

AN INTRODUCTION TO THE BASICS OF RELIABILITY AND RISK ANALYSIS

SERIES ON QUALITY, RELIABILITY AND ENGINEERING STATISTICS

Series Editors: M. Xie (National University of Singapore)
T. Bendell (Nottingham Polytechnic)
A. P. Basu (University of Missouri)

Published

- Vol. 1: Software Reliability Modelling
M. Xie
- Vol. 2: Recent Advances in Reliability and Quality Engineering
H. Pham
- Vol. 3: Contributions to Hardware and Software Reliability
P. K. Kapur, R. B. Garg and S. Kumar
- Vol. 4: Frontiers in Reliability
A. P. Basu, S. K. Basu and S. Mukhopadhyay
- Vol. 5: System and Bayesian Reliability
Y. Hayakawa, T. Irony and M. Xie
- Vol. 6: Multi-State System Reliability
Assessment, Optimization and Applications
A. Lisnianski and G. Levitin
- Vol. 7: Mathematical and Statistical Methods in Reliability
B. H. Lindqvist and K. A. Doksum
- Vol. 8: Response Modeling Methodology: Empirical Modeling for Engineering
and Science
H. Shore
- Vol. 9: Reliability Modeling, Analysis and Optimization
H. Pham
- Vol. 10: Modern Statistical and Mathematical Methods in Reliability
A. Wilson, S. Keller-McNulty, Y. Armijo and N. Limnios
- Vol. 11: Life-Time Data: Statistical Models and Methods
J. V. Deshpande and S. G. Purohit
- Vol. 12: Encyclopedia and Handbook of Process Capability Indices:
A Comprehensive Exposition of Quality Control Measures
W. L. Pearn and S. Kotz

Series in Quality, Reliability and Engineering Statistics **Vol. 13**

AN INTRODUCTION TO THE BASICS OF RELIABILITY AND RISK ANALYSIS

Enrico Zio

Polytechnic of Milan, Italy

 **World Scientific**

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Published by

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data

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

Series on Quality, Reliability and Engineering Statistics — Vol. 13

AN INTRODUCTION TO THE BASICS OF RELIABILITY AND RISK ANALYSIS

Copyright © 2007 by World Scientific Publishing Co. Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN-13 978-981-270-639-3

ISBN-10 981-270-639-9

Printed in Singapore by World Scientific Printers (S) Pte Ltd

To my life team members: Giorgia, Aurora, Cecilia and Matteo
To my work team members: my students and collaborators

Milano, 21 December 2006

This page intentionally left blank

About the Book

This book introduces the principal concepts and issues related to the safety of modern industrial activities and presents the classical techniques for reliability analysis and risk assessment used in the current practice. It is aimed at providing an organic view of the subject.

The contents of the book comprise: *i*) a basic illustration of some methods of system analysis commonly used in practice for the identification of the hazards associated to industrial plants and processes; *ii*) a review of the basics of probability theory, tailored to its application to reliability analysis and risk assessment; *iii*) an overview of the basics of reliability, availability and maintainability applied to standard system configurations, such as series, parallel, stand-by and others; *iv*) a presentation of the fault tree and event tree analysis methods, which constitute powerful tools widely used in practice for the reliability and risk assessment of complex systems; *v*) a review of the statistical methods for the estimation of failure rates; *vi*) a sketch of some modelling techniques of reliability growth and prediction.

The book can serve as any senior undergraduate or post-graduate university course on the subject or as reference for the initiation of young researchers to the field. In this view, several numerical examples are provided when appropriate, as guide for the comprehension.

About the Author

Enrico Zio (BS in nuclear engineering., Politecnico di Milano, 1991; MSc in mechanical engineering., UCLA, 1995; PhD, in nuclear engineering., Politecnico di Milano, 1995; PhD, in nuclear engineering., MIT, 1998) is a full professor of Nuclear Engineering and Dean of the Graduate School of the Politecnico di Milano, Italy. He holds a course on *Computational methods for safety and risk analysis* at the Politecnico di Milano and has served as lecturer at various Master and PhD programs in Italy and abroad.

He has served as Vice-Chairman of the European Safety and Reliability Association, ESRA and as Editor-in-Chief of the International journal Risk, Decision and Policy. He is member of the editorial boards of two recognized international scientific journals and has been involved in the organization of various international conferences, in the field of Safety and Reliability.

His research interests are: analysis of the reliability, safety and security of complex systems under stationary and dynamic operation, particularly by Monte Carlo simulation methods and cellular automata; development of soft computing techniques (neural networks, fuzzy logic, genetic algorithms) for safety and reliability applications, system monitoring, fault diagnosis and optimal design. He is co-author of one international book on Monte Carlo simulation applied to reliability and risk analysis and of more than 100 papers on international journals.

