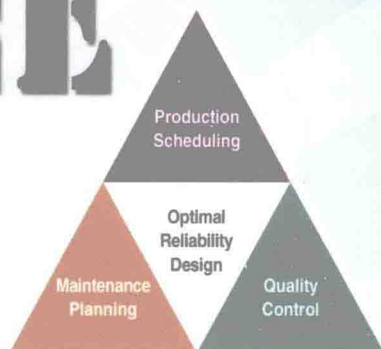


PERFORMABILITY ENGINEERING SERIES

Series Editors: Krishna B Misra and John Andrews

# MACHINE TOOL RELIABILITY



- Bhupesh K. Lad
- Divya Shrivastava
- Makarand S. Kulkarni

# **Machine Tool Reliability**

**Bhupesh K. Lad,  
Divya Shrivastava  
and  
Makarand S. Kulkarni**



**WILEY**

Copyright © 2016 by Scrivener Publishing LLC. All rights reserved.

Co-published by John Wiley & Sons, Inc. Hoboken, New Jersey, and Scrivener Publishing LLC, Salem, Massachusetts.

Published simultaneously in Canada.

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, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at [www.copyright.com](http://www.copyright.com). Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

**Limit of Liability/Disclaimer of Warranty:** While the publisher and authors have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at [www.wiley.com](http://www.wiley.com).

For more information about Scrivener products please visit [www.scrivenerpublishing.com](http://www.scrivenerpublishing.com).

Cover design by Russell Richardson

***Library of Congress Cataloging-in-Publication Data:***

ISBN 978-1-119-03860-3

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

# Machine Tool Reliability

**Scrivener Publishing**  
100 Cummings Center, Suite 541J  
Beverly, MA 01915-6106

**Performability Engineering Series**

Series Editors: Krishna B. Misra (kbmisra@gmail.com)  
and John Andrews (John.Andrews@nottingham.ac.uk)

**Scope:** A true performance of a product, or system, or service must be judged over the entire life cycle activities connected with design, manufacture, use and disposal in relation to the economics of maximization of dependability, and minimizing its impact on the environment. The concept of performability allows us to take a holistic assessment of performance and provides an aggregate attribute that reflects an entire engineering effort of a product, system, or service designer in achieving dependability and sustainability. Performance should not just be indicative of achieving quality, reliability, maintainability and safety for a product, system, or service, but achieving sustainability as well. The conventional perspective of dependability ignores the environmental impact considerations that accompany the development of products, systems, and services. However, any industrial activity in creating a product, system, or service is always associated with certain environmental impacts that follow at each phase of development. These considerations have become all the more necessary in the 21st century as the world resources continue to become scarce and the cost of materials and energy keep rising. It is not difficult to visualize that by employing the strategy of dematerialization, minimum energy and minimum waste, while maximizing the yield and developing economically viable and safe processes (clean production and clean technologies), we will create minimal adverse effect on the environment during production and disposal at the end of the life. This is basically the goal of performability engineering.

It may be observed that the above-mentioned performance attributes are interrelated and should not be considered in isolation for optimization of performance. Each book in the series should endeavor to include most, if not all, of the attributes of this web of interrelationship and have the objective to help create optimal and sustainable products, systems, and services.

*Publishers at Scrivener*

Martin Scrivener (martin@scrivenerpublishing.com)  
Phillip Carmical (pcarmical@scrivenerpublishing.com)

## Preface

---

Reliability engineering as a subject matter is developed vastly in last few decades. Numerous books have been published on the subject, discussing basic principles, theories, models, tools and techniques, in general. However, every system is unique and some of them may require specific treatment while applying various tools and techniques of reliability engineering. This book explores the domain of reliability engineering for one such very important industrial system, called machine tools.

Machine tools are at the heart of the manufacturing systems. Manufacturing industries rely on machine tools to fulfil their customers' demand. Failure of machine tool hampers their production efficiency and creates uncertainties in managing the shop floor operations resulting into significant economic losses. Moreover, the users of such systems are now sharing the risk of failures with the machine tool manufacturers by engaging into long term maintenance or availability contracts. This has created new business avenue for machine tool manufacturers for "Servicizing" their traditionally product focused business. Machine tool manufacturers have the opportunity to package effective life cycle maintenance services with the hardware products, i.e. machine tools. It is therefore important for machine tool manufactures as well as users to focus on core of reliability engineering to model machine tool's failure/repair and its interaction with other measures of system performances.

