

A FRAMEWORK FOR WARRANTY PREDICTION DURING PRODUCT DEVELOPMENT

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ABSTRACT

This paper describes the challenges faced by companies to manage warranty performance during product development. Understanding and reducing warranty cost often focuses exclusively on the analysis of product failures. However, warranty costs can also be incurred by events such as misaligned customer expectations that do not involve a product failure, per se. Many experts agree that effective management of system reliability and reliability validation during product development is a key to achieve superior time to market and life cycle quality. The paper first surveys the challenges faced by various organizations ranging from consumer electronics to aircraft engines to experimental high-energy physics accelerators. From the survey emerge some key and common issues that these companies face: identification of failure events; reliability modeling and prediction; prototyping and validation testing. The paper then reviews the current state of the art to identify areas for improvements as well as needed integrations in order to develop a comprehensive framework that will be useful to product developers to manage and predict warranty performance during product development. This framework extends and integrates three areas: 1) extend scenario-based FMEA to include the diagnosis and repair of failure events as part of the scenario; 2) use of Bayesian methods to integrate field data, product development data and engineering judgments; 3) generate costs models that allow tradeoff studies between product design, service model design and warranty policies. The paper concludes by presenting a future research agenda.

Keywords: Warranty, Reliability, Bayesian Methods, Data Mining

INTRODUCTION

A warranty is a contractual obligation between a consumer and manufacturer that protects the consumer should the product fail to perform its intended function within a given time period. It is the representation of the quality of product and it is an expression of the willingness of a business to stand behind its products and services. As such, offering a warranty can be used as a marketing tool to increase sales of a product thus increasing total revenues. In addition, the better a manufacturer understands its warranty costs the better position it is in to generate service revenue.

The challenge for most manufacturers is that as selling prices drop, this forces the unit costs to drop and the result has been that warranty costs become an increasingly significant portion of the product cost. In order to stay competitive, it is necessary to drive warranty system improvements in terms of improved product reliability, improved service delivery efficiency and properly designed warranty policies.

This paper first gives a summary of the challenges faced in design for reliability and warranty. The summary leads to some common themes and challenges that are faced by most companies today. A review of related work highlights useful concepts as well as areas that need attention to enable better warranty prediction during product development. The paper then proposes a framework for warranty prediction during product development to enable engineers and engineering managers of a company to achieve robust development strategies. The paper closes by outlining future steps of research to consolidate and disseminate such methods and tools.

A SURVEY OF CHALLENGES IN DESIGN FOR RELIABILITY AND WARRANTY

In 1998, the first author was a member of the product development team at the Hewlett-Packard Company (HP) that introduced a new line of Color LaserJet printers. Expecting high reliability, the team was surprised to find higher than expected warranty costs. In fact, following initial product introduction, the new Color LaserJets represented approximately 3% of the high-end department LaserJet units, but accounted for approximately 25% of the total warranty dollars.

An investigation into the HP Color LaserJet warranty experience uncovered two key observations.

- Product reliability was not the main problem, at least not in the traditional sense. Warranty costs were being driven by more than just hardware failures. Some key drivers included misaligned customer expectations relative to what the product could actually deliver; sub-optimal service and support logistics (over-stocking of expensive but infrequently used replacement components, for example); and poorly designed and managed warranty policies [3].

- The traditional methods for assessing the warranty performance were not sufficient to alert the development teams of the impending warranty issues. This manifested itself in three ways: (1) development engineers were aware of the issues, but were unable to properly assess the impact of these issues; (2) development engineers were aware of the issues and had a sense of the potential impact, but when confronted with the information the management did not act on it appropriately; (3) development engineers did not identify the appropriate warranty scenarios so mitigating action could not be taken.

This experience highlights the fact that improving product reliability does not always solve a warranty problem and there are other contributors to increased warranty costs. In addition, improved assessment methods are needed to aid product development teams make decisions related to the warranty performance of the product. In response, Stanford University's Manufacturing Modeling Laboratory had organized and hosted two research roundtables to discuss emerging needs in "Reliability Validation" (2003) and "System Reliability of Product Platforms" (2004). These research roundtables involved speakers who presented the challenges they have had in the area of design for reliability and design for warranty. Discussion points included: 1) adaptation of traditional design for reliability tools such as FMEA 2) coordination of "design for platform system reliability" across globally distributed development partners 3) managing trade-offs between target system reliability, warranty and service cost, 4) dealing with uncertainty associated with reliability and system platforms and 5) rapid validation of reliability.

