

Preface

The concepts behind the design and operation of engineered systems have evolved significantly over the last decades. Engineering design has historically been conceived as an optimization problem consisting of selecting the physical characteristics of a system¹ that satisfy predefined functional requirements at minimum cost. The cost-based optimization approach, fundamentally deterministic in nature, has at the same time recognized that the performance of the system is uncertain and potentially hazardous. During the nineteenth century and the beginning of the twentieth century, safety factors were used implicitly or explicitly to cover design, construction, and operational uncertainties. For example, [1] reports that in the nineteenth century in the UK the average ultimate tensile strength for cast iron beam designs was computed using safety factors between 4 and 5 [1]; similar safety factors were typically used for other type of structures as well. These large safety factors became smaller with time as there was better knowledge of the materials and the mechanical performance of engineering devices; and also as the need to reduce costs became more important. By the mid twentieth century, probability theory began to play an important role in the characterization and management of uncertainties and probabilistic techniques began to augment safety factors in the assessment of engineering safety. The concept of component and system reliability was introduced in industrial manufacturing and later in buildings and civil infrastructure in the form of distributional estimates and risk assessment (e.g., load and resistance partial factors).

As the balance between cost and safety has become more important, industry recognizes that design and construction, based on a deterministic cost minimization objective under certain reliability constraints, lead to suboptimal solutions and higher capital expenditure in the long run. This realization creates an increasing awareness of the importance of future investments (i.e., inspection, maintenance, and repair) for project cost evaluation and brings attention to the assessment of all the uncertainties associated with the lifetime operation; specially, in the case of

¹The term *system* is used generically to describe any engineered artifact or device.

long-lasting projects. This also reinforces the significance of using stochastic processes in engineering design and life-cycle analysis. This new understanding of design and operation of large infrastructure projects opens many new research questions and challenges. This book is intended as a contribution to this important discussion.

A new engineering project management paradigm, where projects are evaluated throughout their lifetime, requires, in addition to the mechanical models, the integration of complex probabilistic tools and operational decisions (e.g., policy to carry out preventive maintenance). Under the assumption that people act rationally, the objective of this book is to present and examine the tools of modern stochastic processes to provide appropriate models to characterize the system's performance over time so that engineers and planners have better evidence to inform their decisions. It should be clear to engineers that mathematical models are only tools that provide input to decision-making. Model-based evidence is not necessarily the most valuable or the most relevant for the overall decision, but we contend that it is essential when it comes to characterizing the system's performance measures in an uncertain operating environment.

This book compiles and critically examines modern degradation models for engineered systems and their use in supporting life-cycle engineering decisions. In particular, we focus on modeling the uncertain nature of degradation, considering both conceptual discussions and formal mathematical formulations. The book also presents the basic concepts and modeling aspects of life-cycle analysis (LCA). Special attention is given to the role of degradation in LCA and in optimal design and operational analysis. Given the relationship between operating decisions and the performance of the systems condition over time, part of the book is also concerned with maintenance models.

The book is organized into ten chapters and one appendix. Chapters have been arranged to take the reader from the basic concepts up through more complex and multidisciplinary aspects. The book is intended for readers with basic knowledge of the fundamentals of probability. However, we have included a brief introduction to the concepts and terminology of probability theory in the appendix and some details on various stochastic process models in the chapters themselves. We do not intend this book to be a monograph on applied probability or stochastic processes, but rather a book on modeling degradation to support decision-making in engineering. The book chapters are organized in four main parts; (see Fig. 1):

1. Conceptual and theoretical basis (Chaps. 1–3).
2. Degradation models (Chaps. 4–7).
3. Life-cycle analysis and optimization (Chaps. 8–9).
4. Maintenance models (Chap. 10).

In the first part of the book, we discuss conceptual aspects that are essential for making predictions and to provide information to decision makers (Chap. 1). Furthermore, we provide an overview of the concepts of risk and reliability and present various approaches used in engineering practice to estimate reliability (Chap. 2). In Chap. 3 we describe, both conceptually and in formal mathematical

