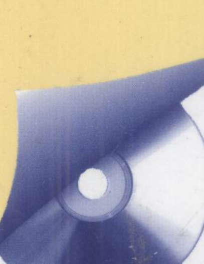
QUALITY and RELIABILITY in ENGINEERING

TIRUPATHI R. CHANDRUPATLA



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Quality and Reliability in Engineering

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QUALITY AND RELIABILITY IN ENGINEERING

Quality and Reliability in Engineering provides an integrated approach to quality specification, quality control and monitoring, and reliability. Examples and exercises stress practical engineering applications. Steps in the development of the theory are implemented in the form of complete, self-contained computer programs. The book serves as a textbook for upper-level undergraduate courses in quality and reliability in mechanical engineering, manufacturing engineering, and industrial engineering programs. It can be used as a supplement to upper-level capstone design courses, short courses for quality training, and as a learning resource for practicing engineers.

Tirupathi R. Chandrupatla has been a professor and Founding Chair of Mechanical Engineering at Rowan University, Glassboro, New Jersey, since 1995. He received his M.S. degree in design and manufacturing from the Indian Institute of Technology (IIT), Bombay, and his Ph.D. from the University of Texas at Austin. He began his career as a design engineer with Hindustan Machine Tools (HMT), Bangalore. His first teaching post was at IIT, Bombay. He has also taught at the University of Kentucky, Lexington, and GMI Engineering and Management Institute (now called Kettering University), Flint, Michigan, before joining Rowan. Chandrupatla is the author of *Introduction to Finite Elements in Engineering, Optimization Concepts and Applications in Engineering,* and *Finite Element Analysis for Engineering and Technology.* The first book has been translated into Spanish, Korean, Greek, and Chinese. Chandrupatla's research interests include design, optimization, manufacturing engineering, finite element analysis, and quality and reliability. He has published widely in these areas and serves as a consultant to industry. Chandrupatla is a registered Professional Engineer and also a Certified Manufacturing Engineer. He is a member of the American Society for Engineering Education (ASEE), the American Society of Mechanical Engineers (ASME), the Society of Automotive Engineers (SAE), and the Society of Manufacturing Engineers (SME).

To Henry M. Rowan

"A detailed attention to quality and reliability is vital to the growth and success of a company."

Henry M. Rowan

Henry M. Rowan is the founder and chairman of Inductotherm Industries, Inc., located in Rancocas, New Jersey. He built his company's first furnace in his backyard; from that humble beginning, Inductotherm has become the world's largest designer and manufacturer for induction melting, heat treating, and welding. Inductotherm is currently a global enterprise of more than eighty companies with facilities in fifteen nations around the world.

A native of Raphine, Virginia, Rowan grew up in Ridgewood, New Jersey. After serving as a pilot in the Army Air Corps during World War II, he earned his B.S. in electrical engineering from Massachusetts Institute of Technology. Rowan took major steps in customer service by creating a highly mobile service team organized around a fleet of company-owned aircraft to ensure maximum uptime of each customer's installation. In 1992, Rowan endowed Glassboro State College with $100 million. It is now known as Rowan University. Rowan's triumphs and tribulations are presented in his autobiography, *The Fire Within* (Penton Publishing, 1995).

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Preface

The text material evolved out of teaching a course on quality and reliability in an undergraduate program in mechanical engineering. This is a required course in the second semester of our junior year. I have taught the course every year for the past ten years. I received positive feedback from the students who took the course and from the managers in industry who employed them. These positive interactions provided the motivation to develop the course material into a book. This book is a culmination of more than forty years of my experience as a design and manufacturing engineer, teacher, researcher, and consultant.

The underlying philosophy of the book is that a quality product results from the specification of quality at the design stage; measurement, monitoring, and control of quality at the production stage; and quality performance at the final stage. A course on quality and reliability covering all three aspects is needed in every mechanical engineering or manufacturing engineering program. Practicing engineers in design, manufacturing, and quality engineering need to have this material handy in one place. Industrial engineering students also need an exposure to quality specification. There are many excellent books on each of the three areas, but books integrating the three areas are not available.

