
- *Age-based maintenance*. PM actions are based on the age of the component. An example of this is the "age replacement" policy.
- *Usage-based maintenance*. PM actions are based on usage of the product. This is appropriate for items such as tires, components of an aircraft, and so forth.
- *Condition-based maintenance*. PM actions are based on the condition of the component being maintained. This involves monitoring of one or more variables characterizing the wear process (*e.g.* crack growth in a mechanical component). It is often difficult to measure the variable of interest directly, and in this case some other variable may be used to obtain estimates of the variable of interest. For example, the wear of bearings can be measured by dismantling the crankcase of an engine. However, measuring the vibration, noise, or temperature of the bearing case provides information about wear, since there is a strong correlation between these variables and bearing wear.
- *Opportunity-based maintenance*. This is applicable for multi-component systems, where maintenance actions (PM or CM) for a component provide an opportunity for carrying out PM actions on one or more of the remaining components of the system.
- *Design-out maintenance*. This involves carrying out modifications through redesigning the component. As a result, the new component has better reliability characteristics.

In general, PM is carried out at discrete time instants. In cases where the PM actions are carried out fairly frequently they can be treated as occurring continuously over time. Many different types of model formulations have been proposed to study the effect of PM on the degradation and failure occurrence of items and to derive optimal PM strategies.

17.3.3 Review of Maintenance Literature

Several review papers on maintenance have appeared over the last 30 years. These include McCall [16], Pierskalla and Voelker [17], Sherif and Smith [18], Monahan [19], Jardine and Buzacott [20], Thomas [21], Gits [22], Valdez-Flores and Feldman [23], Pintelon and Gelders [24], Dekker [25], and Scarf [26]. Cho and Parlar [27] and Dekker *et al.* [28] deal with the maintenance of multi-component systems and Pham and Wang [29] review models with imperfect maintenance. These review papers contain references to the large number of papers and books dealing with maintenance.

17.4 Warranty and Corrective Maintenance

The bulk of the literature on warranty and corrective maintenance deals with warranty servicing costs under different CM actions. We first review the literature linking warranties and CM for new products, then we consider the literature for used items.

Although most warranted items are complex multi-component systems, the 'black-box' approach has often been used to model time to first failure. The items are viewed as single entities characterized by two states—working and failed—and $F(x)$, the distribution function for time to first failure, is usually selected, either on an intuitive basis, or from the analysis of failure data. Subsequent failures are modeled by an appropriate stochastic point process formulation depending on the type of rectification action used. If the times to complete rectification actions are very small in comparison with the times between failures, they are ignored in the modeling.

Most of the literature on warranty servicing (for one- and two-dimensional warranties) is summarized by Blischke and Murthy [3, 10]. We confine our discussion to one-dimensional warranties, for standard products, sold individually, and focus on issues relating to maintenance actions and optimal decision making.

Models where items are subjected to different from new repair (I) include those of Biedenweg [30], and Nguyen and Murthy [31, 32]. Biedenweg [30] shows that the optimal strategy is to replace with a new item at any failure occurring up to a certain time measured from the initial purchase and then repair all other failures that occur during the remainder of the warranty period. This technique of splitting the warranty period into distinct intervals for replacement and repair is also used by Nguyen and Murthy [31, 32], where any item failures occurring during the second part of the warranty period are rectified using a stock of used items [31]. Nguyen and Murthy [32] extend Biedenweg's [30] model by adding a third interval, where failed items are either replaced or repaired and a new warranty is given at each failure.

The first warranty servicing model, involving minimal repair and assuming constant repair and replacement costs, is that of Nguyen [33]. As in Biedenweg [30], the warranty period is split into a replacement interval followed by a repair interval. Under this strategy a failed item is always replaced by a new one in the first interval, irrespective of its age at failure. Thus, if the failure occurs close to the beginning of the warranty then the item will be replaced at a higher cost than that of a repair and yet there will be very little reduction in its effective age. This is the major limitation of this model, and makes the strategy clearly sub-optimal.

Using the same assumptions as Nguyen [33], Jack and Van der Duyn Schouten [34] investigated the structure of the manufacturer's optimal servicing strategy using a dynamic programming model. They showed that the repair–replacement decision on failure should be made by comparing the item's current age with a time-dependent control limit function $h(t)$. The item is replaced on failure at time t if and only if its age is greater than $h(t)$. A new servicing strategy proposed by Jack and Murthy [35] involves splitting the warranty period into distinct intervals for carrying out repairs and replacements with no need to monitor the item's age. In intervals near the beginning and end of the warranty period the failed items are always repaired, whereas in the intermediate interval at most one failure replacement is carried out.

Murthy and Nguyen [36] examined the optimal cost limit repair strategy where, at each failure during the warranty period, the item is inspected and an estimate of the repair cost determined. If this estimate is less than a specified limit then the failed item is minimally repaired, otherwise a replacement is provided at no cost to the buyer.

