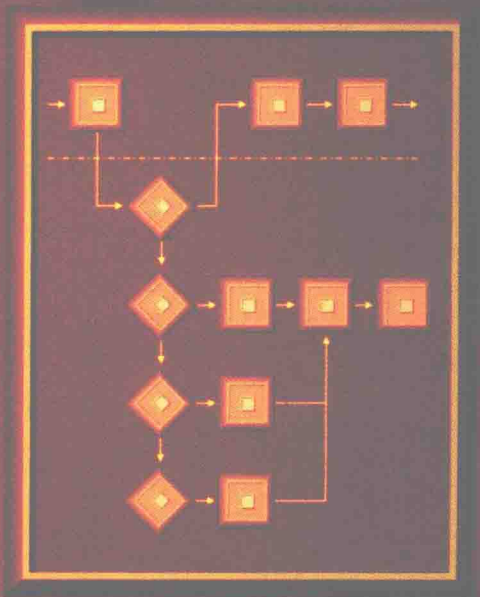
Johannes Ledolter / Claude W. Burrill

Statistical Quality Control

Strategies and Tools for Continual Improvement



STATISTICAL QUALITY CONTROL
Strategies and Tools for Continual Improvement

JOHANNES LEDOLTER
CLAUDE W. BURRILL
University of Iowa

JOHN WILEY & SONS, INC.
New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

To our spouses, Lea and Shew Hui, and our children, Thomas, Jeffrey, and Thomas.

ACQUISITIONS EDITOR Brad Wiley II
MARKETING MANAGER Leslie Hines
DESIGNER Karin Kincheloe
FREELANCE PRODUCTION MANAGER Jeanine Furino
ILLUSTRATION EDITOR Sigmund Malinowski
ELECTRONIC ILLUSTRATIONS Wellington
OUTSIDE PRODUCTION SERVICES Susan Reiland

This book was set in Helvetica by TechBooks and printed and bound by Quebecor Printing/Fairfield. The cover was printed by Phoenix Color Corporation.

This book is printed on acid-free paper. ♾

The paper in this book was manufactured by a mill whose forest management programs include sustained yield harvesting of its timberlands. Sustained yield harvesting principles ensure that the numbers of trees cut each year does not exceed the amount of new growth.

ISBN 0-471-18378-4

AUTHORS

Johannes Ledolter is a Professor at the University of Iowa in the Department of Statistics and Actuarial Science and the Department of Management Sciences, and a Professor at the Wirtschaftsuniversität Vienna, Austria. He received a Ph.D. in Statistics from the University of Wisconsin-Madison in 1975. Professor Ledolter held visiting positions at the University of Wisconsin, Princeton University, and Yale University. His area of research centers around time series analysis and forecasting, statistical methods for quality improvement, and applications of statistics in business and engineering. He has coauthored the books *Statistical Methods for Forecasting*, published by Wiley in 1983, and *Applied Statistics for Engineers and Physical Scientists*, published by Macmillan (Prentice Hall) in 1992. He and Dr. Burrill are coauthors of the book *Achieving Quality Through Continual Improvement*, published by Wiley in 1999. Professor Ledolter is a Fellow of the American Statistical Association, and an Elected Member of the International Statistical Institute.

Dr. Claude W. Burrill is a consultant on quality and project management. He is an Adjunct Professor in the School of Business at the University of Iowa. He received a Ph.D. in Mathematics from the University of Iowa in 1952, and an honorary doctorate from William Patterson College of New Jersey in 1979. His experience includes a year as a Fulbright Scholar at the University of Manchester, UK, ten years as a member of the New York University Graduate Center at Bell Labs, and ten years as a member of the IBM Systems Research Institute. He has held visiting faculty appointments at Columbia University, Dartmouth College, and the National University of Singapore, and has lectured and consulted internationally. He has authored or coauthored eight books on a variety of topics, including mathematics, probability, computer modeling, quality, and project management. He and Professor Ledolter are coauthors of the book *Achieving Quality Through Continual Improvement*, published by Wiley in 1999.

PREFACE

This is a book on problem-solving tools and their use in quality improvement. The book is appropriate as a text for use in colleges, primarily for undergraduate and graduate-level courses on quality. These courses are typically taught in Industrial Engineering programs, Departments of Statistics, and Schools of Business and Management. This text is also appropriate for use in two-year colleges, as well as for in-house company training courses on quality.