The computer, aircraft engine and rocket propulsion industries were represented in addition to organizations such as NASA and the Stanford Linear Accelerator Center. While the diversity of products represented was quite broad, there were some common themes that emerged from these presentations which are summarized below.

Identification of Failure Events

The first step of any reliability improvement activity is to identify the critical failure modes. When dealing with the development of complex systems, particularly those that incorporate new technologies, a class of failures that causes greatest concern is "unknown-unknown". These are unanticipated failures resulting from physical mechanisms that are not understood very well. A second class of failure that generates concern is wear-out modes due to the length of time required to uncover them. A clear need was expressed for strategies to effectively and efficiently discover both of these failure modes.

Reliability Modeling and Prediction

Another prevalent theme was the need for risk management and decision-making tools. A couple of the speakers identified the need for probabilistic physics-based simulations that lead to robust reliability solutions. Key areas of focus to improve predictive reliability modeling include modeling uncertainty, developing efficient probabilistic analysis techniques for rare-event prediction and modeling noise in complex analyses.

In addition to modeling, another opportunity is to develop event rate prediction models that can effectively integrate historical field experience, product development testing data, product development assessment tool data (e.g. FMEA), and engineering judgment. This is an important key to maximize the utility of data streams that exist within the enterprise. A related opportunity is the standardization of a failure description language throughout the organization and the product life-cycle so that data can be more easily imported into decision and assessment tools. A large part of the data integration problems result from the inconsistent ways that the same failure event is described by different parts of the organization and in different phases of the product life-cycle.

Prototyping and Validation Testing

Even with the best modeling effort, prototyping and validation testing will have to be performed. The key lies in the effectiveness of the testing. It is critical that the testing performed generates data that greatly increases the probability of finding the failure modes described above. In addition it is important that the validation testing provides a great degree of confidence regarding the expected warranty performance of the system, yet be cost effective at providing that confidence.

RELATED WORK

Traditionally, warranty has been viewed as just costing out events and these events have typically been generated using classical reliability modeling techniques. However, this is an inadequate way of addressing the problem. In this section, classical reliability and design for reliability techniques will be reviewed, pointing out some short-comings. This will be followed by a review of the current state-of-the-art in warranty and reliability modeling during product development. A section will follow to highlight the first author's personal experience with warranty modeling in industry.

Reliability Modeling

Traditional reliability analysis concerns itself with ensuring that a product can perform the specified function in the designated environment for a minimum length of time, cycles or events. This requires testing over long periods of time to prove that the product as designed and *built* will have an acceptable life [4]. However, Clausing [5] has noted that this approach to reliability is flawed since the main objective during product development is to maximize the improvement in reliability, not necessarily to characterize it. In addition maximizing reliability requires many systematic changes to the design configuration, which makes extensive reliability testing early in the development process impractical. When it becomes practical, it is too late in the development cycle to take the appropriate actions.

That is not to say that characterization of reliability during product development is not important. It simply highlights the need for methods that allow them to be integrated into the decision-making process so that they help to improve the reliability performance of the product, while also monitoring that improvement so that it can be linked to the financial targets of the project. The main issue is that early in the development process there is little direct statistical evidence to predict reliability and the existing prediction methods fall short of providing the required accuracy [2, 6-8].

A related area relevant to reliability prediction during the product development is the use of reliability growth models. These models are based on the observation that the failure rate of a product in development follows a predictable pattern of improvement due to the “learning-curve” effect. This rate of improvement needs to be characterized by an organization based on past projects. However, these models do not explicitly consider the impact of actual design changes and corrections [2].

Even if the issues identified above were to be resolved, a major outstanding issue is that what is characterized in product development may not be relevant to the customer or it may be tested in a manner that is not representative of the customer use environment. It is important that the events that are being characterized are representative of the field experience. Given the severe constraints of time and money imposed by the development process, the need exists to at least correlate the observations during testing with the actual results in the field.

Design for Reliability

A study conducted at a large U.S. electronics firm demonstrated that there was a correlation between eight design for reliability practices and warranty performance, rate of warranty performance improvement and operating profit [4]. These eight activities included:

- 1) Thermal design and measurement
- 2) Worst-case analysis
- 3) Supplier process audits
- 4) Reliability goals are high priority
- 5) Supplier qualification testing
- 6) DFR training
- 7) Component stress derating
- 8) Failure Modes and Effects Analysis

Clearly, these are important activities, some of which lead to analytical outputs and test results, but it is left largely to the engineer and engineering judgment to effectively utilize this information during the design decision-making process. There is valuable information in these DFR activities that should be explicitly integrated into the decision-making process.