For used items, Murthy and Chattopadhyay [2] deal with both FRW and PRW policies with no cost limits. Chattopadhyay and Murthy [37] deal with the cost analysis of limit on total cost (LTC) policies. Chattopadhyay and Murthy [38] deal with the following three different policies—specific parts exclusion (SPE) policy; limit on individual cost (LIC) policy; and limit on individual and total cost (LITC) policy—and discuss their cost analysis.

17.5 Warranty and Preventive Maintenance

PM actions are carried out either to reduce the likelihood of a failure or to prolong the life of an item. PM can be perfect (restoring the item to "good-as-new") or imperfect (restoring the item to a condition that is between as "good-as new" and as "bad-as-old").

PM over the warranty period has an impact on the warranty servicing cost. It is worthwhile for the manufacturer to carry out this maintenance only if the reduction in the warranty cost exceeds the cost of PM. From a buyer's perspective, a myopic buyer might decide not to invest in any PM over the warranty period, as item failures over this period are rectified by the manufacturer at no cost to the buyer. Investing in maintenance is viewed as an additional unnecessary cost. However, from a life cycle perspective the total life cycle cost to the buyer is influenced by maintenance actions during the warranty period and the post-warranty period. This implies that the buyer needs to evaluate the cost under different scenarios for PM actions.

This raises several interesting questions. These include the following:

1. Should PM be used during the warranty period?
2. If so, what should be the optimal maintenance effort? Should the buyer or the manufacturer pay for this, or should it be shared?
3. What level of maintenance should the buyer use during the post-warranty period?

PM actions are normally scheduled and carried out at discrete time instants. When the PM is carried out frequently and the time between the two successive maintenance actions is small, then one can treat the maintenance effort as being continuous over time. This leads to two different ways (discrete and continuous) of modeling maintenance effort.

Another complicating factor is the information aspect. This relates to issues such as the state of item, the type of distribution function appropriate for modeling failures, the parameters of the distribution function, *etc.* The two extreme situations are complete information and no information, but often the information available to the manufacturer and the buyer lies somewhere between these two extremes and can vary. This raises several interesting issues, such as the adverse selection and moral hazard problems. Quality variations (with all items not being statistically similar) add yet another dimension to the complexity.

As such, the effective study of PM for products sold under warranty requires a framework that incorporates the factors discussed above. The number of factors to be considered and the nature of their characterization result in many different model formulations linking PM and warranty. We now present a chronological review of the models that have been developed involving warranty and PM.

Ritchken and Fuh [39] discuss a preventive replacement policy for a non-repairable item after the expiry of a PRW. Any item failure occurring within the warranty period results in a replacement by a new item with the cost shared between the producer and the buyer. After the warranty period finishes, the item in use is either preventively replaced by the buyer after a period T (measured from the end of the warranty period) or replaced on failure, whichever occurs first. A new warranty is issued with the replacement item and the optimal T^* is found by minimizing the buyer's asymptotic expected cost per unit time.

Chun and Lee [40] consider a repairable item with an increasing failure rate that is subjected to periodic imperfect PM actions both during the warranty period and after the warranty expires. They assume that each PM action reduces the item's age by a fixed amount and all failures between PM actions are minimally repaired. During the warranty period, the manufacturer pays all the repair costs and a proportion of each PM cost, with the proportion depending on when the action is carried out. After the warranty expires, the buyer pays for the cost of all repairs and PM. The optimal period between PM actions is obtained by minimizing the buyer's asymptotic expected cost per unit time over an infinite horizon. An example is given for an item with a Weibull failure distribution.

Chun [41] dealt with a similar problem to Chun and Lee [40], but with the focus instead on the manufacturer's periodic PM strategy over the warranty period. The optimal number of PM actions N^* is obtained by minimizing the expected cost of repairs and PMs over this finite horizon.

Jack and Dagpunar [42] considered the model studied by Chun [41] and showed that, when the product has an increasing failure rate, a strict periodic policy for PM actions is not the optimal strategy. They showed that, for a warranty of length W and a fixed amount of age reduction at each PM, the optimal strategy is to perform N PMs at intervals x apart, followed by a final interval at the end of the warranty of length $W - Nx$, where only minimal repairs are carried out. Performing PMs with this frequency means that the item is effectively being restored to as good-as-new condition.

Dagpunar and Jack [43] assumed that the amount of age reduction is under the control of the manufacturer and the cost of each PM action depends on the operating age of the item and on the effective age reduction resulting from the action. In this model, the optimal strategy can result in the product not being restored to as good as new at each PM. The optimal number of PM actions N^*, optimal operating age to perform a PM s^*, and optimal age reduction x^* are obtained by minimizing the manufacturer's expected warranty servicing cost.

