NECIP DOGANAKSOY
WILLIAM Q. MEEKER
GERALD J. HAHN

ACHIEVING PRODUCT RELIABILITY

A Key to Business Success

ASA
CRC Press
Taylor & Francis Group
A CHAPMAN & HALL BOOK

Achieving Product Reliability

ASA-CRC Series on

STATISTICAL REASONING IN SCIENCE AND SOCIETY

PUBLISHED TITLES

Errors, Blunders, and Lies: How to Tell the Difference
David S. Salsburg

Visualizing Baseball
Jim Albert

Data Visualization: Charts, Maps and Interactive Graphics
Robert Grant

Improving Your NCAA® Bracket with Statistics
Tom Adams

Statistics and Health Care Fraud: How to Save Billions
Tahir Ekin

Measuring Crime: Behind the Statistics
Sharon Lohr

Measuring Society
Chaitra H. Nagaraja

Monitoring the Health of Populations by Tracking Disease Outbreaks
Steven E. Fricker and Ronald D. Fricker, Jr.

Debunking Seven Terrorism Myths Using Statistics
Andre Python

Achieving Product Reliability: A Key to Business Success
Necip Doganaksoy, William Q. Meeker, and Gerald J. Hahn

For more information about this series, please visit: https://www.crcpress.com/go/asacrc

Achieving Product Reliability

A Key to Business Success

by

Necip Doganaksoy, William Q. Meeker, and
Gerald J. Hahn

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
A CHAPMAN & HALL BOOK

First Edition 2021
by CRC Press
6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742

and by CRC Press
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

ISBN: 9781032019963 (hbk)
ISBN: 9781138054004 (pbk)
ISBN: 9781003181361 (ebk)

Typeset in Minion
by Deanta Global Publishing Services, Chennai, India

Contents

Preface

THE CHALLENGE

There are many definitions of reliability. Informally, reliability may be defined as "quality over time." Reliability is typically the aspect of quality that impacts customers the most, and there is general agreement that an unreliable product is not a high-quality product. Rapid advances in technology, development of highly sophisticated products, intense global competition, and greater customer expectations have continually placed increasing pressures on manufacturers to design and build increasingly higher reliability products.

Reliability evaluations present a challenge to both manufacturers and consumers because of the elapsed time between when the product is designed and built, and when the needed reliability information is forthcoming. A manufacturer might, for example, need to design and build a product that is demonstrated to operate successfully for ten years but has only three years to do so.

Ensuring high reliability in the design of a modern product is, first and foremost, an engineering challenge. But statistics and statisticians can—and need to—play a key role in measuring and helping to improve reliability expeditiously throughout the lifecycle of products or systems—ranging from personal electronic gadgets, household appliances, medical scanners, and telecommunications equipment to "big iron" items such as power generation equipment and transportation systems.

The prominence of statistics has been especially impacted by the recent shift, as described in Chapter 1, from a reactive to a more proactive approach to reliability assurance. The specific use of statistics in many reliability applications has changed—and is continuing to change—dramatically due to technological advances. Traditionally, reliability data have come from laboratory testing and the use of the product in the field. Today, many products are outfitted with sensors that can be used continuously to capture information about how and when, and under what environmental and operating conditions, the product is being used—as well as its performance. These developments present opportunities and challenges for statistics to predict, and potentially help improve, product performance. Meeting these challenges requires careful planning to ensure that the most meaningful information for analysis is obtained and calls for quantitative methods for predicting and assessing reliability and for providing early information about causes of failure. However, most members of the general public, and even some reliability engineers, fail to recognize the critical role of statistics in reliability assurance. One reason for this is that, as we shall see, statistical applications in reliability often involve specialized concepts and tools different from those taught in most introductory statistics courses. A few specialized courses on reliability planning and data analysis are offered at the upper-undergraduate and graduate college levels, but the vast majority of statistics majors—to say nothing of the general public or even reliability engineers—graduate without taking such a course. This book aims to address this gap.

TARGET AUDIENCE

We have written this book for quantitatively literate readers, predominantly non-statisticians, who wish to learn about how statistics is used in reliability applications. Our comments should be of particular interest to:

- Intellectually curious readers who are interested in the topic for their self-education and enrichment.
- Students in engineering, and other STEM disciplines, and, especially, likely future reliability engineers and statisticians who plan to work in industry.
- Managers and professionals who would like to gain an appreciation of how their reliability initiatives can benefit from the use of statistical methods. Our comments should implant ideas and provide guidance in getting started in employing statistics in assuring high product reliability and provide incentives and a pathway to more advanced study.
- Academicians who want to add more practical applications to courses they teach in engineering design or statistics.

TOPICS AND EMPHASIS

Our comments are based on our many years as company-wide statistical resources for a global conglomerate, consultants to business and government, and researchers of statistical methods for reliability applications. Our collective experiences have involved us in a rich diversity of reliability applications dealing with the design and manufacture of a wide variety of products (e.g., aircraft engines, household appliances, locomotives, plastics, turbines, and semiconductors). Our goal is not to teach the nitty-gritty details or the underlying theory of reliability analyses. Instead, we use real-life examples and case studies to illustrate various applications of statistics.* In so doing we rely heavily on graphical tools to provide a general appreciation of the subject.

This book is organized as follows:

- Chapter 1 sets the stage for the rest of the book by providing an overview of the important role of statistics in reliability assurance.

* The csv data files for the book examples, along with brief instructions on using the JMP software to do the analyses, can be downloaded by searching for the book at www.routledge.com.

- Chapters 2 through 6 describe and illustrate applications of statistics for reliability assurance through the product life cycle, from early stages of product design (Chapter 2), development (Chapter 3), validation (Chapter 4), manufacturing (Chapter 5) to field performance (Chapter 6).
- Chapter 7 describes recent developments that are shaping the evolution of the use of statistics in reliability analysis.
- Chapter 8 provides a review of some statistical concepts that are important for reliability applications but are typically not taught in introductory statistics courses.

TECHNICAL LEVEL OF THE BOOK AND ASSUMED BACKGROUND

Our discussion and illustrations throughout this book are of an introductory and conceptual nature. The aim is to reach readers with a wide range of backgrounds—only a one-semester (perhaps dated) introductory course in statistics is assumed. Readers may refer to Chapter 8 for an overview of relevant key statistical concepts beyond those provided in standard introductory courses. We also use sidebar comments to introduce unfamiliar topics that pertain to the discussion at hand. We provide, at the end of each chapter, a list of references that allow readers to explore subjects in greater depth.

OUR GOAL

To reiterate, our major goal is to provide the general public, and especially professionals and those in management positions, useful illustrations of how statistics helps make reliability assurance more powerful. A further goal is to expose students including, but in no way limited to, statistics majors, an overview of the role of statistics in modern product reliability assurance.