Product Warranty Management and Modeling

Murthy and Blischke [9] develop a comprehensive framework to study warranty from the perspective of the consumer, manufacturer, and public policy decision makers. They employ the systems model approach which considers the manufacturer, the consumer, the product, the product performance, and the warranty policy to analyze warranty. An important observation is that the product performance is a value determined by the interaction between the product characteristics (determined by the manufacturer) and the product usage (determined by the consumer). The usage conditions and the user characteristics will determine whether or not an event (could be a real event or a perceived event) will lead to a warranty event. Factors include whether or not the product was used as intended; whether or not the claim is valid; whether or not the product is user repairable. All of these situations will incur warranty costs. This highlights the importance of going beyond traditional reliability modeling and modeling consumer behavior as well.

Murthy and Blischke [10] performed a brief but comprehensive review of mathematical models that have been developed to study warranty-related problems. They provided a good break-down of resolution actions, of key elements contributing to total resolution time, and of key elements contributing to total resolution costs. These will be discussed in greater detail in later sections of this paper.

Murthy and Blischke [10] concluded by acknowledging that there is a need for further research to link product development and manufacturing quality variations with warranty.

Reliability Modeling During Product Development

As noted earlier, there is little to no direct statistical evidence to predict the reliability of a product early in the product development process. Bayesian methods provide a formal means of including subjective information as part of the analysis methods. Several authors have used Bayesian methods to assess and predict product reliability in the early stages of product development [2, 6-8]. There are two common themes in these references: (1) All data other than test data are incorporated into the model through engineering judgment (2) the use of reliability growth models to project what the fail rate of the released product will be.

Yadav et. al. [2] point out that the existing reliability growth models are based on the assumption of the known probability of improvement and known fail rates without considering the impact of actual design changes. They propose a framework which includes this input through a fuzzy inference model. In addition, the methodology they develop leverages existing warranty data, design of experiments and FMEA analyses to characterize product improvements. They

provide a sound methodology that needs to be extended to account for the additional issues identified above for modeling warranty.

An Industrial Perspective

The following is a summary of some of the industrial practices for warranty prediction encountered by the first author. The typical approach to warranty prediction was to start with the warranty data for the most similar product already in the field to the one under development. The warranty costs and failure rates for each individual component or subsystem was broken out. Using engineering judgments and expert opinions, these broken out data were modified and the numbers were rolled back up. However, by focusing only on components, only a portion of the warranty event was captured. Fortunately, another bucket that involved no parts to rectify (e.g. the service technician simply removed a paper jam for the customer) captured warranty events.

Typically, these estimates were overly optimistic, high-level estimates that were adequate for program-level decisions, but they provided little insight to impact design and service model decisions. In addition, these were one-time analyses that did not facilitate re-use of the analysis to evaluate changes in product design or the service model, which did not allow for “what-if” scenarios to be analyzed. Another drawback to the components approach was that the interactions between the product design, the service model and the warranty policies was not considered.

In response, the first author approached the Strategic Planning and Modeling (SPaM) team for assistance. SPaM is a small team of operations research specialists within HP whose task is to provide internal support to HP product divisions to improve the efficiency, cost-effectiveness, and profitability of HP’s product lines. SPaM worked together with engineers at Color LaserJet to create the quantitative warranty cost modeling approach described in Kakouros, Cargille et. al. [3].

This initial modeling effort was leveraged to support the development of the follow-on Color LaserJet product. The slight difference in approach was that engineering judgment and expert opinion was used to modify the event rates calculated in the original work by Kakouros, Cargille et. al. [3]. This activity focused attention on the importance of warranty and on validation testing. As a result of the increased attention on warranty, the actual product warranty performance was better than initially expected.

While this was a successful outcome, the process was less than perfect. System testing, which was still focused on defect discovery, occurred too late in the development process. The role of validation testing should be just that. Better tools are needed to anticipate system issues earlier develop process. In addition, the event rate prediction models need to better integrate historical field experience, product development testing data, assessment tool information, and engineering judgment.

FRAMEWORK PROPOSAL

Objectives

Predicting warranty performance during the product development phases has two main objectives.

- 1) It must facilitate decision-making by increasing the product developers’ and managers’ confidence that their actions are leading to improved warranty performance in the field. In addition, these models should provide insights to the development team for actions they can take to mitigate warranty costs.
- 2) It must provide the management team an accurate projection of warranty costs so that the enterprise can appropriately plan for the financial impact of these costs. These impacts include, product pricing, extended warranty support pricing, service inventory requirements, warranty accruals, etc.