This advanced text on machine tool reliability modelling aims to provide a consolidated volume on various dimensions of machine tool reliability and its implications from manufacturers and users point of view. From manufacturers point of view novel methodologies for reliability and maintenance based design of machine tools are covered. From users point of view novel methodologies are presented to integrate reliability and maintenance of machine tools with production scheduling and quality control. Application area, i.e. machine tools is very important and it covers entire manufacturing sector.

The target audience of the book are researchers and practicing engineers in the field of reliability engineering and operations management. The

book can also be helpful to undergraduate students in the area of reliability to get an application flavour of the subject. It opens up various research dimensions for researchers. All the approaches are illustrated with the help of numerical examples. This makes the approaches easy to understand.

This book does not intend to provide coverage to basic of reliability engineering. It is expected here that the readers have some basic knowledge of the reliability engineering, probability and statistics. However, Chapter 2 is provided for the reader to refresh their basic of probability and statistics required to follow the text.

## **Acknowledgements**

Authors would like to acknowledge the help received from Dr. Avinash Samvedi and Mr. Vikas Sankhla in writing some of the codes used in this book. We also acknowledge the help of Mr. Sandeep Kumar who helped in editing the references.

# Contents

<b>Preface</b>	<b>xi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Basic Reliability Terms and Concepts	2
1.2 Machine Tool Failure	6
1.3 Machine Tool Reliability: Manufacturers' View Point	7
1.4 Machine Tool Reliability: Users' View Point	11
1.5 Organization of the Book	12
<b>2 Basic Reliability Mathematics</b>	<b>17</b>
2.1 Functions Describing Lifetime as a Random Variable	17
2.2 Probability Distributions Used in Reliability Engineering	21
2.2.1 Exponential Distribution	21
2.2.2 Weibull Distribution	22
2.2.3 Normal Distribution	23
2.2.4 The Lognormal Distribution	23
2.3 Life Data Analysis	24
2.3.1 Empirical Methods	27
2.3.2 Unbiased Estimation of Parameters	28
2.4 Stochastic Models for Repairable Systems	28
2.5 Simulation Approach for Reliability Engineering	31
2.6 Use of Bayesian Methods in Reliability Engineering	32
2.7 Closing Remarks	33
<b>3 Machine Tool Performance Measures</b>	<b>35</b>
3.1 Identifying Performance Measures	36
3.2 Mechanism to Link Users' Operational Measures with Machine Reliability and Maintenance Parameters	41
3.2.1 Availability Model	42
3.2.2 Performance Rate Model	45
3.2.3 Quality Rate Model	46



3.2.4	Overall Equipment Effectiveness Model	48
3.2.5	Life Cycle Cost (LCC) Model	49
3.2.6	Cost Per Piece (CPP) Model	51
3.3	Closing Remarks	53
<b>4</b>	<b>Expert Judgement Based Parameter Estimation Method for Machine Tool Reliability Analysis</b>	<b>55</b>
4.1	Expert Judgement as an Alternative Source of Data in Reliability Studies	57
4.2	Expert Judgement Based Parameter Estimation Methods	58
4.2.1	Non-Repairable Component	59
4.2.2	Repairable Assembly	74
4.3	Some Desirable Properties of A “Good” Estimator	79
4.4	Closing Remarks	80
<b>5</b>	<b>Machine Tool Maintenance Scenarios, Models and Optimization</b>	<b>81</b>
5.1	Overview of Maintenance	82
5.1.1	Maintenance Models	84
5.1.2	Maintenance Optimization Techniques	86
5.2	Machine Tool Maintenance	87
5.3	Machine Tool Maintenance Scenarios	89
5.4	Preventive Maintenance Optimization Models for Different Maintenance Scenarios	91
5.4.1	Preventive Maintenance Optimization in Maintenance Scenario 1 (MSc 1) (Replacement model)	93
5.4.2	Preventive Maintenance Optimization in Maintenance Scenario 2 (MSc 2) (Repair-Replacement Model)	99
5.4.3	Preventive Maintenance Optimization in Maintenance Scenario 3 (MSc 3) (Overhauling Model)	104
5.5	Closing Remarks	110
<b>6</b>	<b>Reliability and Maintenance Based Design of Machine Tools</b>	<b>113</b>
6.1	Optimal Reliability Design	115
6.2	Optimal reliability design of machine tools	122
6.2.1	Machine Tool Functional Design	126
6.2.1.1	Special Purpose Machine Tool Design	126
6.2.1.2	General Purpose Machine Tool Design	126
6.2.1.3	Customized Machine Tool Design	126