While this book alone should fully satisfy the interests of many readers, we hope that it will leave others eager to pursue more advanced study. We would be most pleased if our comments will inspire, at least a few, readers to start the journey to becoming valuable on-the-job contributors in applying statistical tools to successfully address key challenges of modern reliability assurance.

Necip Doganaksoy
William Q. Meeker
Gerald J. Hahn

Acknowledgments

We would like to express our deep appreciation to Roelof L. J. Coetzer, Roger W. Hoerl, Carolyn B. Morgan, and Jacques van der Westhuizen for their detailed and highly useful inputs on our manuscript. We also would like to thank our editor John Kimmel for his patience, encouragement, and helpful comments.

We frequently use or adapt relevant comments from our past publications. These include our yearly articles (since 1999) in *Quality Progress* (American Society for Quality), published as part of the, currently entitled, "Statistics Spotlight" Series. The examples in Sections 2.5, 3.3, 5.5, 6.3, 6.4, and 7.2 are adapted, with permission, from Hahn and Doganaksoy (2008).* The example in Sidebar 2.4 is adapted, with permission, from Example 5.3 in Meeker, Escobar, and Pascual (2021).†

Finally, we would like to thank and acknowledge our wives, Reyhan Doganaksoy, Karen Meeker, and Bea Hahn for their understanding and support throughout this project.

* Hahn, G. J., and N. Doganaksoy (2008). *The Role of Statistics in Business and Industry*, Wiley.

† Meeker, W.Q., L.A. Escobar, and F.G. Pascual (2021). *Statistical Methods for Reliability Data*, Second Edition, Wiley.

Authors

Dr. Necip Doganaksoy is an associate professor at the School of Business of Siena College, following a 26-year career in industry, mostly at General Electric (GE).

Dr. William Q. Meeker is a professor of statistics and distinguished professor of liberal arts and sciences at Iowa State University and a frequent consultant to industry.

Dr. Gerald J. Hahn is a retired manager of statistics at GE Global Research after a 46-year career at GE.

All three authors are Fellows of the American Society for Quality and the American Statistical Association, elected members of the International Statistical Institute, authors of three or more books, and recipients of numerous prestigious professional awards.

CHAPTER 1

Reliability and the Role of Statistics

An Introduction

RELIABILITY IS A KEY concern for all products. In this chapter, we describe the critical role of statistics in reliability assurance and discuss the unique challenges associated with defining, measuring, and improving reliability. We set the stage for the remainder of the book by discussing the role of statistics in reliability assurance through the product cycle from early stages of design to manufacturing and field use.

1.1 RELIABILITY: AS THE CUSTOMERS SEE IT

Are you buying a new car or smartphone or dishwasher? What are the top three things that you wish from your purchase? We bet your list includes long-term, trouble-free operation (i.e., high reliability). The buyer of a new car knows its price, takes it on a test drive, judges its appearance by looking at it, and evaluates its technical features by reviewing published specs. Assessing its reliability, however, is not that easy. You want to know, for example, whether—if the car is properly cared for—it will provide trouble-free service for the next, say, 12 years or if it is going to lead to mounting problems after just a few years. Its true reliability will be known to you only after you have used it for some (hopefully, a very long) period of time. Thus, new customers need to depend on such things as a seller company's reputation, online reviews, and friends' experiences to assess a product's reliability. In addition, product warranty terms, while largely a tool for marketing, do provide indicators of the confidence that producers have in the reliability of their products.

We do not hear much about reliability when things go right—which, fortunately, is much of the time. It is, after all, not news that your plane landed safely. Unfortunately, the unexpected sometimes happens—especially in dealing with complex systems. Reliability problems can lead to everything from minor inconveniences (e.g., no toast for breakfast or a delay in getting to work) to potential human disasters (e.g., severe injury, or even death, due to a pacemaker or aircraft engine failure). We are all keenly aware of catastrophes that can result from poor reliability. Sidebar 1.1 briefly describes a small collection of well-publicized cases involving poor reliability of manufactured products or systems.

SIDEBAR 1.1 SOME INFAMOUS RELIABILITY PROBLEMS*

- In September 2016, Samsung recalled 2.5 million Galaxy Note 7 smartphones after reports of large numbers of phones catching fire due to faulty batteries. Studies showed that the problems were caused by a combination of inadequate design and manufacturing flaws.

* References to learn more about these cases are provided at the end of the chapter.

- The National Highway Traffic Safety Administration (NHTSA) in 2015 recalled 28 million vehicles equipped with Takata airbags due to inflators rupturing during deployment. Data analysis showed that older airbags and those in regions with high temperatures and humidity, such as the Gulf Coast, were up to ten times more likely to rupture. It was determined that moisture could penetrate the inflator canister and make the propellant more explosive over time.
- In 2007, DaimlerChrysler had to recall over 270,000 minivans in regions in the U.S. where roads are salted heavily during the winter to avert icing. Salting tends to corrode airbag sensors, thus preventing the airbag from deploying when needed. The affected sensor components were replaced.
- Rollovers in the late 1990s of Ford Explorer sport utility vehicles equipped with Bridgestone/Firestone tires, resulting in the loss of numerous lives. After a lengthy investigation, it was determined that a design change introduced by the tire manufacturer played a key role in leading to the rollovers.

Many other reliability failures do not make the news, and do not have disastrous consequences, but still cause customers appreciable inconvenience and/or cost companies large amounts of money in warranty and possibly product recall costs, as well as much goodwill, negatively affecting future sales. The penchant for reliability sends a clear message to manufacturers that wish to delight customers, earn their repeat business, have them recommend the product to friends, and avoid lawsuits. A key lesson learned is the importance of gaining an understanding during product design of the environments in which the product might be required to operate and how this might affect its performance and reliability. However, this is usually easier said than done. In applications, both reliability measurement and reliability assurance pose some unique challenges.

A careful study of field reliability issues, such as those described in Sidebar 1.1, usually suggests the right data and analyses at the right time, coupled with prompt action, could have avoided—or at least appreciably mitigated—the severity of the problem. Much of this book is devoted to describing how statistical tools are used to help ensure high product reliability, based upon the collection and analysis of the relevant data. In practice, the hard part of such evaluations is not the statistical analysis, but getting the "right data" in the first place. Thus, a key goal in statistical reliability assurance is to help ensure that the right data are being collected and appropriately kept throughout the process. Even though opportunities for acquiring large quantities of data on units in the field have advanced tremendously in recent years with the evolution of automated measurement systems, there are still challenges. Practitioners expend much effort, often with a limited payoff, in trying to understand and to compensate for poor data. Sidebar 1.2 provides a striking illustration of the undesired consequences of insufficient data and not paying enough attention to the data that were available.