This page intentionally left blank

Contents

1. Introduction.....	1
2. Basic concepts of safety and risk analysis	3
2.1 A qualitative definition of risk.....	3
2.2 A quantitative definition of risk.....	4
2.3 Risk analysis.....	6
3. Methods for hazard identification	11
3.1 Hierarchical	12
3.2 Systematic identification of release points (SIRP)	13
3.3 Failure mode and effect analysis (FMEA).....	14
3.4 Hazard and operability analysis (HAZOP).....	19
4. Basics of probability theory for applications to reliability and risk analysis.....	21
4.1 Definitions	21
4.2 Boolean logic operations	22
4.3 Logic of uncertainty: definition of probability	27
4.3.1 Axiomatic Definition	27
4.3.2 Empirical Frequentist Definition.....	28
4.3.3 Classical Definition.....	29
4.3.4 Probability space	30
4.4 Probability laws	31
4.4.1 Union of non-mutually exclusive events.....	31
4.4.2 Conditional Probability	33
4.4.3 Theorem of Total Probability.....	35
4.4.4 Bayes Theorem	37

4.5 Random variables	39
4.5.1 Probability functions	40
4.5.2 Summary measures: percentiles, median, mean, variance	41
4.5.3 The hazard function	49
4.6 Probability distributions	51
4.6.1 Univariate discrete distributions	51
4.6.2 Univariate continuous distributions	55
4.7 Regression and correlation analyses	65
4.7.1 Regression with constant variance	65
4.7.2 Regression with non-constant variance	68
4.7.3 Multiple linear regression	69
4.7.4 Non Linear Regression	71
4.7.5 Correlation Analysis	71
5. Reliability of simple systems	77
5.1 Simple system configurations	77
5.2 Series system	78
5.3 Parallel system	79
5.4 r-out-of-N systems	80
5.5 Standby systems	81
5.5.1 Cold Standby	82
5.5.2 Hot Standby	85
6. Availability and maintainability	89
6.1 Introduction	89
6.2 Availability definition	89
6.3 Contributions to unavailability	91
6.4 The availability of an unattended component (no repairs)	92
6.5 The availability of a continuously monitored component	92
6.6 The availability of a component under periodic test and maintenance	97

6.6.1 Single component under periodic maintenance: a more realistic case.....	100
6.7 Maintainability	104
6.8 A policy of preventive and corrective maintenance	106
6.9 A policy of preventive replacement with economical optimization	110
7. Fault tree analysis.....	115
7.1 Introduction	115
7.2 Fault tree construction	116
7.3 Qualitative analysis: coherent structure functions and minimal cut sets	128
7.3.1 Structure functions	128
7.3.2 Coherent structure functions and minimal cut sets	131
7.4 Quantitative analysis.....	132
7.5 Comments.....	135
8. Event tree analysis	137
8.1 Introduction	137
8.2 Event tree construction	138
8.3 Event tree evaluation	141
9. Estimation of reliability parameters from experimental data.....	147
9.1 Estimation of equipment reliability from tests	147
9.1.1 Complete data set.....	147
9.1.2 Censored data sets.....	148
9.1.3 Test plans	149
9.1.4 The method of maximum likelihood applied to test components lifetimes.....	151
9.1.5 Statistics of exponential components with or without replacement.....	152
9.1.6 Confidence limits for reliability parameters	157
9.2 Accelerated Life Testing	167

9.2.1 Introduction	167
9.2.2 Experimental designs for ALT	168
9.2.3 Parametric models used in step-stress accelerated tests	171
9.2.4 Exponential distribution under design I	172
9.2.5 Inverse gaussian fatigue failure time distribution under design III.....	176
9.3 Empirical determination of distribution models	179
9.3.1 Probability paper	179
9.3.2 The normal probability paper	180
9.3.3 The log-normal probability paper	181
9.3.4 Construction of a probability plotting paper	182
9.3.5 Testing the validity of an assumed distribution	185
9.4 Kaplan-Meier estimator of the survivor function	189
9.5 Reliability growth	197
9.5.1 Maximum likelihood estimation	199
9.5.2 Least square estimation	200
9.6 Reliability prediction from stress-strength models	208
9.6.1 Introduction	208
9.6.2 Internal and external causes of stress	213
9.6.3 Physics of failures	214
9.6.4 Reliability from stress-strength distributions	215
Appendix A: Table of Standard Normal Cumulative Distribution	217
Appendix B: Table of Chi-Square Cumulative Distribution.....	222