Sahin and Polatoglu [44] discussed two types of preventive replacement policy for the buyer of a repairable item following the expiry of a warranty. Failures over the warranty period are minimally repaired at no cost to the buyer. In the first model, the item is replaced by a new item at a fixed time T after the warranty ends. Failures before T are minimally repaired, with the buyer paying all repair costs. In the second model, the replacement is postponed until the first failure after T. They considered both stationary and non-stationary strategies in order to minimize the long-run average cost to the buyer. The non-stationary strategies depend on the information regarding item age and number of previous failures that might be available to the buyer at the end of the warranty period. Sahin and Polatoglu [45] dealt with a model that examined PM policies with uncertainty in product quality.

Monga and Zuo [46] presented a model for the reliability-based design of a series–parallel system considering burn-in, warranty, and maintenance. They minimized the expected system life cycle cost and used genetic algorithms to determine the optimal values of system design, burn-in period, PM intervals, and replacement time. The manufacturer pays the costs of rectifying failures under warranty and the buyer pays post-warranty costs.

Finally, Jung *et al.* [47] determined the optimal number and period for periodic PMs following the expiry of a warranty by minimizing the buyer's asymptotic expected cost per unit time. Both renewing PRWs and renewing FRWs are considered. The item is assumed to have a monotonically increasing failure rate and the PM actions slow down the degradation.

17.6 Extended Warranties and Service Contracts

The literature on extended warranties deals mainly with the servicing cost to the provider of these extended warranties. This is calculated using models similar to those for the cost analysis of base warranties with only CM actions.

Padmanabhan and Rao [48] and Padmanabhan [49] examined extended warranties with heterogeneous customers with different attitudes to risk and captured through a utility function. Patankar and Mitra [50] considered the case where items are sold with PRW where the customer is given the option of renewing the initial warranty by paying a premium should the product not fail during the initial warranty period.

Mitra and Patankar [51] dealt with the model where the product is sold with a rebate policy and the buyer has the option to extend the warranty should the product not fail during the initial warranty period. Padmanabhan [52] discussed alternative theories and the design of extended warranty policies.

Service contracts also involve maintenance actions. Murthy and Ashgarizadeh [53, 54] dealt with service contracts involving only CM. The authors are unaware of any service contract models that deal with PM or optimal decision making with regard to maintenance actions.

17.7 Conclusions and Topics for Future Research

In this final section we again stress the importance of maintenance modeling in a warranty context, we emphasize the need for model validation, and we then outline some further research topics that link maintenance and warranty.

Post-sale service by a manufacturer is an important element in the sale of a new product, but it can result in substantial additional costs. These warranty servicing costs, which can vary between 0.5 and 7% of a product's sale price, have a significant impact on the competitive behavior of manufacturers. However, manufacturers can reduce the servicing costs by adopting proper CM and PM strategies, and these are found by using appropriate maintenance models.

Models for determining optimal maintenance strategies in a warranty context were reviewed in Sections 17.4 and 17.5. The strategies discussed, whilst originating from more general maintenance models, have often had to be adapted to suit the special finite time horizon nature of warranty problems. However, all warranty maintenance models will only provide useful information to manufacturers provided they can be validated, and this requires the collection of accurate product failure data.

We have seen that some maintenance and warranty modeling has already been done, but there is still scope for new research, and we now suggest some topics worthy of investigation.

1. For complex products (such as locomotives, aircraft, *etc.*) the (corrective and preventive) maintenance needs for different components vary. Any realistic modeling requires grouping the components into different categories based on the maintenance needs. This implies modeling and analysis at the component level rather than the product level (see Chukova and Dimitrov [55]).
2. The literature linking warranty and PM deals primarily with age-based or clock-based maintenance. Opportunity-based maintenance also offers potential for reducing the overall warranty servicing costs. The study of optimal opportunistic maintenance policies in the context of warranty servicing is an area for new research.
3. Our discussion has been confined to one-dimensional warranties. Optimal maintenance strategies for two-dimensional warranties have received very little attention. Iskandar and Murthy [56] deal with a simple model, and there is considerable scope for more research on this topic.
4. The optimal (corrective and preventive) maintenance strategies discussed in the literature assume that the model structure and model parameters are known. In real life, this is often not true. In this case, the optimal decisions must be based on the information available, and this changes over time as more failure data are obtained. This implies that the modeling must be done using a Bayesian framework. Mazzuchi and Soyer [57] and Percy and Kobbacy [58] dealt with this issue in the context of maintenance, and a topic for research is to apply these ideas in the context of warranties and extended warranties.
5. The issue of risk becomes important in the context of service contracts. When the attitude

to risk varies across the population and there is asymmetry in the information available to different parties, several new issues (such as moral hazard, adverse selection) need to be incorporated into the model (see Murthy and Padmanabhan [59]).

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