SIDEBAR 1.2 THE CHALLENGER SPACE SHUTTLE FAILURE

The Challenger space shuttle was scheduled for launch on the morning of January 28, 1986. According to the Rogers Commission (1986) that subsequently investigated the launch, on the evening of 27 January, the risk posed to next morning's planned launch by the predicted launch temperature of 30°F was discussed during a three-hour teleconference between engineers and managers from NASA and NASA's contractor, Morton Thiokol. Low temperature was believed by some to increase the risk of failure of the O-rings that were used in critical joints of the solid rocket motor during launch. Most of the 24 previous launches had been at temperatures between 65°F and 77°F, with the lowest at 54°F.

Based upon the analysis of the data presented to them on O-ring failures during past launches, NASA management concluded that the probability of launch failure was in the order of one in a hundred thousand (engineering estimates were one in a hundred). Based on this evaluation and despite a strong recommendation not to launch from some of its engineers, Morton Thiokol acquiesced and the launch proceeded the next morning.

A subsequent review determined that the pre-launch analysis of the available O-ring data, as presented to management, was inadequate and erroneous. There was only a handwritten list of the dates of O-ring failures, the number of such failures, and the temperature. No plots of the data were presented. Most importantly, the "analysis" completely ignored information from the previous launches for which there were *no* O-ring failures. In particular, analyses omitting this information provided no clear evidence of a relationship between temperature and O-ring failure. However, when the data on the launches without any O-ring failures are correctly included in the analysis, a strong association between temperature and O-ring failure probability is evident. This is illustrated by Figures 1.1a and 1.1b, adapted from plots in the Rogers Commission (1986) report. Figure 1.1a is a plot of the number of failures per flight versus launch temperature excluding the flights with no failures. This limited data plot shows no clear evidence of a relationship between temperature and O-ring failure. Figure 1.1b shows all the data, including the flights with no failures. This plot suggests a strong association between temperature and the number of O-ring failures, with low temperatures being particularly risky.

There were two O-rings at each of six field joints in the space shuttle's solid rocket motors. If only one of these

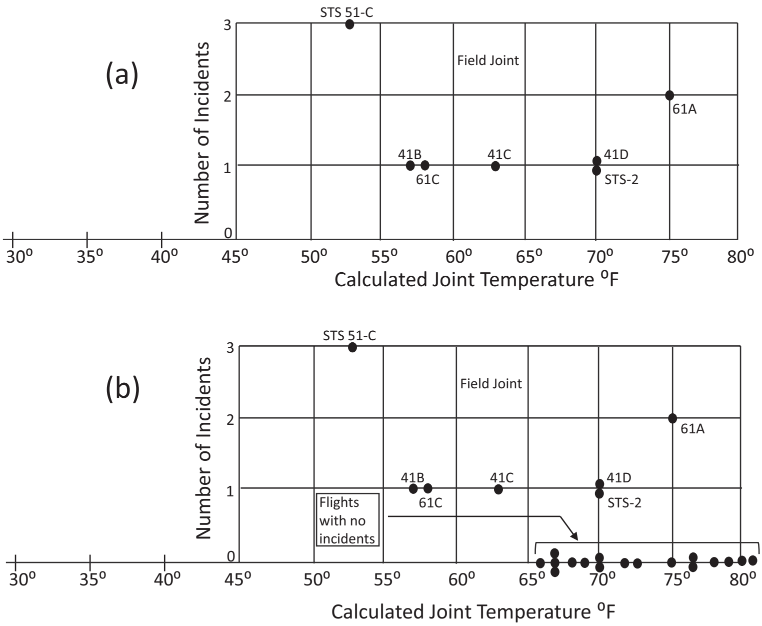

FIGURE 1.1 Plots of the number of O-ring failures per flight versus launch temperature, (a) excluding and (b) including flights with no failures. The labels on the points indicate flight numbers. These figures were adapted from the Rogers Commission (1986) report. We extended the temperature axes to include the forecast temperature of 30°F for the planned launch.

O-rings failed at any location, it would not be a problem. If both failed at one location, it would be catastrophic. In the January 28, 1986 Challenger launch, both O-rings failed in one of the field joints. A subsequent careful statistical analysis of all the available data (Dalal, Fowlkes, and Hoadley, 1989) estimated the risk of failure for a 31°F launch to have been at least one in eight.

The Challenger shuttle disaster was, at least in part, attributable to obtaining insufficient data and not paying enough attention to the data that were available. It also illustrated the usefulness of appropriate plots of the data. Finally, it highlights the importance of the skills that engineers and statisticians must possess in order to communicate complex technical matters to upper-level management.

In this chapter, we

- Define reliability and the challenges associated with reliability measurement and assurance.
- Describe the recent shift from a reactive to a more proactive mindset in reliability assurance.
- Discuss the evolving role of statistics in helping improve reliability throughout the product life cycle.

1.2 WHAT IS RELIABILITY?

Reliability has informally been referred to as both "failure avoidance" and "quality over time." A field reliability problem is one that results in the product failing to perform its intended function, as experienced by the customer, over time. For example,

- You bought a new car and on your first drive, it started to drizzle. Much to your chagrin, the windshield wiper does not work. The inability of a product to function upon delivery (so-called dead on arrival) is especially unpleasant.
- You are unable to start your car. Further investigation shows that the timing belt is broken.
- The battery in your new cell phone typically provides the required power for ten hours between charges. As the battery ages, this time gradually decreases. You may consider the battery failed when it is unable to provide power for more than, say, three hours.

The first two examples illustrate so-called "hard failures." Such failures are usually sudden, and generally require the failed part to be repaired or replaced before the product can be restored to function properly. In contrast, the third example deals with a "soft failure." Such failures are a consequence of degradation and may or may not be evident to the customer over time. Soft failures will also eventually lead to repair or replacement.

Product reliability is defined more formally as the probability that the product (or, equivalently, a fraction or percentage of a product population) will satisfactorily perform its intended function under operational conditions for a specified period of time (such as warranty or design life). For example, if 0.01 (or 1%) of the units of a product population fail within the first five years of service, the product's five-year reliability is 0.99 (or 99%). Time might be expressed in terms of calendar time (cellphones), miles (moving parts in automobile engines), operating cycles (garage door springs), number of startups (gas turbines) or, whatever is most relevant for the product.

Figure 1.2 shows a histogram of some typical lifetime data involving 100 randomly selected electronic devices from a product population of interest for which all devices were run and observed to failure.

Figure 1.3 provides a smoothing of the preceding histogram in the form of a probability distribution of product lifetimes that

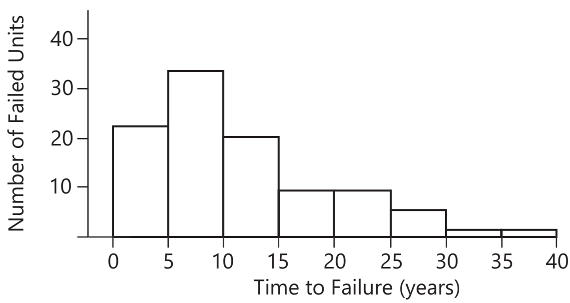

FIGURE 1.2 Histogram of lifetimes of 100 electronic devices.