6.2.2	Simultaneous Optimization of Reliability and Maintenance Under Three Functional Design Scenarios	127
6.2.2.1	Simultaneous Optimization for Special Purpose Machine Tool	127
6.2.2.2	Simultaneous Optimization for General Purpose Machine Tool Design Scenario	133
6.2.2.3	Simultaneous Optimization for Customized Machine Tool Design	137
6.3	Failure Mode and Effects Analysis	139
6.3.1	Cost Based FMEA Approach	145
6.4	Closing Remarks	155
<b>7</b>	<b>Machine Tool Maintenance and Process Quality Control</b>	<b>157</b>
7.1	Development of Statistical Process Control (SPC)	158
7.2	Economic Design of Control Chart	159
7.3	Process failure	165
7.4	Joint Optimization of Maintenance Planning and Quality Control Policy	166
7.4.1	Problem Description	169
7.4.2	Assumptions and Conditions	171
7.4.3	Integration Approaches	172
7.5	Joint Optimization of Maintenance Planning and Quality Control Policy Using $\bar{X}$ -Control Chart	172
7.5.1	Expected Cost Model for Corrective Maintenance due to $FC_1$	174
7.5.2	Expected Cost Per Preventive Maintenance for a System	176
7.5.3	Determination of the Expected Cost Associated with the Process Quality Control	177
7.5.3.1	Expected Process Cycle Length	178
7.5.3.2	Expected Process Quality Control Cost ( $E[C_{\text{process}} - \text{failure}]$ ) Model	182
7.5.4	Numerical Illustration	185
7.5.4.1	Sensitivity Analysis	186
7.5.5	Comparative Study of Integrated Model with Stand-alone Models	190
7.5.5.1	Maintenance Models	190
7.5.5.2	Statistical Process Control (SPC) Model	191
7.5.5.3	Comparison of Results	191

7.6	Joint Optimization of Preventive Maintenance and Quality Policy Incorporating Taguchi Quadratic Loss Function	192
7.6.1	Optimization Model	193
7.6.2	Numerical Example	196
7.6.2.1	Sensitivity Analysis	198
7.7	Joint Optimization of Preventive Maintenance and Quality Policy based on Taguchi Quadratic Loss Function Using CUSUM Control Chart	200
7.7.1	Optimization Model	201
7.7.2	Numerical Example	203
7.8	Extension of the Joint Optimization of Maintenance Planning and Quality Control Policy for Multi-component System	207
7.8.1	Problem Description	207
7.8.2	Joint Optimization of Maintenance Planning and Quality Control Policy Using Taguchi Loss Function Approach for a Multi-component System	208
7.8.3	Expected Cost Model for Corrective Maintenance due to $FC_1$ for Multicomponent	209
7.8.4	Expected Cost per Preventive Maintenance for Multi-component System	209
7.8.5	Expected Cost Model for Quality Loss due to Process Failure ( $E[TCQ]_{process-failure}^{M-C}$ )	210
7.8.6	Numerical Example	214
7.9	Closing Remarks	216
8	<b>Joint Optimization of Integrated Maintenance Scheduling and Quality Control Policy with Production Scheduling</b>	<b>219</b>
8.1	Production Scheduling	220
8.2	Exploring the Link Between Production Scheduling and Maintenance	226
8.3	The Optimal Scheduling Problem	231
8.3.1	Expression for Expected Penalty Cost Incurred due to Batch Schedule Tardiness	232
8.3.2	Expression for Inventory Carrying Cost of Raw Material	233
8.3.3	Optimization Problem for Batch Scheduling	234