Courses on quality are generally taught in two different ways: "technique-oriented" courses, which emphasize the statistical tools, and "management-oriented" courses, which stress the managerial side of quality. This book is intended as a main text for a technique-oriented course. However, it is also useful in a managerial-type course on quality, as it serves as a useful primer and reference book on problem-solving tools.

Problem-solving skills are important for improving quality. This text provides the reader with a general and widely applicable problem-solving strategy. It covers a variety of "nonstatistical" problem-solving tools, which are neglected in most statistically oriented texts on quality. Furthermore, it discusses techniques that are useful when problems are solved by groups or teams of people. This discussion is important since most problem solving takes place within an organizational framework; in addition to the technical aspects, there is a human side to problem solving that cannot be neglected. This book shows how the success of problem solving is influenced by the style of management and the type of management–employee interaction.

This book gives a comprehensive treatment of statistical tools for problem solving and quality improvement. Our discussion starts from elementary principles of data analysis. No prior background in statistics is needed; only minimal mathematics background is required. The coverage is self-contained, and concepts and techniques are presented in a logical sequence. This text is not intended to be a "cookbook"; the emphasis of this book is on understanding and on laying the foundation for further continual learning.

The book provides a solid introduction to commonly used probability distributions, including the binomial, Poisson, and normal distributions, and it illustrates their importance in the quality arena. An introduction to surveys and sampling is

given, and it is shown how methods of statistical inference can be used to generalize sample findings. The text covers sample inspection plans, statistical process control, control charts, and capability indexes. It provides an extensive discussion of the statistical design of experiments; this discussion starts from basic principles, and proceeds to the analysis of factorial and fractional factorial designs. The book also contains a chapter on Taguchi methods, illustrating their main features with examples that can be easily understood. Furthermore, the text includes a comprehensive chapter on regression.

Appropriate exercises are included in each chapter, and many references for further reading are listed. Each major section of the book concludes with the assignment of several projects. The aim of these end-of-section projects is to show, by example, how quantitative analysis can contribute to the solution of problems. Problem-solving techniques and statistical analysis are most meaningful when you have personal experience with their use.

Several large data sets are analyzed or assigned as exercises and projects. To save you the work of entering the data, we have stored data files on the Wiley web site given below. The computer files are in ASCII format. Files start with a brief description of the variables, and then list the observations. The first four symbols of each file name indicate the chapter or the project in which these data are first used; the next four symbols provide an abbreviated informative title.

There are many books that can be used in a course on the tools for quality improvement, and one may ask why one should prefer this text over all others. We believe that this book stands out for several reasons:

1. Discussion of nonstatistical problem solving tools found in Chapters 2–5 covers the organizational aspects of general or team-based problem solving techniques—topics not usually found in other statistical quality control books.

2. Thorough coverage of statistical quality control, with emphasis on the understanding of concepts and their practical use in solving quality problems. Coverage of sample inspection plans, control charts, and capability indexes includes a careful discussion of the differences between statistical control and capability.

3. Extensive discussion of design of experiments for process improvement, from basic principles through the analysis of factorial and fractional factorial designs, concludes with a chapter on Taguchi methods.

4. The large collection of exercises for each chapter is supported by Problem Solving Projects at the end of each of the five sections of the text. Several of the exercises and projects involve the analysis of large, case-oriented data sets. An ASCII version of all data sets from the text can be found on the Wiley Web Site at www.wiley.com/college/ledolter/qualitytools.

We hope you will find our book useful. If you have any comments or suggestions that could help us improve this book, please let us know. You can reach us through the Department of Statistics and Actuarial Science at the University of Iowa, Iowa City, IA 52242, or through e-mail at ledolter@stat.uiowa.edu.

A note to instructors: There may be more material in this book than can be covered comfortably in a one-semester or, especially, a one-quarter course. How much can be covered and which chapters should be emphasized or omitted will depend on the background of your students. Chapters 1 through 14 can be covered if your students have had no prior background in statistics. In fact, we have done this at the University of Iowa in our statistics modules for MBA students (in ten weeks) and for Executive MBA students (in eight weeks, without Chapter 14). If your students have had some introduction to statistics and if they are familiar with the material in Chapters 6 through 10, then the course can focus on Chapters 1 through 5 (problem solving) and Chapters 11 through 17 (sample inspection, statistical process control, design of experiments, and regression).