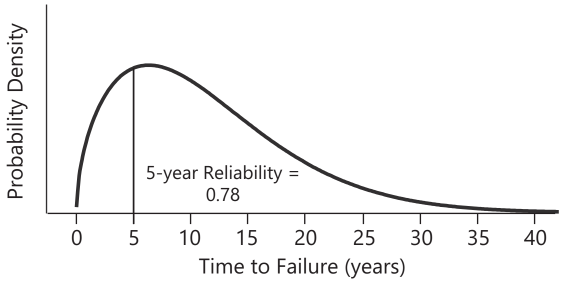

FIGURE 1.3 Lifetime distribution for electronic devices.

provides an approximate summarization of the data in Figure 1.2. Note that the probability of failure at five years is determined to be 0.22 because 0.22 of the area under the probability distribution curve is to the left of five years. Equivalently, the five-year reliability is 1 − 0.22 = 0.78.

An important goal in reliability evaluations is to estimate the product lifetime distribution at different times throughout the product life cycle, from the early stages of design through the transition to manufacturing to use in the field. This often presents a challenge because there is an elapsed time between when the product is built and when the reliability information is forthcoming. Suppose based on market research, customer feedback, and competitive assessment, a dishwasher manufacturer tasks its design team to develop a new dishwasher with ten-year reliability of 0.95. In order to launch the new product in the marketplace, the manufacturer must have high confidence that the new product will fulfill its reliability goals. However, the development team has only three years to design the new product and demonstrate its ten-year reliability before mass production. This situation is typical of new product development ventures.

In order to address the challenge of assuring (and demonstrating) high reliability, modern programs for new product introduction include the collection and analysis of reliability data from laboratory tests of materials, devices, and components; tests on early prototype units; careful monitoring of early production units in the field; analysis of warranty data; and systematic longer term tracking of product in the field. One of the main challenges addressed by statistical reliability analyses is to establish, approximately, such lifetime distributions starting at the early phases of product design.

Increasingly, many products depend on software in addition to hardware. In addition to such obvious commonplace products, such as personal computers and smartphones, many consumer products rely on software residing in microprocessors that are being used to control system operation. These products include automobiles, many home appliances, and various other systems involving a combination of mechanical and electronic components. For such products, controlling product failures due to software bugs involves the areas of software quality and reliability (see Sidebar 1.3).

SIDEBAR 1.3 SOFTWARE RELIABILITY

Software problems vary in their criticality. Most of us have learned to live with the inconvenience of rebooting our computer to get around a software problem. Safety-critical software failures—such as in medical, air traffic control, telecommunication, or military systems—can, on the other hand, have serious, and even life-threatening, consequences and need to be addressed before product release.

Most software, unlike most hardware, generally does not degrade over time; failures are usually due to inherent faults present from the start. Such faults may, however, remain undiscovered until a specific set of inputs is used or a particular system state, such as heavy user load, is encountered. In addition, for at least some software, it may not always be clear when a failure has occurred. Billing errors created by a software problem, for example, might only become known when a customer complains of being overcharged.

Identifying important failure modes and removing them before product release, typically calls for testing software at conditions, often identified by experts, that are expected to maximize the number of errors detected (and corrected) as speedily as possible.

1.3 SHIFT FROM A REACTIVE TO A PROACTIVE MINDSET IN RELIABILITY ASSURANCE

The desire for high reliability is not new. Throughout history, people learned from their successes and mistakes in, for example, building durable wheels, larger domes, stronger ships, and longer bridges. What is different today is the emphasis placed by many companies on assuring the reliability of a product up-front during product design and development.

In the past, reliability assurance was often an afterthought—even in organizations that emphasized quality. This is sometimes referred to as the Design–Build–Test–Fix cycle. This basically meant that manufacturers strived to discover and fix reliability failures through extensive testing after the product has already been designed and early units had been built. Sometimes, the time allotted for such testing did not allow all-important failure modes to be identified and addressed, and the product was released before its reliability had been fully validated. As a result, much effort was spent responding to crises and fixing problems after they had already created some damage to the customer and the reputation of the manufacturer. There was a heavy reliance on end-of-line product testing and fixing problems in the field after they occurred.

If reliability problems arise after a product has been released for production and, especially, if units in the field need to be recalled for retrofit, the cost can be severe and may rapidly dwarf a product's profit margin. Pennies saved per unit in selecting, without adequate scrutiny, a less expensive supplier can, for example, result in many millions of dollars in costs fixing a subsequent reliability problem. Also, because a few early dissatisfied customers can give a product a bad name, it is particularly important for the product to be reliable when first brought to the market. As global competition increased, this Design–Build–Test–Fix approach to product development became unsustainable for commercial products (but interestingly is still used in military system development, as described in the report on Reliability Growth by the National Research Council of the National Academies, 2015).

Forward-looking leaders in business and industry have come to realize that achieving reliability by reactive measures is unacceptably expensive and potentially disastrous to retaining customer confidence. This has become especially relevant with the prominence of consumer-review journals and with dissatisfied customers' ability to rapidly "spread the word" about problems or poor product experiences through social media. Moreover, these experiences are typically on units manufactured soon after product release and at a time that, without appropriate diligence, product reliability problems may not yet have been discovered. Thus, there is now general agreement that reliability needs to be built into the design of products and processes proactively. Problems discovered in design, though often more difficult to identify, are usually less costly and much easier to fix. Problems found after the design has been frozen, and especially after significant quantities of the product have been built, although easy to identify, are often difficult and expensive to fix. As a result, the traditional Design–Build–Test–Fix approach has been replaced—at least in the minds of most reliability practitioners in the commercial product sector—by a proactive "do it right the first time" mindset. This has led to the widespread implementation of Design for Reliability processes even though the details of such processes are company specific. Sidebar 1.4 provides some further comments on the trade-off between reactive and proactive approaches to reliability improvement.

SIDEBAR 1.4 MAKING THE CASE FOR PROACTIVE RELIABILITY IMPROVEMENT

Despite the compelling arguments in favor of a proactive approach, it has traditionally been easier—and often still is—to gain management support for *responding* to a tangible, existing problem than for *avoiding*, vague and possibly poorly defined potential future problems.

One reason for this is that it seems, in our experience, that recognition by management, and often promotions, are typically based on the most recent tangible achievements. Benefits from reactive projects, typically aimed at reducing scrap, rework, and warranty costs, are often readily quantifiable in advance and easily demonstrated shortly after implementation. In contrast, for most proactive projects, there is often a large up-front cost—generally incurred long before any concrete product benefit is achieved.

