Statistics for Engineers an Introduction

S.J. Morrison

WILEY
A John Wiley and Sons, Ltd., Publication

Statistics for Engineers

Statistics for Engineers an Introduction

S.J. Morrison

WILEY
A John Wiley and Sons, Ltd., Publication

This edition first published 2009
© 2009, John Wiley & Sons, Ltd

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Library of Congress Cataloguing-in-Publication Data

Morrison, S. J.
Introduction to engineering statistics / S.J. Morrison.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-74556-4
1. Engineering—Statistical methods. I. Title.
TA340.M67 2009
620.0072′7—dc22
2009001815

A catalogue record for this book is available from the British Library.

ISBN: 978-0-470-74556-4

Set in 10/12.5pt Times by Integra Software Services Pvt. Ltd. Pondicherry, India
Printed and bound in Great Britain by TJ International, Padstow, Cornwall

Contents

About the Author **vii**
Foreword **ix**
Preface **xi**
Acknowledgements **xiii**

1 Nature of Variability **1**

2 Basic Statistical Methods **9**
2.1 Variance 9
2.2 Divisor 'n' or '$n-1$'? 11
2.3 Covariance and Correlation 13
2.4 Normal Distribution 14
2.5 Cumulative Frequency Distributions 18
2.6 Binomial Distribution 20
2.7 Poisson Distribution 25
2.8 Chi-squared Distribution 26
Bibliography 31

3 Production **33**
3.1 Sampling Inspection 34
3.2 Control Charts 37
3.3 Cusum Charts 40
3.4 Significance Tests 43
3.5 Analysis of Variance 49
3.6 Linear Regression 52
Bibliography 57

4 Engineering Design **61**
4.1 Variance Synthesis 61
4.2 Factors of Safety 68
4.3 Tolerances 69
4.4 The Future 71
Bibliography 72

5 Research and Development **75**
5.1 Design of Experiments 76
5.2 Evolutionary Operation 95
5.3 Multiple Regression 96
5.4 More Statistical Methods 111
Bibliography 115

6 Background **119**
6.1 Measurement 119
6.2 Statistical Computing 121
Bibliography 127

7 Quality Management **129**
7.1 Quality Planning 129
7.2 Quality Organisation 135
7.3 Directing the Quality Function 137
7.4 Controlling the Quality Function 140
7.5 Statistical Engineering 141
Bibliography 142

8 Conclusion **145**

Appendix A: Guidelines **147**

Appendix B: Recommended Books **151**

Appendix C: Periodicals **161**

Appendix D: Supplementary Bibliography **165**

Appendix E: Statistical Tables **171**

Index **173**

About the Author

S.J. Morrison is a Fellow of the Institution of Mechanical Engineering, the Royal Statistical Society and the Chartered Management Institute.

Morrison is also a Senior Member of the American Society for Quality.

Foreword

Jim Morrison is to be congratulated on producing this very important book. It used to be thought that to make the nearest thing to a perfect car, it was necessary for each component to be produced to satisfy the very narrowest specifications. This is the philosophy that produced the Rolls Royce. Unfortunately the car was not only exceptional in reliability but also exceptional in cost.

It is remarkable that as far back as 1957 Jim Morrison came up with a very different and important concept. This was to use in engineering design the concept of transmission of error. With this approach, it became clear that to produce low error transmission in the characteristics of an assembly, certain components had to satisfy very tight specifications and these were expensive to achieve. However, other components that had much less effect on the performance of the assembly could have much wider and less expensive specifications. He showed us how to find out which components must have very narrow specifications and which could be much less narrow. By spending money where it would do the most good, it was possible to produce a car at a moderate cost whose performance and reliability were extremely high. Morrison's concept can be applied in all areas of engineering design. His concept has had profound effects. Those companies that ignore it do so at their peril.

History is full of examples where the origin of an important concept was not known or was ignored until a much later time. This has been true in the case of robust design described above. Sometimes not only has the originator of the idea been forgotten but the essentials which he developed have been misapplied. In particular, Jim had pointed out the importance of knowing, at least approximately, the variances of the components in order to determine the variance of the assembly. In later versions of this concept such matters have been given far too little attention. We are particularly grateful, therefore, for this book in which Jim describes these techniques with clarity and accuracy.

George E.P. Box, FRS
Emeritus Professor, University of Wisconsin, USA
Honorary Member of the American Society for Quality
Inaugural holder of the George Box Medal for outstanding contributions to business and industrial statistics awarded by the European Network of Business and Industrial Statisticians (ENBIS)

Preface

This introductory text on statistical engineering is written by an engineer for an engineering readership. It is hoped it will appeal both to practising engineers and to students, and (indeed) to school leavers contemplating engineering as a career. It may also be useful to managers who are concerned with the quality of manufactured products. In spite of all the effort over centuries to achieve absolute precision, engineering is still (and probably always will be) beset by variability which is manifest in many different ways – properties of raw materials, the environment, measurement error, process variability, etc.