As pointed out by Clausung [5], these objectives are incompatible because quantification of reliability requires extensive testing of a single configuration, while maximizing reliability requires many systematic changes to the design configuration. Given that most current approaches to warranty prediction are extensions of traditional reliability modeling, it is not surprising that those approaches suffer from this same incompatibility.

While reliability characterization may not be a main objective from a design standpoint, it is important from a program standpoint in that it will be a major driver of warranty performance and customer satisfaction; therefore, both objectives need to be achieved.

The remainder of this section will define a framework that leads to satisfying the two objectives outlined above. The key to satisfying these objectives is the observation that system reliability, as observed by the customer, is an intrinsic property of the system architecture and design for given a market, a given production capability and a given service model. Therefore, it should be possible to proactively define the critical warranty scenarios, particularly during the early phases of product development, and to use data generated during the entire product life-cycle to characterize each scenario at each step in the product development life-cycle while fulfilling the aforementioned objectives.

Overview

The major steps involved in predicting the warranty performance of a system are illustrated in Figure 1. The following briefly summarizes each step, which will be discussed in greater detail below. The first step in the process is to identify the important warranty scenarios. This is accomplished by extending the idea of a failure scenario used in Advanced FMEA [1] to include the diagnosis and repair events as well. Each independent warranty scenario can be characterized in terms of its probability of occurrence and its cost. These two characteristics can be used to calculate an expected cost for each warranty scenario. This becomes a useful metric for two reasons: (1) Expected cost is an accepted

and universally understood measure of risk that allows the prioritization of the different scenarios so that appropriate mitigating action can be taken. (2) It provides the basis by which a warranty cost estimate can be generated.

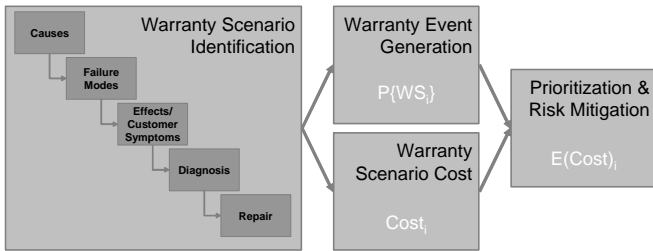


Figure 1: Framework for Predicting Warranty Performance during Product Development.

Warranty Scenario Identification

In developing Advanced FMEA, Kmenta and Ishii [1] adopted the use of failure scenarios to represent failures. A failure scenario is defined as “an undesired cause-and-effect chain of events. Each scenario can happen with some probability and results in negative consequences.” It seems only natural to include the diagnosis and repair events when identifying warranty scenarios.

Figure 2 shows a failure scenario example [1] expanded to include the diagnosis and repair events. For space and clarity considerations, only a partial list of these events is included. In the original work, there were 12 independent failure paths. For each of the 12 independent paths, there would be an additional 8 independent paths (assuming the each diagnosed event could have either a repair or replacement). While it is possible that many of these paths do not make sense, it nonetheless creates a mechanism to model misdiagnosis and irrational events, which do happen in the field.

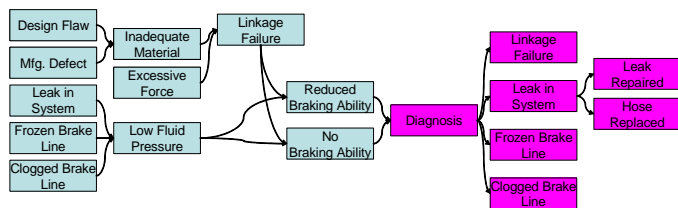


Figure 2: Warranty Scenario for Brake Failure adapted from Kmenta and Ishii [1]

Warranty Event Generation

In principle, once each warranty scenario has been identified assessment becomes a straight-forward proposition of assigning a probability of occurrence for each scenario and a cost. However, the assignment of a probability is less than straight-forward. Challenges include, but are not limited to:

- The scenario event rate is often dependent on the particular market segment the product is in, making representative testing during development difficult.
- The scenario event rate is time dependent.
- The technological and design decisions are different enough from past decisions that using historical data is troublesome.

The following sections will discuss the data sources that are available for use in this modeling as well as some potential modeling approaches that hold some promise to best take advantage of these data sources and address the modeling objective addressed above.

Data Sources

There are four classes of data that are typically available during the development of a complex system. Each will be describe in greater detail below. This discussion will set the stage for another discussion about promising modeling techniques that will be able to exploit the available data streams.