This book is intended as a textbook for an upper-level course in mechanical engineering, manufacturing engineering, and industrial engineering programs. The book can be used as a reference book for upper-level capstone design courses, and also as a learning resource for practicing engineers. Each chapter introduces the underlying concepts and attempts to explain the origin of some of the data in the tables. As an example, the estimation of the standard deviation in terms of the sample range used in various process control charts is shown to come from order statistics. These and other relationships have been implemented in generating the tables available in the Appendix. The corresponding tables provided on the CD included with this book have active formulas.

Complete computer programs that implement and parallel the theory have been provided. These programs are in Microsoft Excel and are available on the CD included with the book. Several full-fledged programs have spreadsheet simplicity. Pressing Alt+F11 will show the modules and functions that have been developed. Several programs have interactive features using the spin buttons in Microsoft Excel. All tables given in the Appendix are available on the CD in the form of spreadsheets or programs.

The book is organized as follows: Chapter 1 gives definitions of quality and reliability providing a brief historical development. Quality philosophies are presented. Chapter 2 develops the concept of preferred numbers before introducing the international tolerance system. The relationship of manufacturing processes and tolerances is presented. Tolerance selection and tolerance allocation decisions are also discussed. Chapter 3 gives an overview of geometric dimensioning and tolerancing. Tolerances of form, profile, orientation, location, and runout are discussed. Evaluation aspects of form tolerances – straightness, flatness, circularity, and cylindricity – are discussed, and several computer programs are included.

Chapters 4, 5, and 6 provide the key concepts of probability and statistics, sampling concepts, and data presentation tools. Chapter 7 introduces the concepts of order statistics and other preliminaries and goes on to present various control charts for variables and attributes. Operating characteristic curves are given for both variables and attributes. Chapter 8 discusses process capability, measurement system analysis, error propagation, and tolerance intervals. Chapter 9 presents acceptance sampling for attributes and variables. Interactive programs are provided for the design of sampling plans for both attributes and variables.

Chapter 10 gives concepts of experimental design. Completely randomized single-factor experiments, randomized block experiments, two-factor factorial experiments, and 2^k factorial experiments are discussed. Chapter 11 introduces reliability concepts, and various failure distributions are presented. The evaluation of system reliability of series and parallel systems, K-of-N systems, and standby systems are discussed. Chapter 12 discusses parameter estimation aspects for Weibull and lognormal distributions and sampling procedures for reliability life testing.

Programs in mechanical engineering and manufacturing engineering are expected to cover all chapters. Chapter 6 may be covered through some discussion followed by assignments. Some topics in Chapters 7, 8, 9, and 12 may be left as reading material. A course on quality improvement in industrial engineering programs may use Chapter 2 as optional reading material and skip Chapter 3. Needed material from Chapters 4 and 5 may be reviewed. Chapters 6, 7, 8, 9, and 10 should be covered in their entirety. Chapters 11 and 12 may be used as needed. A first course on reliability may cover Chapters 1, 4, 5, 6, 10, 11, and 12, and other chapters may be used as needed.

Junior- or senior-level capstone design and project-based courses in mechanical and manufacturing engineering may use this book as a study reference, with students expected to study Chapters 1, 2, 3, 4, 5, 6, 10, and 11. Some testing aspects of Chapter 12 may also be used.

Training programs in the areas of quality and reliability may use relevant chapters and programs for short courses. Practicing professionals should find the book useful for self-learning.

The use of computer programs must be stressed; the included Excel programs should serve well for this purpose. I would like to get your feedback concerning the included software (you may contact me at Chandrupatla@rowan.edu). Use of software such as MINITAB and other commercial software is encouraged.

Acknowledgments

I would like to thank several reviewers who gave many constructive suggestions. In particular, I would like to thank Dr. Srinivas Chakravarty, Professor of Operations Research and Statistics, Department of Industrial and Manufacturing Engineering, Kettering University, Flint, Michigan, who has been a continuing source of encouragement for many years as a colleague and friend. I cherish all the interesting discussions on statistics, quality, and reliability that we had. I am deeply indebted to Dr. Prabhaker R. Gangasani, Technical Director, Dura-Bar, a division of Wells Manufacturing Company, Woodstock, Illinois, for providing me with valuable insight through his review. I express my sincere thanks to Dr. Ashok D. Belegundu, Professor, Department of Mechanical Engineering, Pennsylvania State University, who, as coauthor of my previous books, always encouraged me to write this book. I thank all the students who took the course and provided many valuable suggestions.