Supplements

Instructor's Solutions Manual. Provides extensive solutions for end-of-chapter exercises and end-of-section problems.

Data Disk. Contains all data sets from the text. Files are in ASCII format and are included with the Instructor's Solutions Manual available only upon request to adopting instructors. The files can also be found on the Wiley Web Site at www.wiley.com/college/ledolter/qualitytools.

Acknowledgments

We greatly appreciate the writings and teaching of people from whom we learned. Learning is incremental, and we could not have written this book without being able to stand on the shoulders of the books that came before us. A most heartfelt "thank you" goes to George Box, who was the catalyst and who triggered my (Ledolter's) desire to learn more about statistics. By watching a true master problem solver, I learned more about statistics during George's weekly "Monday Night Beer Seminars" than at any other course I have ever taken. Thank you, George!

We thank the various professional societies, companies, and publishers who have given permission to reproduce their materials in our text. Permission credit is acknowledged at appropriate places in the book. We also acknowledge the comments of our students at the University of Iowa and at Yale University who were exposed to previous versions of this material. Your feedback helped us greatly in improving this manuscript.

We would also like to thank the following people for their many constructive comments during the development of this book: Michael Adams (University of Alabama), Bala Balasubramanian (California Polytechnic State University), Milton Chen (San Diego University), Amanda Chou (University of Texas at San Antonio), Charles Cwiek (University of Tennessee), Steve Hillmer (University of Kansas), Bob Hogg (University of Iowa), Stu Hunter (Princeton University), Marie Klugman (Drake University), Mike Longnecker (Texas A&M University), David Lopez (Central Michigan University), Douglas Pollock (NORTEL), Victor Prybutok (University of North Texas), Elizabeth Rose (University of Southern California), Diane Schaub (University of Florida), D.G. Vandenberghe (University of Regina, SK).

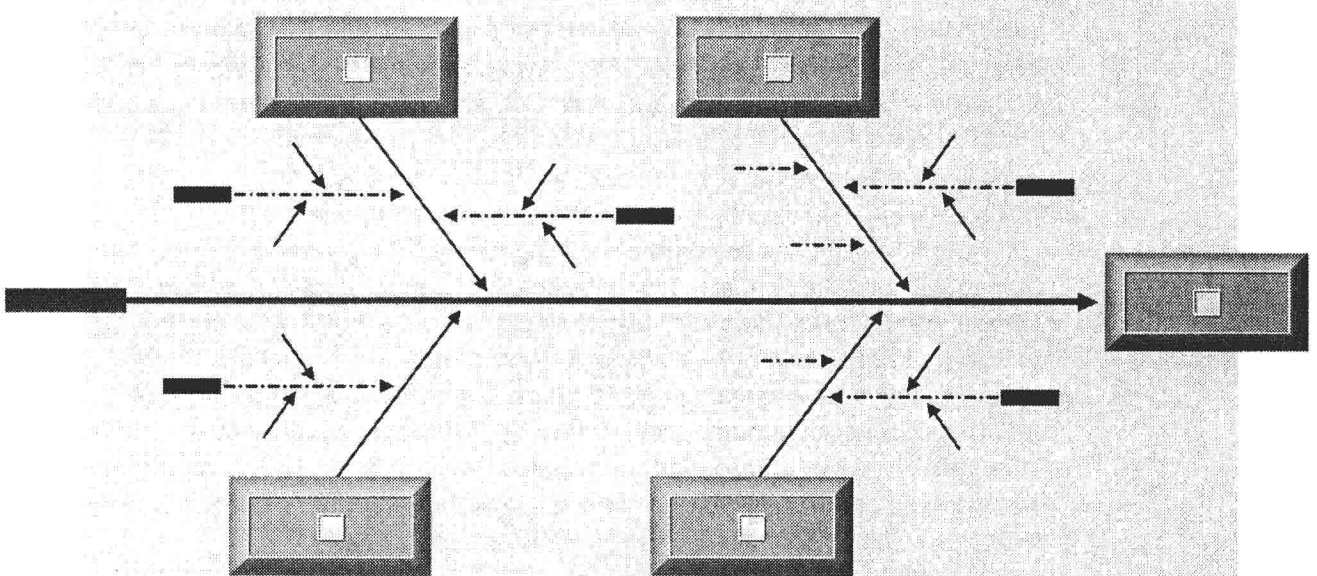
We would like to express our thanks and appreciation to our editor, Brad Wiley, and his efficient staff. Brad was always here for us. He helped us along by providing insightful reviews at just the right times; and he always seemed to sense when encouragement was needed.