8.4	Joint Optimization of Preventive Maintenance and Quality Control Policy	235
8.5	Integration of Production Scheduling with Jointly Optimized Preventive Maintenance and Quality Control Policy	235
8.5.1	Expression for Expected Penalty Cost Incurred due to Batch and Maintenance Delay	236
8.5.2	Expression for Inventory Carrying Cost of Raw Material for an Integrated Model	240
8.5.3	Joint Optimization of Preventive Maintenance and Quality Control Policy with Production Scheduling	241
8.6	Numerical Illustration	242
8.6.1	Solution Procedure for the Integrated Problem	244
8.7	Solving Larger Problem	247
8.7.1	The Backward Forward Heuristic Algorithm	247
8.7.2	Genetic Algorithm	252
8.7.3	Numerical Illustration for Integrated Model for Large Number of Batches	252
8.8	Extension of the Integrated Approach Multiple Machine in Series	257
8.9	Closing Remarks	263
<b>9</b>	<b>Machine Tool Reliability: Future Research Directions</b>	<b>267</b>
9.1	Moving towards Servitization	268
9.2	Multi Agent-Based Systems	271
9.3	Closing Remarks	274
	<b>References</b>	<b>277</b>
	<b>Appendices</b>	
	Appendix A1: Java Code for Estimating Expected Number of Failures	297
	Appendix A2: 'MATLAB' Genetic Algorithm Code for Joint Optimization of Production Scheduling and Maintenance Planning	303
	<b>Index</b>	<b>309</b>

# 1

## Introduction

Reduced cost of production, timely delivery and high quality of products are the prime objectives for manufacturing industries. Breakdowns of production machinery or machine tools affect the manufacturer's ability to meet the goals of Cost, Time and Quality (CTQ). One of the studies suggests that the economic loss due to an unexpected stoppage in industry can be as high as US \$70,000 to US \$420,000 per day [1]. Application of reliability engineering tools and techniques to machine tools for improving the manufacturing system performance is therefore a vital area of study.

The machine tool industry is one of the supporting pillars for the competitiveness of the entire manufacturing sector since it produces capital goods which in turn may produce manufactured goods. Customers of machine tool manufacturers (termed as "users" in this book) are, in many cases, vendors to other customers and have commitments to meet. Breakdowns of machine tools may jeopardize their ability to meet these commitments and also cost a lot of money to the users in terms of poor quality, slower production, downtime, etc. Since poor reliability and improper maintenance of a machine tool greatly increase the life

cycle cost to the users, many machine tool users have changed their purchase criteria for a machine tool from initial acquisition cost to Life Cycle Cost (LCC) or Total Cost of Ownership (TCO).

As reliability engineering plays an important role in reducing the LCC of machine tools, this book will be equally appealing to machine tool manufacturers and users.

The book covers both the manufacturer's and user's viewpoint of machine tool reliability. Decisions made during the design phase of a product have the largest impact on the life cycle cost of a system. The inherent failure and repair characteristics of components and assemblies are frozen with the selection of the machine tool configuration at the design stage. Therefore, the maintenance requirements of the machine tools are also fixed at the design stage itself. For example, a higher reliability component may require a lower replacement frequency for the same operating profile compared to a lower reliability component. Therefore, machine tool manufacturers need to consider the reliability and maintenance aspects at the design stage itself. On the other hand, the cost effectiveness of machine tools at the user's end also depends on the shop-floor level operations planning decisions, i.e., scheduling, inventory, quality control, etc. These shop-floor level operations planning decisions have interaction effect with machine tool reliability and maintenance. Therefore, machine tool users need to consider the reliability and maintenance aspects during operations planning. The goal of this book is to provide a consolidated volume on various dimensions of machine tool reliability and its implications from the manufacturer's and user's point of view.

The introductory chapter of the book describes basic reliability terms and defines machine tool failures. The importance of machine tool reliability from the manufacturers' and users' point of view is also discussed.

## 1.1 Basic Reliability Terms and Concepts

This section introduces important reliability terms and concepts which will help the reader in following the rest of the sections of the book.

*Reliability:* This is the probability that an item can perform its intended function for a specified interval under stated conditions [2].

In other words, it is the probability of survival over time. To determine the reliability of a particular component or system, an

unambiguous and observable description of failure is essential. The machine tool failures are defined in the next section.