Reliability performance—or lack thereof—takes time to validate. The major gains of reliability improvement come from failure-cost avoidance—averted field repairs, recalls, and product redesign—and from greater customer satisfaction, often resulting in increased business in the *long run*. The savings from proactive work are, therefore, more speculative, accrue over time, and, sometimes, are unknown or unknowable—especially for problems that have been avoided. The costs of reliability assurance during design are, after all, immediate—but the rewards come much later and typically come in the form of "non-events" (i.e., failures that would have otherwise occurred that did not happen) and, therefore the resulting savings remain unrecognized. Thus, the negative consequences of a manager's failure to conscientiously uncover and address potential reliability issues might only assert themselves under his or her successor's watch.

Businesses are becoming increasingly aware of the need to focus on proactive reliability assurance. Ensuring up-front reliability makes business sense. It is generally much less expensive in the long run to build reliability into products during design than to fix a flawed design—to say nothing of the impact on customer relations. Thus, long-term gains as well as costs and short-term gains, need to be considered in arriving at a reasonable trade-off between a reactive and a proactive approach.

1.4 RELIABILITY ASSURANCE OVER THE ENTIRE PRODUCT LIFECYCLE

Setting Reliability Goals

Reliability assurance needs to start with clearly defined goals. They begin—like those for other product characteristics—with the identification of customer needs. These are often stated in general terms—such as that the product always starts up smoothly; operates well and consistently; requires no or very few unscheduled shutdowns or repairs (if applicable); and "lasts" for a long time. The result may be a broad range of interpretations of a product's reliability or lack thereof. A customer's assessment of unsatisfactory dishwasher reliability might, for example, range from a perception that the product does an increasingly less effective job in washing dishes over time to repeated failure of a critical component. To provide actionable goals for the design team, the reliability goals need to be translated into measurable, quantifiable requirements along with a precise description of the stresses and environmental conditions under which the product is expected to be used. These goals are also impacted by a producer's desire to make product warranty protections as attractive as possible, without incurring high warranty costs. Technological lifetime is another important concept for setting meaningful reliability goals (see Sidebar 1.5).

SIDEBAR 1.5 TECHNOLOGICAL LIFETIME

Technological lifetime is related to reliability. It is generally thought of in terms of time to replacement; reliability deals with time to failure. Consumers often replace their electronic appliances (e.g., smartphones) that are in working condition in order to gain access to features offered in a new generation of products. For this type of product, questions arise about the value of adding significant cost to design a product for a very long life (say ten years) when the vast majority of the product units will be voluntarily retired after three or four years.

The approach to setting reliability goals is somewhat different for nonrepairable and repairable products.

Nonrepairable Products

Nonrepairable products are ones whose life comes to an end when the unit fails. Rather than being repaired, a failed unit may be replaced, presumably by a new one. Nonrepairable products might be stand-alones, such as a light bulb, or they may be components of a larger system, such as various parts of a computer (e.g., memory, hard drive, power supply, video card).

For a nonrepairable product or component, we may, for example, require no more than 0.005 failures (i.e., 0.995 reliability) during the first year, and no more than 0.03 failures during the first five years of life.

Traditionally, and especially for electronic parts, the reliability of nonrepairable products has been characterized by mean time to failure (MTTF). For high-reliability products, MTTF is generally a less useful metric than, say, the proportion of a product failing by a specified time. When the statistical distribution for lifetimes is highly skewed, (e.g., has a long right tail, as in many lifetime data applications and as illustrated by the histogram of Figure 1.2), a large value of MTTF does not necessarily result in acceptable reliability. For example, a product population having individual lifetimes described by an exponential distribution (described in Chapter 8) with an MTTF of 25 years is still expected to have 0.18 of the population fail in the first five years.

Repairable Products

Most systems and some parts are repaired when a failure occurs. For systems, this may involve replacing a failed component or subsystem. Repairable products typically generate a sequence of failure and repair times on the same unit.

For repairable systems, one is frequently concerned with the proportion of time that the system is available for operation, known as its availability. Thus,

$$\text{Availability} = \frac{\text{uptime}}{\text{uptime} + \text{downtime}}$$

where uptime and downtime are the amounts of time that the system is operational and non-operational, respectively, over a specified time period of interest. We might, for example, require a repairable system, like an office printer, to have 0.99 (or 99%) availability over a ten-year period. High availability, in addition to requiring high reliability, also requires adequate maintainability, where maintainability deals with the time required to repair the system. Improving reliability improves availability by increasing uptime; improving maintainability improves availability by decreasing downtime.

Similar to MTTF for nonrepairable products, the reliability of repairable products and systems has frequently been characterized by the mean time between failures (MTBF). MTBF increases as reliability improves.

Evolution of the Role of Statistics in Reliability Assurance

The preceding discussion already suggested the key role of statistics and statisticians in measuring reliability. Ensuring high reliability in the design of manufactured products, just as in developing the design itself, is, first and foremost, an engineering challenge. Design engineers strive to understand different ways in which the product may fail so that the causes of such failures can be addressed through design improvements and material selection. Statistics and statisticians also play a key role.

The evolution of the role of statistics in reliability assurance closely parallels the shift from a reactive to a proactive mindset. Initially, the role of statistics in reliability was limited principally to reactive "fire-fighting"—that is, to quantifying problems and helping minimize the damage. Typical questions addressed by statistics were "is a recall of product in the field (or for sale on the shelf) needed?" and if so, "what segment of the product population should be recalled?" Some manufacturing lots may, for example, be more susceptible to failure than others. Or failures might be more likely to occur in extreme environments, such as locations with high temperature and/or high humidity, or under certain usage modes. Such assessments are often required for quantifying the magnitude of a problem and evaluating alternative ways of selectively addressing it in the short run.

As recognition grew of the importance of *avoiding* premature field failures, statistics was used to help plan reliability demonstration programs. This involved responding to such questions as "how large a sample is needed and for how long must one test to ensure with 90% confidence that 0.99 of the product will operate successfully for ten years?" This question, however, was often asked at a time when design and development were essentially complete and it was difficult and expensive to adequately address the underlying problem(s) if the test failed to provide the desired demonstration. Reliability engineering has evolved as a new discipline that combines engineering knowledge and statistics with managerial processes to provide program oversight to reliability assurance efforts (see Sidebar 1.6).

SIDEBAR 1.6 RELIABILITY ENGINEERING

Reliability engineering involves the application of engineering principles during design, development, validation, manufacture, and field use of a product to achieve reliability assurance and improvement. In many organizations, reliability engineers are tasked with defining and leading a disciplined process of activities related to reliability measurement and assurance throughout the product life cycle. Reliability engineering has in fact become a recognized profession—even though currently only a small number of universities offer degrees in the subject. Instead, most reliability engineers have backgrounds in mechanical engineering, electrical engineering, industrial engineering, or physics. Reliability engineers also need to be skilled in areas such as reliability project management, design reviews, risk analysis and mitigation, physics of failure, failure root cause analysis, and reliability testing and assessment. They also need to be knowledgeable in statistical tools for the planning and analysis of data from reliability studies.