Finally, we would like to thank our families for their understanding and their assistance in making this book a reality. Writing a book is a time-consuming and daunting process. By providing the push "to finally get it done," and by giving us the time needed to actually do it, our families made this book happen.

CONTENTS

SECTION 1

QUALITY PROBLEMS AND PROBLEM-SOLVING STRATEGIES



CHAPTER 1
INTRODUCTION AND OUTLINE OF THE BOOK

In this introductory chapter we summarize the objectives that we pursue with this text. The aim of this book is to provide the reader with an effective set of tools that he or she can use in problem solving, especially in problems that relate to quality and quality improvement issues. We start this chapter by giving a brief introduction to the area of quality. Quality and its continual improvement are critical to the success of any organization, and workers and managers must have familiarity with the appropriate tools for achieving and improving quality.

Our book emphasizes problem-solving tools and says very little about the managerial aspects of quality. Nevertheless, we need the subsequent brief introduction to the concept of quality to describe the background in which these tools operate. The following section gives only a very rudimentary introduction to quality. If you want to learn more about management issues of quality, then you should consult our other book, *Achieving Quality through Continual Improvement*, which is also published by John Wiley & Sons, 1999. This second book gives a detailed discussion of the managerial aspects of quality and covers the organizational and tactical issues of implementing quality.

1.1 QUALITY: AN OVERVIEW

1.1.1 A Brief History

Quality has been a concern of humankind since the beginning of time. Throughout history, the wealthy and powerful sponsored artisans who produced quality

products for them. Over time, various guilds were formed to promote professionalism and standards for quality.

The industrial revolution made goods available to the masses, but introduced a basic change in commerce by separating the workers who made products from the customers who received them. This depersonalization of production introduced the need for producers to evolve new means to monitor and control the quality of their products. Originally, the focus was on *quality control*, that is, on inspection to identify faulty products and prevent their being shipped to customers. In the early part of this century, this inspection approach to quality was augmented with the employment of *statistical process control* (SPC), also known as *statistical quality control* (SQC), a concept developed by W. A. Shewhart of Bell Labs. SPC comprises a set of techniques for monitoring a production process to determine if it is stable over time and capable of producing quality products. It shifts the focus of attention from the product to the process that is used to make the product. SPC was widely practiced by U.S. industry during World War II, and it is credited by many observers as playing a key role in bringing about the defeat of Japan.

In the period following World War II, U.S. manufacturers enjoyed a huge pent-up demand for their products. They could sell whatever they produced, so their emphasis was on quantity of production, not product quality. Many of the wartime quality lessons were forgotten by manufacturers, and consumers did not seem to care because jobs were plentiful, wages were good, and if something broke, one could always replace it. The United States developed into a "throw-away" society—one bought a product, soon discovered that it failed to perform satisfactorily, threw it away, and bought another.

Postwar Japan faced an entirely different situation. With food and shelter scarce and their factories in ruins, Japan assessed and corrected the causes of their failure. Product quality was one area where America had definitely outperformed Japan, so they attempted to correct this situation. They soon mastered the inspection and SPC quality concepts, and went on to invent their own quality improvement techniques. By the 1970s, they had achieved world leadership in quality.

Today, some Western firms have closed the quality gap with Japan, and a few of them have managed to surpass their Japanese competitors. But much of the Western World still is playing catch-up with Japan in the quality arena. The aim of this book is to provide you with knowledge that you can use to help organizations improve the quality of their products.

1.1.2 Quality in Goods, Services, and Information Products

There are various formal definitions of quality; one is the definition of the *International Organization for Standardization* (ISO):

> ***Quality*** *is the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs.*

As this definition implies, quality is an attribute of a product. A product is a quality product if it meets all the requirements established for it; that is, it is a defect-free product. In other words, *quality* means meeting requirements.