Historical Field Data

In many cases, the systems under design are not new systems. Therefore, historical data in the form of service records are available. The value of these data is that they are representative of actual customer and field behavior. In addition, there is no disputing that the costs associated with these events are representative of the warranty performance of the product and the delivery efficiency of the service model. The problem lies in the fact that field data is traditional considered “dirty” data. Service personal are typically measured and rewarded on the amount of time it takes them to resolve a customer problem. If the problem is incorrectly resolved, ineffectively resolved (from the standpoint of cost), or not logged properly does not affect their reward system. Therefore, it is not uncommon to be able to tell little about neither the customer symptom, nor the resolution path from these service records. To put this issue in context, from the first author’s personal experience manually reviewing approximately 2500 service records, a little less than half, or 1200 service records were “useable”. Of these 1200, many were such broad categories, that one would consider the event un-actionable from the standpoint of design improvements.

Even if the issue of data integrity were resolved, there is still the issue of a time-lag. In the first author’s experience, by the time stable field data was available, the second generation product was already under development. This also limits the utility of the data. That being said, it is a valuable data source that must be taken advantage of in the appropriate context.

Product Development Testing Data

There are a whole host of tests that are conducted during the product development process. These include, but are not limited to feasibility testing, tests aimed at defect discovery, reliability growth testing, individual subsystem testing, component testing and system integration testing. These data represent the cleanest data as they are under the direct control of the product development enterprise. However, the

challenge with these data are that they may not be (and usually are not) representative of the conditions under which the product is used. In addition, the time scales for testing are compressed relative to actual product usage not to mention the fact that the system configurations that are being tested are continually changing as design improvements are continually being introduced.

Failure Assessment Tool

There are tools such as FMEA, fault tree analysis and physics of failure models, that all provide valuable insight to identify the significant risks. Some of these techniques have been leveraged above in order to identify warranty scenarios. However, there is also data that is generated to give some information about the likelihood of occurrence of particular failures. While these data are valuable, they tend to be less quantitative in nature and need special treatment.

Engineering Judgment

The collective experience of a design and management team is vast. As human beings, we have a great capacity for noting patterns and processing vast amounts of complex and disparate data to arrive at valuable conclusions. Given the complexity of the systems under development and the complexity of predicting warranty performance, it is imperative that engineering judgment be appropriately included in any modeling activity.

Event Rate Prediction Model

Bayesian Methods

Yadav et. al. [2] provide an excellent conceptual and mathematical framework for the integration of the data sources described above. The input-output model that they proposed has been adapted in Figure 3.

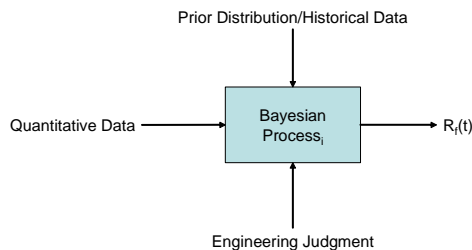


Figure 3: Input-Output Bayesian Model [2]

The following issues need to be addressed in order to make their process more useful for monitoring warranty performance. The output of the current problem formulation is the reliability performance at stage i , where i represents a reliability review milestone. As progressively more information is available, this estimate is updated. While this is a useful piece of information, the premise of this work is that the reliability performance of a product is an intrinsic property of a design given a particular usage, a particular production capability, and a particular service model. The output of interest is the likely reliability performance at product release,

$R_i(t)$. Thus, at each stage, i , the product development team will have the capability to see not only what the current performance levels are, but what they are likely to achieve. This could lead to different decisions.

It was noted earlier that a reliability event does not necessarily translate into a warranty event. The implication is that there needs to be some sort of thresholding that is a function of user market segment. This allows the same fundamental model to be used not only in different market segments, but opens up the possibility to model the cost of quality as well. The more difficult case to handle is the warranty event that is a perceived failure, rather than an actual failure. The typical source of this type of failure is a product that is sold into the wrong market space. While this may be much harder to define beforehand, in principle it can be modeled using these same techniques.

In addition to these changes, the type of repair action also needs to be factored into the event rate model. If the item is repairable, there are 5 repair actions that may be taken [10]:

- 1) Repaired good as new - the repaired item is assumed to be like that of a new item.
- 2) Minimal repair - the failed item is repaired to the same failure rate just before the product failure
- 3) Repaired items are different from new (I) - an items failed components are replaced in addition to deteriorated components. The item is assumed to be the same after each repair.
- 4) Repaired items are different from new (II) – same as (I), but the failure distribution of a repaired time is a function of the number of times the item has been repaired.
- 5) Imperfect repair - the failure rate of the repaired item is uncertain.