Focus on up-front reliability assurance has led to using statistics proactively to help improve reliability during product design and development. This requires quantitative methods for predicting and assessing reliability and for providing early information on causes of failure, as well as—and perhaps most importantly—for careful planning to ensure that the most meaningful information for analysis is obtained.

Statistical tools play a key role in all phases of the product life cycle, from product design, development, and scale-up to manufacturing to tracking field performance. Table 1.1 provides an overview of some of the key application areas of statistics for reliability assurance in the product life cycle.

The remainder of this book aims principally to elaborate on the preceding.

TABLE 1.1 Statistical Application Areas for Product Reliability Assurance

Design, Development, and Scale-Up (Chapters 2, 3, 4)	Manufacturing (Chapter 5)	Field Tracking (Chapters 6 and 7)

• Reliability evaluation of a conceptual design
• Product reliability development and assessment
  • Use rate acceleration
  • High-stress testing and product aging acceleration
  • Degradation testing
• Reliability validation and demonstration
  • In-house testing
  • Beta site testing
	• Statistical process monitoring
	• Audit testing
	• Burn-in testing
		• Field reliability data tracking
		  • Nonrepairable products
		  • Repairable products
		• Segmented analysis of field reliability data
		• Proactive product servicing
		  • Maintenance scheduling
		  • Parts replacement
		  • Automated monitoring

Chapter 8 of this book provides an overview of relevant key statistical concepts for reliability

Reliability Evaluation of a Conceptual Design (Chapter 2)

Early design choices, such as the selection of components for an electronic circuit, affect ultimate product reliability. It is, therefore, important to identify and confront, as early as possible, issues that may affect the final product or system reliability, despite the fact that it may be difficult to do so while the design is still evolving and the product operating conditions are not well established. The reliability of a product is assessed by viewing it as a system comprised of subsystems of assemblies and components. Reliability engineers use system probability models to study the potential effect of individual components on system reliability.

Product Development and Assessment (Chapter 3)

During product development, a major goal is to achieve the reliability targets set for the components, subsystems, and the system as a whole. Design engineers strive to understand how failures might occur so that their causes can be addressed. Testing is used to obtain, as early as possible, an improved understanding of known failure modes, to discover unsuspected failure modes, and to assess the associated causes and mechanisms.

Statistically planned investigations may be conducted during product design to assess the reliability that can be expected for components, assemblies, subsystems, and eventually the final product or system. Estimating the lifetime distribution or long-term performance of components of high-reliability products within a short, for practical purposes, time span is particularly difficult. This is because modern products are designed to operate without failure for years, decades, or longer. Thus, we might expect (and hope) that few units will fail in a test of practical length at normal use conditions. Three common approaches for addressing this challenge are:

- Use rate (cycling rate) acceleration. This involves running products at rates that typically and appreciably exceed those encountered in field operations. Use rate acceleration is especially appropriate for products, such as household appliances, that are in operational use only a fraction of the time. For example, running a washing machine 24 hours per day for three months might provide exposure similar to that incurred in the field over five years.
- Accelerated life testing. This calls for increasing the aging rate during testing by using a harsher operating environment than that encountered in field operations (e.g., increased temperature or humidity) and/or hastening failures by using higher stress (e.g., increased voltage or pressure) during testing. For example, the chemical composition of an adhesive typically degrades more rapidly at high levels of temperature. Thus, testing is often conducted at high levels of temperature or stress and the results are extrapolated—by fitting a physically

reasonable statistical model—to obtain estimates of lifetime or long-term reliability at lower, normal levels of temperature or stress.

- Degradation testing. This requires knowledge of some measurement(s) of product degradation that is (are) directly related to product lifetime. This approach is especially useful when the testing to date has resulted in very few or no failures. For example, the light output of LED bulbs decreases over time and, thus, failure is usually defined as light output having decreased by, say, 60% of the original. Moreover, measurements of light output reduction observed over time can be used to estimate the expected (future) failure time for a bulb that has not yet failed.

Reliability Validation (Chapter 4)

Much testing during early development is at the component or subsystem level. Even when system testing is conducted, it is likely to be on prototypes rather than normal production. Also, it might be difficult to simulate the field operating environment in the manufacturer's facility. Reliability validation aims to ensure, to the greatest extent possible, that the reliability goals will be met on scaled-up manufactured products under field operating conditions. Reliability validation is usually conducted using either in-house testing at the manufacturer's facility or so-called beta site testing (i.e., early testing of the product by selected customers under normal use conditions). If reliability issues are identified during validation, these need to be addressed immediately.

A key goal is quantifying reliability to determine whether a product is ready for release; that is, does the product meet its specified reliability goal? This often involves a (statistical) reliability demonstration test. A reliability demonstration test aims to show, with a specified high degree of statistical confidence, that a product's reliability meets a specified target value.

Manufacturing (Chapter 5)
We need to ensure that nothing that is done during manufacturing compromises the high level of reliability that, hopefully, was built into the product during design. Therefore, the design of the new manufacturing process must proceed in close collaboration with product design. Product reliability might worsen over time due to factors such as changes in raw materials or parts, wearout of equipment or tools, deterioration of raw materials during storage, operator turnover, inadequate training of new operators, and various cost-cutting initiatives by suppliers or by the manufacturer. Statistical process monitoring, audit life testing, and product burn-in are the most common reliability assurance measures used in manufacturing.

Statistical process monitoring (also known as statistical process control or SPC) provides a formal framework to track key process variables that have been determined to affect reliability. This way unknown process changes can be detected, and hopefully addressed, before they lead to bigger problems.

Audit life testing calls for an ongoing program of reliability testing of random samples of recently manufactured products to assess whether the product continues to meet or exceed its established and previously demonstrated (on prototype product) reliability goals and to provide timely signals of deterioration in reliability.

Product or component burn-in is sometimes used to combat one or more so-called "infant mortality" failure modes that lead to premature field failures. Burn-in involves the manufacturer running *all* product units for an initial period of time, perhaps in an accelerated environment, so as to weed out all, or a high proportion of, such units by having them fail in the manufacturer's hands, rather than in the field. An important part of developing a product burn-in program is the initial determination of how long each unit should be exposed to burn-in, and at what operating conditions, so as to remove the maximum number of premature field failures at a minimum cost (and loss of subsequent product life). In passing, we note that product burn-in, though proactive in the emphasis on avoiding premature field failures is reactive in the sense of accepting the existence of such failure modes rather than eliminating them.

Field Tracking (Chapters 6 and 7)

Even though a product has been successfully built and sold, manufacturers' interest and concern in product performance, in general, and reliability, in particular, continues, with the ultimate objective of assuring complete customer satisfaction and "delight." Also, experience in the field for existing products is used to build ever-better products in the future. Companies, therefore, need to continue to scrutinize their products, collect appropriate data about performance, reliability, and customer satisfaction over time, and carefully evaluate such data.