The pioneers of the quality movement—Walter A. Shewhart, W. Edwards Deming, Joseph M. Juran, Philip B. Crosby, and Kaoru Ishikawa—all were physical scientists or engineers. The focus of their quality efforts was on *goods*—manufactured or constructed products—and their approach to quality improvement leaned heavily on the use of statistical methods. More recently, the focus of quality efforts has been expanded to include *services*—the performance of labor for the benefit of another. This expansion has placed a greater emphasis on human factors and their impact on product quality.

Service is a broad category, including food services, health care, cleaning and building services, transportation, education, finance, government, and so on. Service accounts for about two-thirds of the jobs in an industrial economy; even in manufacturing, about two-thirds of the jobs are in service areas such as design, finance, advertising, and sales (*The Economist*, May 6, 1995, p. 15).

The traditional view of the economy in terms of goods and services tends to obscure what people in America really do for a living. About 60 percent of U.S. employment is in two categories—(1) managerial and professional specialty, and (2) technical, sales, and administrative support—both white-collar jobs (*Bureau of Labor Statistics*, U.S. Department of Labor Employment; 1993 counts). Most of these employees do not deal with physical objects, such as nuts and bolts; instead they deal with sales slips, correspondence, reports, checks, and the like. Thus, at least half the people in this country are *information workers*—some estimates place the number as high as 70 percent. In industries such as banking and insurance, the number is almost 100 percent. What these people deal with are *information products*. Quality products for information workers means instructions that are clear and complete, documents that are correct, checks in the right amount, and so on.

Quality in the office is every bit as important as quality on the factory floor. To appreciate this, think about what takes place when a customer buys a "widget" from a manufacturing company: A salesperson obtains and documents an order; components and supplies are ordered; incoming goods are stockpiled and listed in inventory; a production order is written, causing a worker to build the widget; the widget is built and sent to the customer with a shipping slip and an invoice; the customer pays, and appropriate transactions are made in the accounting system; checks are issued to the worker for his or her effort and to the people providing supplies, heat, light, and space; and, finally, the government gets tax reports and a check for part of the profit. This is a very much abbreviated list of activities and products, but notice that for each physical product (components, supplies, widgets, and so on) there are many information products (orders, inventory records, production orders, accounting statements, check, bills, reports, and so on). To provide proper service to the customer, *all* products—goods, services, and information—must be quality products.

1.1.3 Processes and Quality

The starting point in understanding how to achieve quality is to examine how products come into being. A product is the output of a *production process* (or simply a *process*), which is a logically related collection of actions or operations that produce results, called the *outputs* of the process. A process must be supplied with necessary ingredients, and those are the *inputs* to the process. For a manufacturing process, the inputs include parts and components, and the outputs include the finished products as well as scrap. For a service process, inputs may include a package and delivery instructions, and the output may be a delivered package. For an information product, inputs may be a class assignment and source materials, and the output a term paper. In all cases, the process involves some arrangement of equipment, tools, methods, procedures, and instructions for converting appropriate inputs into the desired product (and ancillary outputs, such as scrap). The quality of a product depends heavily on the production process that is used to produce it. If you want to produce quality widgets, then you must have an effective widget-producing process. If you want to produce quality cars, then you must have an effective assembly line. A major cause of poor products is the failure to build effective production processes.

Every production process can be thought of as consisting of four stages: analyze, design, build, test. *Analyze* involves learning what customers want and expressing these "wants" as a set of customer requirements. *Design* means establishing the requirements for a product that will meet the customer requirements. *Build* means actually building the product. *Test* involves checking to learn whether the product meets the customer requirements that were established for it. Each of these four subprocesses must be carried out properly to have a product that meets customer requirements. *Quality control* is an important component, especially in the fourth step of the production process. Here we confirm that the product meets the requirements that were established for it. If the product does, it is judged to be a *quality product.*

1.1.4 Management and Quality

Our focus in this book is on the *tools* that can be used to improve quality. But tools are only one part of the total effort required to achieve quality. Because management has ultimate control of all resources in an organization, it also has ultimate responsibility for the quality of all products. To make its views on quality known, management must establish a *quality policy* in which it states the organization's commitment to quality and establishes general guidelines for supporting that policy. Management must then support the quality policy by properly managing work, workers, work processes, and the work environment. There is an extensive literature on each of these topics. You should consult our other book for information on these issues.