Statisticians, too, are beset by variability. If variability did not exist their branch of mathematics would (probably) never have come into existence. Variability is their focal point. They have developed powerful analytical techniques which can be of enormous benefit to society in general and to specialists in other branches of science and technology in particular.

Engineers using statistical methods need not concern themselves with profound issues of statistical inference or the subtleties of statistical mathematics. They require only familiarity with relevant statistical methods, an understanding of how they work and how to use them safely without running into danger. Some familiarity with statistical terminology is also desirable so that they can communicate with statisticians when the need arises. That is what this book is all about.

The sequence of topics is not linked in any way to the theoretical development of mathematical statistics. The text begins with a nonmathematical examination of the nature of variability in engineering data, followed by an explanation of some basic statistical methods for dealing with variability. It then follows the pursuit of variability reduction in manufacturing industry, starting with production, followed by engineering design, then research and development. Finally, measurement, statistical computing, and quality management are dealt with as background topics. Although it is convenient to use the manufacturing industry as a vehicle for demonstrating the use of statistical methods, it must be emphasised they are widely applicable in other branches of engineering.

Statistical methods provide the only satisfactory way of dealing with the variability that exists in every engineering situation. The buck doesn't stop at ground level. The responsibility for dealing with variability is carried by engineers and managers at all levels, right up to chief executive. The engineer who is lacking in statistical skill is less than competent to handle variability. For that reason statistical engineering should be a continuing professional development interest for practising engineers, irrespective of seniority.

Engineering students must recognise that statistical skills will be important to them in their future careers, no matter what branch of technology they enter or how high they set their sights. As fee-payers they are entitled to look critically at their academic curricula. If they graduate in an academic establishment at which no provision is made for teaching the elements of statistical engineering, they will find themselves later in life competing on unequal terms with statistically competent engineers who are better equipped to deal with the reality of the world.

There is a message here, too, for school leavers who are considering a professional career in engineering. They should enquire carefully about the curriculum of any engineering degree course they are thinking of entering. If there is no evidence of statistical engineering content they should pass it by and look at the next on their list before committing themselves.

This book introduces a broad range of statistical methods that are relevant to engineering. These are presented with the minimum of mathematics and the maximum of explanation. Where statistical jargon is used the words and phrases are printed in italics at the first entry so that the meaning will be self-evident from the context. The object is to build bridges of understanding between the professional disciplines of engineering and statistics.

To assist the readers who may wish to take the subject further than a basic introduction (particularly in areas of research) extensive reference lists are provided at each chapter end. In addition, four appendices offer guidance for further study. A fifth appendix accommodates statistical tables.

Lastly, by linking together the basic elements of quality – technology, management, and statistics – in a compact readable text this book should assist academic engineering schools to satisfy the requirements of the accreditation committees of professional institutions making their assessments of degree courses.

Acknowledgements

The Institution of Electrical Engineers has agreed to parts of the article 'Engineering Design – The Fount of Quality', published in the August 2000 issue of *Engineering Management Journal*, and repeated under the title 'Quality Engineering Design' in the June 2001 issue of *Manufacturing Engineer*, to be included in Chapter 4. Thanks are due to Tim Davis, Henry Ford Technical Fellow for Quality Engineering at the Ford Motor Company, for permission to use his case study in this chapter as an example of the application of variance synthesis.

Material in Chapter 7 has been reproduced from 'Quality Management' in the *Proceedings of the Institution of Mechanical Engineers* 1985, vol. 199, No. B3, 153–159 pp. by permission of the Council of the Institution of Mechanical Engineers.

The author is grateful to Elwyn Davies and Hefin Rowlands of the former IEE Quality Management Professional Group and to Clare Morris and Dan Grove of the RSS Quality Improvement Committee for their support and encouragement in organising joint discussions in 1999/2000 on statistical engineering issues between the Institution of Electrical Engineers and the Royal Statistical Society in London.

Thanks are due to Julian Booker, Simon Edwards, Allan Reese and Dave Stewardson who have all been helpful in a variety of ways. Thanks are also due to the staff of the Industrial Statistics Research Unit at the University of Newcastle upon Tyne for assistance in preparing the text for distribution on disc in CD ROM format in 2004, and also to Dan Grove for updating references to computer software in Chapter 6.