Recent advances in sensor technologies have enabled companies to acquire large volumes of operational and performance data from the field. In Chapter 7 of this book, we describe emerging opportunities for proactive product servicing owing to the enhanced capabilities in the types and volume of field data that companies are able to gather.

MAJOR TAKEAWAYS

- High reliability, or quality over time, is a key concern for all products.
- Building high reliability into the *design* of products is receiving increasing recognition. This requires a team effort with reliability engineers and statisticians as important members.
- The role of statistics in reliability assurance has evolved from fire-fighting to validation testing to actively contributing to proactive reliability improvement.
- The first step in a product reliability assurance program is to set clear and measurable reliability goals.

- The next phase involves the evaluation of the reliability of the conceptual design. This may require the construction of a probabilistic reliability model and its assessment.
- Empirical reliability estimates are obtained through the analysis of statistically based tests on components, assemblies, subsystems, and eventually the final product or system. Use-rate acceleration, accelerated life tests, and/or degradation testing are used to speed up the process. The resulting tests may also identify reliability problems that require immediate attention and corrective action.
- Validation involves further testing to ensure that product or system reliability goals are likely to be met under conditions that closely resemble normal manufacturing conditions and field operations. This typically involves in-house systems testing and, sometimes, in-field (beta site) testing.
- Audit life testing on samples of manufactured products is used to signal possible deterioration of reliability over time.
- Product burn-in may be needed, for some products, to remove early life failures.

REFERENCES AND ADDITIONAL RESOURCES

- Well-known reliability disasters (Sidebar 1.1):

Samsung Galaxy Note 7 battery failures. Available from: https://www.nytimes.com/2017/01/22/business/samsung-galaxy-note-7-battery-fires-report.html

Takata airbags. Available from: https://www.nhtsa.gov/recall-spotlight/takata-air-bags

Daimler Chrysler minivan airbag sensors. Available from: https://www.autoblog.com/2007/05/11/chrysler-group-recalling-270-000-minivans-to-fix-airbag-sensors/

Ford Explorer/Firestone tire problems.

National Highway Safety Administration (2001). Engineering Analysis Report and Initial Decision Regarding EA00-023: Firestone Wilderness AT Tires, October 2001. Available from:

https://icsw.nhtsa.gov/nhtsa/announce/press/Firestone/firestonesummary.html

- Challenger Space Shuttle O-ring Failure (Sidebar 1.2):

Rogers Commission (1986). *Presidential Commission on the Space Shuttle Challenger Accident Report* (Vols. 1 & 2), Washington, DC. Available from: https://spaceflight.nasa.gov/outreach/SignificantIncidents/assets/rogers_commission_report.pdf

Dalal, S.R., E.B. Fowlkes, and B. Hoadley (1989). "Risk Analysis of the Space Shuttle: Pre-Challenger Prediction of Failure," *Journal of the American Statistical Association*, 84, 945–957.

- Reliability assurance in military systems design and development:

National Research Council (2015). *Reliability Growth: Enhancing Defense System Reliability*, The National Academies Press. Available from: https://www.nap.edu/catalog/18987/reliability-growth-enhancing-defense-system-reliability

Reliability and the Role of Statistics

Well-known reliability disasters (Sidebar 1.1):

Samsung Galaxy Note 7 battery failures . Available from: https://www.nytimes.com/2017/01/22/business/samsung-galaxy-note-7-battery-fires-report.html

Takata airbags . Available from: https://www.nhtsa.gov/recall-spotlight/takata-air-bags

Daimler Chrysler minivan airbag sensors . Available from: https://www.autoblog.com/2007/05/11/chrysler-group-recalling-270-000-minivans-to-fix-airbag-sensors/

Ford Explorer/Firestone tire problems .

National Highway Safety Administration (2001). Engineering Analysis Report and Initial Decision Regarding EA00-023: Firestone Wilderness AT Tires, October 2001. Available from: 25 26 https://icsw.nhtsa.gov/nhtsa/announce/press/Firestone/firestonesummary.html

Challenger Space Shuttle O-ring Failure (Sidebar 1.2):

Rogers Commission (1986). Presidential Commission on the Space Shuttle Challenger Accident Report (Vols. 1 & 2), Washington, DC. Available from: https://spaceflight.nasa.gov/outreach/SignificantIncidents/assets/rogers_commission_report.pdf

Dalal, S.R. , E.B. Fowlkes , and B. Hoadley (1989). Risk Analysis of the Space Shuttle: Pre-Challenger Prediction of Failure, Journal of the American Statistical Association, 84, 945957.

Reliability assurance in military systems design and development:

National Research Council (2015). Reliability Growth: Enhancing Defense System Reliability, The National Academies Press. Available from: https://www.nap.edu/catalog/18987/reliability-growth-enhancing-defense-system-reliability

System Reliability Evaluation of a Conceptual Design

System reliability modeling:

Ebeling, C.E. (2010). An Introduction to Reliability and Maintainability, Second Edition, Waveland Press.

Modarres, M. , M. Kaminskiy , and V. Krivtsov (2017). Reliability Engineering and Risk Analysis: A Practical Guide, Third Edition, CRC Press.

OConnor, P.D.T. , and A. Kleyner (2012). Practical Reliability Engineering, Fifth Edition, Wiley.

Yang, G. (2007). Life Cycle Reliability Engineering, Wiley.

Critical review of reliability growth testing:

Peter, A. , D. Das , and M. Pecht (2015). Critique of MIL-HDBK-217, Appendix D in Reliability Growth: Enhancing Defense System Reliability. Panel on Reliability Growth Methods for Defense Systems, Committee on National Statistics, Division of Behavioral and Social Sciences and Education, The National Academies Press.

McDonnell Douglas DC-10 accident:50

Wikipedia Contributors , United Airlines Flight 232, Wikipedia, The Free Encyclopedia.

Product Reliability Development

Foundational references on statistical analysis and modeling of data from reliability studies:

Meeker, W.Q. , L.A. Escobar , and F.G. Pascual (2021). Statistical Methods for Reliability Data, Second Edition, Wiley.

Nelson, W.B. (2004). Accelerated Testing: Statistical Models, Test Plans, and Data Analysis, Paperback Edition, Wiley.

Tobias, P.A. , and D. Trindade (2011). Applied Reliability, Third Edition, CRC Press.

Statistical DOEs (Section 3.2):

There are numerous texts on DOEs. Box, Hunter, and Hunter (2005) is a popular easy-to-read introduction. Myers, Montgomery, and Anderson-Cook (2016) is at a more advanced level and emphasizes designs for response surface estimation, optimization, and robust product design.

Box, G.E.P. , J.S. Hunter , and W.G. Hunter (2005). Statistics for Experimenters: Design, Innovation, and Discovery, Second Edition, Wiley.