1.1.5 ISO 9000 and Quality

For years, many organizations have strived for quality because they were convinced it was good business practice—it increased the demand for their products and reduced the cost of production. But others were not always convinced that costs would decrease so their quality initiatives were half-hearted. Now, however, many of these reluctant organizations are pushing for quality because of an initiative of the *International Organization for Standardization*, commonly referred to as ISO.

ISO was founded in 1946 to establish a series of international standards for products and production processes. Currently over 90 countries are members, including the United States and all of its major trading partners. In 1987, the organization published the ISO 9000 series of generic standards for quality management and quality assurance. These standards apply to companies of every size and to all industrial sectors—goods, services, and information. Various extensions of the original ISO 9000 standards have been introduced since 1987; ISO 14000, a new environmental management systems standard, was added in 1996.

The ISO 9000 standards provide guidance for suppliers who want to implement effective quality systems. Also, they can be used by customers to evaluate the adequacy of a supplier's quality system. To avoid the need for each customer to check each supplier, a system of *registration* has been established. A group of registrars has been accredited by ISO to audit quality systems of suppliers and certify those suppliers that are in compliance with a specific standard of the ISO series. A customer can then ask a supplier to become registered as a precondition to placing an order with that supplier. Registration gives the customer an assurance that the supplier has an effective quality system in place; this increases the likelihood that the supplier will provide quality products. In the past, suppliers were motivated to establish quality systems by the carrot of increased customer satisfaction. Today, many suppliers are motivated by the stick of ISO 9000—if they don't register, then they may not be able to sell to some potential customers.

1.1.6 Achieving Quality

There are two basic strategies for achieving quality: *prevention* and *improvement*. One strategy is to prevent quality problems by having a good understanding of customer requirements, by designing, building, and documenting production processes capable of producing the required products, and by using well-trained, highly motivated process operators who consistently do first-class work. Some organizations do a very good job on all of these tasks, which helps them avoid quality problems. However, many times companies will fall far short of this ideal, and they need to employ an equally important second strategy, namely, to practice continual process improvement.

Quality improvement efforts are designed to make a production process less likely to produce defective products. Examples of typical improvement efforts are:

Document a process in an attempt to make it more consistent; train operators to improve their job performance; collect and analyze defect information to determine the causes of product defects; make process changes to remove the causes of product defects; redesign the product to make its production less error-prone. The aim of this book is to present techniques and tools that aid such quality improvement efforts.

1.2 OUTLINE OF THIS BOOK

1.2.1 Quality Problems and Problem-Solving Strategies

This is a book on problem-solving tools and their use in quality improvement. Problem-solving skills are important for achieving and improving quality. Above all, one needs to have a general strategy for solving problems, and one must know techniques that help to *find*, *prioritize*, and *solve problems*. Useful systematic techniques for detecting and prioritizing problems are discussed in *Chapter 2*. Flowcharts and Pareto diagrams are explained. Flowcharts are important tools for visualizing the sequence of events in a process and they can help locate problems and unneeded complexity. Pareto diagrams are useful tools for prioritizing problems by focusing one's attention on the most commonplace problems.

A general four-step problem-solving strategy and a collection of simple but helpful problem-solving techniques are given in *Chapter 3*. Different ways of approaching the solutions to problems are explored. Cause-analysis and Ishikawa cause-and-effect diagrams are explained; these diagrams represent useful graphical displays of possible causes and their interrelationships.

Team-based approaches to problem solving are vital, as more and more problems are solved in groups. In order to solve problems within a team structure, we must have procedures for sharing and assessing information. *Chapter 4* of this book emphasizes the benefits of team-based approaches to problem solving, and discusses brainstorming, the nominal group technique, and the Delphi method—three useful techniques for the structured exchange of information.

Problem solving usually takes place within an organizational framework, and certainly not in a vacuum that is devoid of human interaction. In addition to the technical aspects, there is a human side to problem solving that cannot be neglected. The reward system and leadership, in particular, have a major influence on the creation as well as the solution of problems. These issues are explored in *Chapter 5*. We discuss how the success of problem solving is influenced by the style of management and the type of management-employee interaction.

1.2.2 Management Based on Facts: The Importance of Data and Data Analysis

We need to understand how data helps us solve problems. The *collection* and the *analysis* of relevant data through appropriate statistical techniques are important