1

Nature of Variability

There is no engineering product so simple that only one source of variability affects its dimensions or properties. Take two examples of products which are relatively simple in their physical appearance – high-carbon steel wire and milk bottles.

The tensile strength of steel wire depends on numerous factors: the carbon content of the ingot from which rods were made in the rolling mill; the temperature of the heat treatment furnace through which the rods were passed; the rate of passage through the furnace; the temperature of the quenching bath; the ambient temperature in the heat treatment shop; the number of dies through which the rods were drawn to finished wire size; the rate of drawing; the ambient temperature in the wire mill, etc. Variability in any of these factors is likely to generate variability in tensile strength.

One of the hazards of a milkman's life is the possibility of being stopped in the street by a weights and measures inspector. Milk bottles are filled to a predetermined level on automatic machines. The capacity at that level is determined by the external profile of the bottle and by its wall thickness. The bottles are made on multi-head automatic machines by dropping gobs of molten glass into metal moulds (one at each work station), piercing them hollow, then inflating them with compressed air until they fill the moulds. The external profile can be affected by different settings at each work station, by mould differences, by fluctuations in air pressure, by sagging after release from the moulds, and by malfunctioning of the automatic timing gear which

Statistics for Engineers: an Introduction S.J. Morrison
© 2009 John Wiley & Sons, Ltd

controls the various functions. The wall thickness is determined by the setting of the gob feeder and this in its turn is affected by the viscosity of the glass, the forehearth temperature, and the action of the shears which cut off successive gobs from the continuous flow of the feeder. Variability in any of these process factors may contribute to variability in the volumetric capacity of bottles in continuous production.

It must be assumed that most engineering products which are infinitely more complex than steel wire or milk bottles will be equally susceptible to a multitude of factors located in raw materials, components, processes and the environment which are capable of affecting the properties and dimensions of a finished product. It is therefore important for engineers to have an understanding of the way in which random combinations of independent sources can affect the variability of a finished product.

This can be demonstrated with random combinations of the variables R, Y and B in Table 1.1. These single-digit numbers in the range 0–9 were generated by throwing twenty-faced icosahedron coloured dice (red, yellow and blue) with the numbers zero to nine engraved twice on each die. The dice were invented in 1950/60 by Mr Yasushi Ishida and patented by Tokyo-Shibaura Electric Company. They were marketed and distributed by the Japanese Standards Association for demonstrating the principles of statistical quality control. In the discussion that follows the data in Table 1.1 will be used to demonstrate some of the phenomena of variability that are encountered in engineering data without resort to the mathematics of probability theory. It is hoped this will help the reader to understand the relevance of statistical methods to be described later.

Table 1.1 Dice scores

R	Y	B	$R+Y+B$	Mean	Range	$R \times Y$
0	6	5	11			0
0	8	9	17			0
4	6	5	15	13.8	6	24
7	0	6	13			0
9	4	0	13			36
1	9	4	14			9
7	0	3	10			0
7	3	6	16	12.2	9	21
2	4	1	7			8
1	9	4	14			9

Continued for one hundred trials

One hundred trials were conducted, but only the first ten are recorded in the table.

Readers who are not convinced that the trials are properly reported are at liberty to conduct their own time-consuming experiments. Also recorded in the table are the sums $R + Y + B$, and the products $R \times Y$, along with the *mean* and the *range* of groups of five. In statistical terms, the mean of a set of data is the sum of the individuals divided by the number of individuals. The range is the difference between the largest and smallest individuals.

The *frequency distributions* are as follows;

R, Y and B	*Frequency*	$R + Y + B$	*Frequency*
0	30	0, 1	0
1	38	2, 3	1
2	20	4, 5	2
3	38	6, 7	7
4	29	8, 9	12
5	31	10, 11	15
6	29	12, 13	24
7	32	14, 15	17
8	21	16, 17	4
9	32	18, 19	9
		20, 21	5
		22, 23	3
		24, 25	1
		26, 27	0

These can be represented graphically in Figures 1.1 and 1.2.

In a perfect world one might expect Figure 1.1 to display 30 scores in each of the 10 categories 0–9, but the bar chart (or *histogram*, to use a statistical term) shows some degree of irregularity. If bias was suspected it would be necessary to run a much more extensive series of trials to show whether the dice were loaded in favour of scores 1 and 3 at the expense of scores 2 and 8. In the absence of such evidence it can be assumed that the scoring conforms to a rectangular distribution and that the irregularity is no more than is commonly encountered in real life collections of data.

In sharp contrast, the bar chart for the sum of the three colours (Figure 1.2) shows an entirely different pattern of distribution. There is a marked central tendency around a mean score of 13.5 which is easy to explain. All possible combinations of scores on the three dice are equally likely. There are many