Data Mining

Data mining is an area that holds much promise to aid in the analysis of warranty data given the complexity of the interactions between the user, the environment, and the product. The objective of data analysis is “to model the underlying structures which give rise to consistent and replicable patterns” [11]. As Hand [11] points out, data mining is geared towards finding unsuspected relationships which are of interest or value. Hand [11] identified some issues that are characteristics of data mining problems. These are summarized below with their relevance to warranty data:

Large Data Sets: Given the proliferation of memory devices and the miniaturization of computing power, our ability to collect data during product development, during product manufacture and in the field is staggering.

Contaminated Data Sets: This is a problem inherent to warranty data collection and has been discussed above.

Changing population structures and selection bias: Warranty data is continually streaming in. As time progresses there are a variety of factors that lead to changing population. First is that high usage customers are likely to stress products differently than low usage customers. Also, as a product becomes more mature, the type of user buying the product is likely to change. For

example, the more conservative user may wait until the product has been out in the market for a while.

Non Numeric Data: This has been discussed in the previous section.

It is clear that the warranty data and data available for reliability prediction fit the description of the type of data that is commonly analyzed in data mining problems. Letting automated algorithms and processes aid in the discovery of useful patterns seems like a prudent course of action and should be integrated into a process for modeling and predicting warranty performance.

Cost Models

To model costs, one has to consider many factors. The primary factors that will contribute to costs are the length of time and the materials necessary to resolve the event. The total time involved in the resolution of an event consists of the processing time of the warranty claim, the investigation time, the diagnosis and troubleshooting time, the repair/replace time, the testing time and the time to return item to the buyer [10]. Some of these can be predicted precisely while others can be highly variable; some of these will be directly impacted by the product design and other will not. The modeling of subsequent failures will depend on the means of resolution.

An item resolved under warranty can incur the following costs to the manufacturer: administration costs, transportation costs, repair/replacement costs, travel time of the technician, handling costs, and spare parts inventory costs.

The key to modeling the costs is conditioning the cost elements on the events (for example, the probability of incorrect diagnosis, and hence the wrong service action might be higher for a particular type of event). Other considerations include the service model employed and the geographical region the failure occurred in.

RESEARCH AGENDA

The immediate research agenda is to develop the mathematical framework to integrate Bayesian methods and data mining techniques to develop the event generation engine. This will build on the work developed by Yadav et. al. [2]. There will undoubtedly be many challenges, so the initial effort will focus on demonstrating the feasibility of the approach. Ideally, we could develop a relationship with an industrial partner to use actual data to uncover additional issues that need to be solved, yet it leads to a more robust event generation solution.

The following step will need to research the best way to represent consumer and environmental effects to convert reliability events into warranty events. In addition to determining thresholds, a promising approach is to draw analogies to stress-strength statistical models.

Whether or not the mathematical framework and the usage models are developed with an industrial partner, by the time cost models are developed, it will be essential to have forged a relationship with an industrial partner. The complexity of the cost models is typically driven by the

complexity of the organization and it will be important to capture those issues.

The next phase of the research needs to focus on validation. Two approaches to validation are a retrospective case study and a predictive case study. For the retrospective case study, a past development project with a complete set of product development data and stable field data will be examined in order to test the models and develop insights into their strengths and weaknesses. Following this activity, the true test of the methodology will be to apply it to a product under development. The key will be to structure a monitoring process to determine if the methodology aided product developers in the decision making process. If the team feels that they gained insights that they would not have gained otherwise, then that will also be deemed a success for the process.

Future research opportunities include the use of other statistical modeling methods such as neural networks and genetic algorithms. Also, the extension of the cost model to include the cost of quality can expand the utility of this framework to impact more than just warranty performance; it could affect overall customer satisfaction.

CONCLUSIONS

The distinction between reliability modeling and warranty modeling has been described. In warranty modeling it is necessary to understand that reliability events only become warranty events if the consumer initiates them. A framework was described that extends scenario-based FMEA to identify warranty events; that seeks to utilize Bayesian methods and data mining techniques to better accommodate the requirements for predicting warranty performance; and that defines the requirements for cost models. A research agenda to develop this framework was also described. This modeling approach has great potential. If successful, there are opportunities to extend this framework to include customer satisfaction issues, making it an even more powerful tool.

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