Myers, R.H. , D.C. Montgomery , and C.M. Anderson-Cook (2016). Response Surface Methodology: Process and Product Optimization Using Designed Experiments, Fourth Edition, Wiley.

Robust design in reliability (Section 3.2):8586

Grove, D.M. , and T.P. Davis (1992). Engineering, Quality, and Experimental Design, Longman Scientific and Technical.

Hamada, M. (1995). Using Statistically Designed Experiments to Improve Reliability and to Achieve Robust Reliability, IEEE Transactions on Reliability, 44, 206215.

Phadke, M.S. (1989). Quality Engineering Using Robust Design, Prentice Hall.

Common pitfalls of ALTs (Section 3.3):

Meeker, W.Q. , G. Sarakakis , and A. Gerokostopoulos (2013). More Pitfalls of Accelerated Tests, Journal of Quality Technology, 45, 213222.

Ford Explorer/Firestone tire failures (Sidebar 3.5):

National Highway Safety Administration (2001). Engineering Analysis Report and Initial Decision Regarding EA00-023: Firestone Wilderness AT Tires, October 2001. Available from: https://icsw.nhtsa.gov/nhtsa/announce/press/Firestone/firestonesummary.html

Champkin, J. (2006). A Life in Statistics: Driving out Failure, Significance, June Issue, 7780.

This is an informative interview with Tim Davis, a Ford statistician, who played a lead role in the Ford Explorer/Firestone tire failure investigations.

Simulation for life test planning (Sidebar 3.7):

Meeker, W.Q. , G.J. Hahn , and N. Doganaksoy (2005). Planning Reliability Assessment, Quality Progress, June Issue, 9093.

AT&T round cell battery (Sidebar 3.10):

Biagetti, R.V. (1991). The AT&T Lineage 2000 Round Cell Revisited: Lessons Learned; Significant Design Changes; Actual Field Performance Vs. Expectations, Proceedings of the Thirteenth International Telecommunications Energy Conference-INTELEC 91, 3236.

Cannone, A. , W.P. Cantor , D.O. Feder , and J.P. Stevens , (2004). The Round Cell: Promises vs. Results 30 Years Later, Proceedings of the 26th Annual International Telecommunications Energy Conference-INTELEC 2004, 401410.

Sharpe, J.R. , J.R. Shroff , and F.J. Vaccaro (1970). Post Seals for the New Bell System Battery, The Bell System Technical Journal, 49, 14051417.

Reliability Validation

Statistical analysis of life data with multiple failure modes:

Meeker, W.Q. , L.A. Escobar , and F.G. Pascual (2021). Statistical Methods for Reliability Data, Second Edition, Wiley.

Reliability growth analysis:

Tobias, P.A. , and D. Trindade (2011). Applied Reliability, Third Edition, CRC Press.

GE compressor example:

OBoyle, T.F. (1990). Chilling Tale: GE Refrigerator Woes Illustrate the Hazards in Changing a Product, Wall Street Journal, May 7, 1.

Reliability Assurance in Manufacturing

Jurans Quality Handbook is considered a classic in quality literature and provides a comprehensive introduction to quality management:

Defeo, J.A. (2016). Jurans Quality Handbook: The Complete Guide to Performance Excellence, Seventh Edition, McGraw-Hill.

Montgomery (2020) provides a more technical exposure to commonly used tools and methods in quality assurance:

Montgomery, D.C. (2020). Statistical Quality Control, Eight Edition, Wiley.

Comprehensive FMEA process developed by the Ford Motor Company for reliability-oriented design of new products and manufacturing processes:

Ford Motor Company (2011). Failure Mode and Effects Analysis, Ford Motor Company. Version 4.2. Available from: https://tinyurl.com/Ford-FMEA-HDBK-4p2.

Field Reliability Tracking

Data and analysis for the aircraft engine bleed systems example:

Abernethy, R.B. , J.E. Breneman , C.H. Medlin , and G.L. Reinman (1983). Weibull Analysis Handbook, Air Force Wright Aeronautical Laboratories Technical Report 171 172AFWAL-TR-83-2079. Available from: http://apps.dtic.mil/dtic/tr/fulltext/u2/a143100.pdf.

Takata airbags:

Barnett, A. (2016). Expert Answers, Quality Progress, May Issue, 89.

National Highway Traffic Safety Administration , Takata Air Bag Recall Information. Available from: https://www.nhtsa.gov/recall-spotlight/takata-air-bags.

A useful resource to learn more about the estimation of the mean cumulative function for repairable systems is Nelson (2003):

Nelson, W.B. (2003). Recurrent Events Data Analysis for Product Repairs, Disease Recurrences, and Other Applications, SIAM.

Prediction of a future number of failures:

Meeker, W.Q. , N. Doganaksoy , and G.J. Hahn (2010). Predicting Problems: Forecasting the Number of Future Field Failures, Quality Progress, November Issue, 5255.

Online supplement Available from: http://asq.org/quality-progress/2010/11/statistics-roundtable/predicting-problems.html#online

A Peek into the Future

Hong, Y. , M. Zhang , and W.Q. Meeker (2018). Big Data and Reliability Applications: The Complexity Dimension, Journal of Quality Technology, 50, 135149.

Meeker, W.Q. , and Y. Hong (2014). Reliability Meets Big Data: Opportunities and Challenges, Quality Engineering, 26, 102116.

Statistical Concepts and Tools for Product Lifetime Data Analysis

Foundational references on statistical analysis and modeling of data from reliability studies:

Meeker, W.Q. , L.A. Escobar , and F.G. Pascual (2021). Statistical Methods for Reliability Data, Second Edition, Wiley.

Nelson, W.B. (2003). Applied Life Data Analysis, Paperback Edition, Wiley.

Nelson, W.B. (2004). Accelerated Testing: Statistical Models, Test Plans, and Data Analysis, Paperback Edition, Wiley.

Tobias, P.A. , and D. Trindade (2011). Applied Reliability, Third Edition, CRC Press.

Pitfalls of lifetime data analysis:216

Hahn, G.J. , and W.Q. Meeker (1982a). Pitfalls and Practical Considerations in Product Life Analysis-Part I: Basic Concepts and Dangers of Extrapolation, Journal of Quality Technology, 14(3), 144152.

Hahn, G.J. , and W.Q. Meeker (1982b). Pitfalls and Practical Considerations in Product Life AnalysisPart II: Mixtures of Product Populations and More General Models, Journal of Quality Technology, 14(4), 177185.

Bayesian methods:

Gelman, A. , J.B. Carlin , H.S. Stern , D.B. Dunson , A. Vehtari , and D.B. Rubin (2013). Bayesian Data Analysis, Third Edition, CRC Press.

Li, M. , and W.Q. Meeker (2014). Application of Bayesian Methods in Reliability Data Analyses, Journal of Quality Technology, 46(1), 123.