I express my deep gratitude to Mr. Henry M. Rowan of the Inductotherm Group of companies, who has been a constant source of inspiration. I also thank Dr. Dianne Dorland, Dean, College of Engineering at Rowan University, for her encouragement and support in this endeavor. The encouragement received from the entire faculty in the College of Engineering at Rowan is highly appreciated.

I express my sincere thanks to Mr. Peter Gordon, Engineering Editor at Cambridge University Press. He handled the project efficiently and with great speed. I would like to express my thanks to the copyeditor, Ms. Heather Phillips, the project manager, Ms. Peggy M. Rote, and the production team for the fine job that they accomplished.

I would like to thank my wife, Suhasini; my sons, Sreekanth and Hareesh; my daughter-in-law, Vandana; and my grandchildren, Sumanth and Sriya. They all turned this major undertaking into a pleasant chore.

Tirupathi R. Chandrupatla
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1

Quality Concepts

1.1 Introduction

Quality is perceived differently by different people. Yet, everyone understands what is meant by "quality." In a manufactured product, the customer as a user recognizes the quality of fit, finish, appearance, function, and performance. The quality of service may be rated based on the degree of satisfaction by the customer receiving the service. The relevant dictionary meaning of quality is "the degree of excellence." However, this definition is relative in nature. The ultimate test in this evaluation process lies with the consumer. The customer's needs must be translated into measurable characteristics in a product or service. Once the specifications are developed, ways to measure and monitor the characteristics need to be found. This provides the basis for continuous improvement in the product or service. The ultimate aim is to ensure that the customer will be satisfied to pay for the product or service. This should result in a reasonable profit for the producer or the service provider. The relationship with a customer is a lasting one. The reliability of a product plays an important role in developing this relationship.

1.2 Quality and Reliability Defined

There are many definitions of quality available in the literature. A definition attributed to quality guru Crosby states the following:

Quality is conformance to requirements.

The preceding definition assumes that the specifications and requirements have already been developed. The next thing to look for is conformance to these requirements. Another frequently used definition comes from Juran:

Quality is fitness for use.

This definition stresses the importance of the customer who will use the product.

W. Edwards Deming defined quality as follows:

Good quality means a predictable degree of uniformity and dependability with a quality standard suited to the customer.

The underlying philosophy of all definitions is the same – consistency of conformance and performance, and keeping the customer in mind.

Another definition that is widely accepted is

Quality is the degree to which performance meets expectations.

This definition provides a means to assess quality using a relative measure.

We provide here the definition adopted by the American Society for Quality (ASQ):

Quality denotes an excellence in goods and services, especially to the degree they conform to requirements and satisfy customers.

This definition assimilates the previous ones and is our definition of choice.

Reliability implies dependability – reliability introduces the concept of failure and time to failure:

Reliability is the probability that a system or component can perform its intended function for a specified interval under stated conditions.

Quality and reliability go hand in hand. The customer expects a product of good quality that performs reliably.

1.3 Historical Development

The history of quality is as old as civilization. The Harappans of the ancient Indus Valley civilization (3000 BC) achieved high precision in the measurement of length, mass, and time. The smallest division, which is marked on an ivory scale from Lothal, was approximately 1.704 millimeters, recorded in the Bronze Age. The dimensions of the pyramids, built around 2500 BC, show a high degree of accuracy. However, the use of tolerancing systems for the specification of quality and statistical principles to monitor quality are of recent origin. The quality movement may be traced back to medieval Europe. Craftsmen began organizing into unions called guilds in the late thirteenth century. Manufacturing in the industrialized world followed the craftsmanship model throughout the eighteenth century. The factory system, with its emphasis on product inspection, started in Great Britain in the mid-1750s and grew into the Industrial Revolution in the early nineteenth century. In 1798 Eli Whitney introduced the concept of producing interchangeable parts to simplify assembly.