If  $T$  is a random variable, representing time to failure of the system or component, then reliability can be expressed as:

$$R(t) = \Pr\{T \geq t\} \quad (1.1)$$

It is contextual here to clearly differentiate the term “quality” and “reliability.” If quality is the conformance to the specifications at  $t = 0$ , then reliability can be considered as conformance to the specifications at  $t > 0$ . However, in this book, “reliability” is used in the context of the machine tools, while “quality” is used in the context of the products produced using machine tools.

*Failure Rate (Hazard Rate):* Failure rate or hazard rate is the instantaneous (at time  $t$ ) rate of failure [3]. It is the instantaneous failure rate. This index is normally used for non-repairable components. A component of the system may have increasing, decreasing, or constant failure rate. It is further discussed in Chapter 2.

*Rate of Occurrence of Failure (ROCOF):* This index is often used in place of hazard rate for repairable system. Failures occur as a given system ages and the system is repaired to a state that may be the same as new, or better, or worse. Let  $N(t)$  be a counting function that keeps track of the cumulative number of failures a given system has had from time zero to time  $t$ .  $N(t)$  is a step function that jumps up one every time a failure occurs and stays at the new level until the next failure. The ROCOF is the total number of failures within an item population, divided by the total number of life units expended by that population during a particular measurement period under stated conditions [2].

Every system will have its own observed  $N(t)$  function over time. If we observed the  $N(t)$  curves for a large number of similar systems and “averaged” these curves, we would have an estimate of  $M(t) =$  the expected number (average number) of cumulative failures by time  $t$  for these systems.

*Maintenance:* All actions necessary for retaining an item in or restoring it to a specified condition [2].

*Corrective Maintenance (CM):* All actions performed as a result of failure, to restore an item to a specified condition [2]. Corrective maintenance can include any or all of the following steps: localization, isolation, disassembly, interchange, reassembly, alignment and checkout.

*Preventive Maintenance (PM):* All actions performed to retain an item in a specified condition by providing systematic inspection, detection, and prevention of incipient failures [2].

*Predictive Maintenance:* Predictive maintenance or Condition Based Maintenance (CBM) is carried out only after collecting and evaluating enough physical data on performance or condition of equipment, such as temperature, vibration, particulate matter in oil, etc., by performing periodic or continuous (online) equipment monitoring [4].

*Maintainability:* It is the relative ease and economy of time and resources with which maintenance can be performed. More precisely, it is the probability that an item can be retained in, or restored to, a specified condition within a specified time when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair [2].

*Availability:* Depending on the purpose of analysis, a number of different definitions are used in the literature, some of which are given below [3]:

*Instantaneous or Point Availability,  $A(t)$ :* It is the probability that a system will be operational at any random time  $t$ . Unlike reliability, the instantaneous availability measure incorporates maintainability information.

*Average Availability:* It is the proportion of time a system is available for use during a mission. Mathematically, it is calculated as the mean value of the instantaneous availability function over the period  $(0, T)$ .

$$A(T) = \frac{1}{T} \int_0^T A(t) dt \quad (1.2)$$

*Steady State Availability:* The steady state availability of the system is the limit of the instantaneous availability function as the time approaches infinity.



$$A = \lim_{T \rightarrow \infty} A(T) \quad (1.3)$$

*Inherent Availability:* It is the steady state availability when considering only the corrective maintenance downtime of the system. It does not include delays due to unavailability of maintenance personnel, unavailability of spare parts, administrative procedures, etc. The inherent availability of a system is a function of the reliability of its components and maintainability, which more or less get defined at the design stage of the equipment.

$$A = \lim_{T \rightarrow \infty} A(T) = \frac{MTBF}{MTBF + MTTR} \quad (1.4)$$

where MTBF is the mean time between failures and MTTR is the mean time to repair.

*Operational Availability:* It is a measure of the average availability over a period of time, including all the delays due to unavailability of maintenance personnel, spare parts, administrative procedures, etc. Operational availability is the availability that the customer actually experiences.

$$A_o = \frac{MTBM}{MTBM + MTTR + SDT + MDT} \quad (1.5)$$

where MTBM is the mean time between maintenance, SDT and MDT are the supply and maintenance delays respectively.

Inherent availability and operational availability are used in this book and are discussed further in Chapter 3.

*Life Cycle Cost (LCC):* It is the sum of acquisition, logistics support, operating, and retirement and phase-out expenses [2].