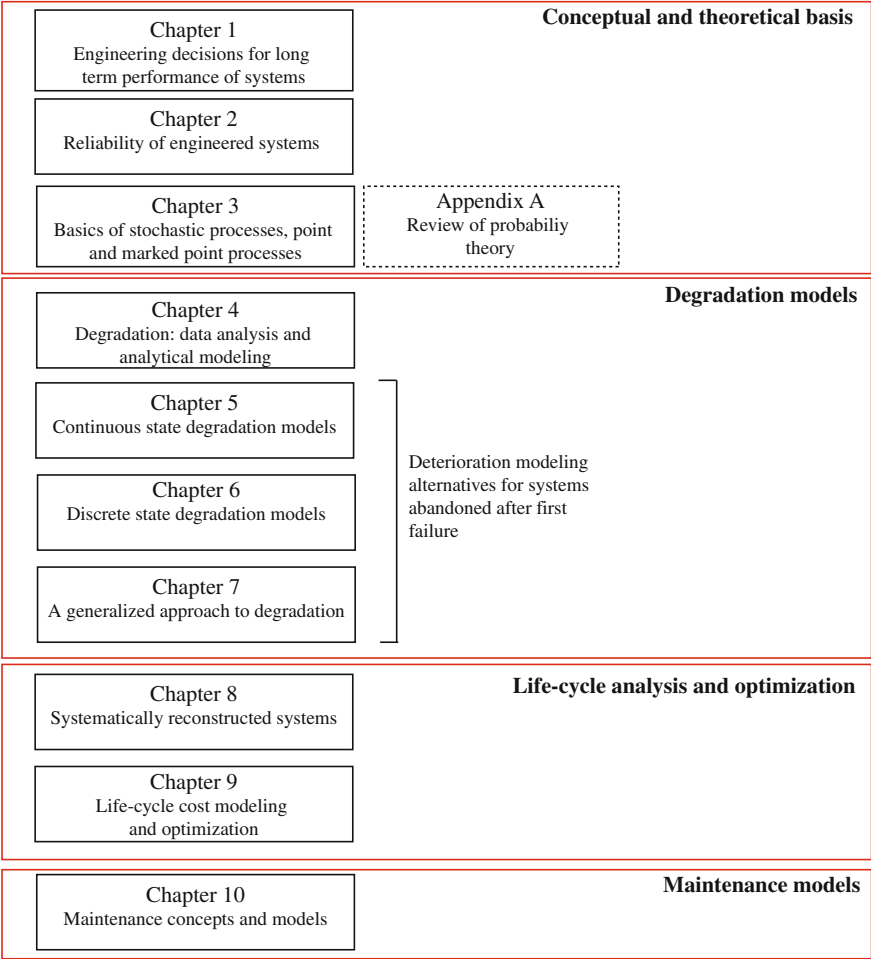


Fig. 1 Book organization

terms, important aspects of selected stochastic process as a tool for prediction; and emphasize the underlying assumptions to provide some context as to when these particular models are relevant or useful. These results will be used in the models developed for degradation in subsequent chapters.

Predicting the performance of engineered systems involves characterizing changes in the system state as it evolves over time; in particular, this includes how system performance degrades over time, which is the main topic of this book. Then, the second part of the book, Chaps. 4–7, deals with degradation models. Chapter 4 discusses the foundations of degradation from a conceptual and theoretical point of view. In this chapter we also review briefly the problem of obtaining and analyzing degradation data, while in Chaps. 5–7 we are concerned with modeling degradation

mechanisms for systems that are not maintained and are abandoned after failure. In particular we distinguish between continuous and discrete space state degradation models. In Chap. 7, we present a general approach to degradation based on the Lévy process, which is a flexible approach to accommodate most models presented in previous chapters. The models presented in these chapters are illustrated with cases that are of interest in engineering applications.

With the background on degradation models presented in Chaps. 2 through 7, in the third part of the book, i.e., Chaps. 8 and 9, we present the conceptual and theoretical bases behind life-cycle analysis (LCA). First, as a preamble, in Chap. 8 we describe the performance of systems that are successively intervened or reconstructed. By doing this we include in the analysis the concept of system interventions (e.g., maintenance and repair), which clearly modify both the system's performance and the future investments. Afterwards, in Chap. 9, both LCA and life-cycle cost analysis (LCCA) are introduced. In particular we focus on LCCA as a project evaluation techniques conceived to study the performance (and the associated costs) of an engineered system within a given time-window. They are used to estimate system availability and maintenance needs in order to make better investment and operational decisions. Life-cycle analyses can also be used as a stochastic optimization technique to determine the design parameters and maintenance strategy that maximize the benefit derived from the existence of the system. The value of LCCA is that they are able to integrate the mechanical performance with the financial and economic considerations within a framework of uncertainty.

Finally, in the last part of the book, Chap. 10, we address the task of defining optimum intervention strategies; in other words, defining maintenance programs that maximize the profit derived from the existence of the project while ensuring its safety and availability. Maintenance activities are understood to include all physical activities intended to increase the useful life of the system. These activities may be initiated because the system is observed to be in a particular system state, e.g., failure state (e.g., corrective maintenance), or they may be initiated before such a fault is observed (e.g., preventive maintenance). After a conceptual discussion about some key aspects of maintenance, we address traditional maintenance models. Finally, towards the end of the chapter, we study the case of maintenance of systems that exhibit nonself announcing failures, as well as systems that are continuously monitored.

The book is intended to be used by educators, researchers, and practitioners interested in topics related to risk and reliability, infrastructure performance modeling, and life-cycle assessment. The concepts and models presented have applications in a large variety of engineering fields such as civil, environmental, industrial, electrical, and mechanical engineering. However, special emphasis is given to problems related to managing large infrastructure systems.

More specifically, this book is aimed at two main audiences. First, it can be used as reference for research in topics involving degradation of a variety of large, complex engineered systems. Some examples include civil infrastructure, such as bridges, buildings, water distribution systems, sewage systems, pipelines, ports and offshore structures, and so forth. Other examples include complex consumer

products, such as automobiles, and large-scale commercial undertakings, such as aircraft, ships, and power generation and distribution systems.

The second use of the book is as a guide for a graduate course on infrastructure modeling and management. In this regard, the book compiles and explains, both conceptually and formally, key aspects for modeling the stochastic nature of degradation. In this regard, we view the book as a major contribution to the field, since many courses in design and operation of civil infrastructure focus exclusively on management aspects and do not do justice to the performance modeling and analysis of the problem.

July 2015

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Reference

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Reliability and Life-Cycle Analysis of Deteriorating
Systems

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2016, XXIV, 355 p. 106 illus., Hardcover

ISBN: 978-3-319-20945-6