Objective methods of measuring and ensuring dimensional consistency evolved in the mid-1800s with the introduction of go gages. A go gage for a hole checks for its lower limit (maximum material condition). No-go gages, which are used to check the upper limit for a hole, were introduced much later. Frederick W. Taylor introduced the principles of scientific management around 1900 and emphasized the division of labor with a focus on productivity. There was a significant rise in productivity but it had a negative effect on quality. Henry Ford's moving automobile assembly line was introduced in 1913. This required that consistently good-quality parts were available so that the production assembly line would not be forced to slow down. In 1924 Walter A. Shewhart introduced the basic ideas of the statistical process control chart, which signaled the beginning of the era of statistical quality control. By the mid-1930s, statistical quality control methods were widely used at Western Electric, a manufacturing arm of the Bell system.

World War II brought increased recognition of quality in manufacturing industries and military applications. The American Society for Quality Control was formed in 1946. (Eventually it shortened its name to ASQ in 1997.) A quality revolution in Japan followed World War II: the Japanese began applying the lessons learned in producing military goods produced for export. Quality stalwarts W. Edwards Deming and Joseph M. Juran lectured extensively in Japan. As a result, the Japanese became leaders in quality by the 1970s. Japanese manufacturers began increasing their share in American markets, resulting in widespread economic effects in the United States. The U.S. response emphasized not only statistics but approaches that embraced the entire organization – a movement that became known as Total Quality Management. Several other quality initiatives followed. The ISO 9000 quality system standards were published in 1987. The Baldrige National Quality Program and the Malcolm Baldrige National Quality Award were established by the U.S. Congress in the same year. The quality philosophies that introduced the modern concepts of quality are presented in the next section.

1.4 Quality Philosophies

Several individuals made significant contributions to quality control and improvement. We take a closer look at the approach and philosophies of W. Edwards Deming, Joseph M. Juran, Philip B. Crosby, and Armand V. Feigenbaum.

W. Edwards Deming

W. Edwards Deming is perhaps the best-known quality expert in the world. He was instrumental in the post-war industrial revival of Japan. Subsequently his ideas were increasingly adopted in industry in the United States and other countries. Deming received his electrical engineering degree from the University of Wyoming and his Ph.D. in mathematical physics. He worked for the Western Electric Company with Walter A. Shewhart, the developer of the control chart. Deming then worked with the U.S. Department of Agriculture and the U.S. Census Bureau. Starting in 1950 he delivered a series of lectures to top management in Japan on statistical process control. Japanese industry adopted his methods which resulted in a significant improvement in quality. Deming firmly believed that quality is the responsibility of the management. The Deming philosophy is summarized in the following fourteen points,[1] which were included in his monumental work *Out of the Crisis*.

The fourteen points apply to both small and large organizations, to the service industry as well as to manufacturing. They also apply to a division within a company. The fourteen points are presented here.

1. *Create constancy of purpose for improvement of product and service.* The point stresses the need for a mission statement which must be understood by all employees, suppliers, and customers. The strategic plan should look for the long-term payback.

2. *Adopt the new philosophy.* Management must learn the responsibilities and take on leadership for change. Poor workmanship, defective products, or bad service are not acceptable.

3. *Cease dependence on mass inspection.* Eliminate the need for inspection on a mass basis by building quality into the product in the first place. Statistical methods of quality control are more efficient.

4. *End the practice of awarding business on the basis of price tag alone.* Instead, minimize the total cost. The aim in the purchase of new tools and other equipment should be to minimize the net cost per hour of operation or per piece produced. Move toward a single supplier for any one item, on a long-term relationship of loyalty and trust.

5. *Improve constantly and forever the system of production and service.* The improvement of product and service is an ongoing process. The Deming cycle involves the four-step process of plan, do, check, act. At the *plan* stage, the opportunities for improvement are identified. The theory is tested on a small scale at the *do* stage, the results of the test are analyzed at the *check* stage, and the results are implemented in the *act* stage.

6. *Institute training.* On-the-job training must be provided for all employees. Employees must be encouraged to implement the knowledge developed through training.

7. *Adopt and institute leadership.* The aim of supervision should be to help people to do a better job using machines. Supervision must create an environment where the workers take leadership roles in accomplishing their work.

[1] Deming, W. Edwards, *Out of the Crisis*, pp. 23–24, © 2000, Massachusetts Institute of Technology, by permission of the MIT Press.

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