SYSTEMS ENGINEERING AND ANALYSIS

FOURTH EDITION

Benjamin S. Blanchard

Wolter J. Fabrycky

PRENTICE HALL INTERNATIONAL SERIES IN
INDUSTRIAL AND SYSTEMS ENGINEERING
W. J. FABRYCKY and J. H. MIZE, editors

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This book is about *systems.* It concentrates on the *engineering* of human-made systems and on systems *analysis.* In the first case, emphasis is on the process of bringing systems into being, beginning with the identification of a need and extending through requirements determination, functional analysis and allocation, design synthesis and evaluation, validation, operation and support, and disposal. In the second case, focus is on the improvement of systems already in being. By employing the iterative process of analysis, evaluation, modification, and feedback most systems now in existence can be improved in their effectiveness, product quality, affordability, and stakeholder satisfaction.

Systems engineering may be defined and/or described as a technologically based interdisciplinary process for bringing systems, products, and structures (technical entities) into being. While the main focus is nominally on the entities themselves, systems engineering offers organizations a better strategy. Systems engineering is inherently oriented to considering "the end before the beginning" and concentrates on *what the entities do* before determining *what the entities are.*

Instead of offering systems or system elements and products per se, systems engineering focuses on designing, delivering, and sustaining *functionality, a capability,* or a *solution.* This strategic thinking is now being considered by forward-looking organizations in both the private and public sectors. It is applicable to most types of technical systems encompassing the domains of communication, defense, education, healthcare, manufacturing, transportation, and others. The advancement and promulgation of this emerging strategy through education is the primary aim of this textbook.

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Systems Engineering and Analysis

Fourth Edition

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Preface

This book is about *systems*. It concentrates on the *engineering* of human-made systems and on systems *analysis*. In the first case, emphasis is on the process of bringing systems into being, beginning with the identification of a need and extending through requirements determination, functional analysis and allocation, design synthesis and evaluation, validation, operation and support, and disposal. In the second case, focus is on the improvement of systems already in being. Systems analysis methods and techniques are embedded within the *systems engineering process,* which is the overarching theme for this book.

Systems may be classified as either *natural* or *human-made*. Natural systems came into existence by natural processes. Human-made, or technical systems, come into being by human intervention in the natural order utilizing pervasive technologies through system components, attributes, and relationships. The types and variety of technical systems are numerous and encompass the domains of communications, defense, education, healthcare, manufacturing, transportation, and others. Through the iterative steps of analysis, evaluation, modification, and feedback most systems in existence today can be improved in their effectiveness, product quality, affordability, and stakeholder satisfaction.

Human-made systems are the central focus in this book. The experience of recent decades indicates that a properly coordinated and functioning technical system, with a minimum of undesirable side effects, requires the application of an integrated life-cycle oriented "systems" approach. Accordingly, the main objective of this textbook is to provide engineers, systems analysts, and technical managers with the essential system thinking, concepts, methodologies, models, and tools needed to understand and apply *systems engineering* to many types of human-made systems.

The topics presented in this book are organized into 6 parts encompassing 19 chapters and 8 appendices. Part I provides an introduction to systems and systems engineering in the context of system science and good engineering practice for bringing systems into being. Part II presents the system design process characterized by a series of evolutionary steps, progressing from the identification of a need through conceptual design, preliminary design, detail design and development, and test and evaluation. Part III derives and explains many useful mathematical models and analytical tools for systems analysis. Emphasis is placed on the application of modeling and systems

analysis techniques as an integral part of the systems engineering process. Part IV addresses design for operational feasibility by examining those design characteristics found to be most significant for successful system operation and user satisfaction. Separate chapters are devoted to reliability, maintainability, usability (human factors), supportability (serviceability), producibility and disposability, and affordability (life-cycle costing). Part V provides an overview of systems engineering management, with planning and organization concentrated in one chapter and program management and control in another. Part VI contains a set of comprehensive appendices providing special topics, checklists, tables, and references.

This fourth edition retains the comprehensive topical coverage that was key to the success of earlier editions. Also, the overall organization of material has not changed. However, each of the 6 parts is now preceded by a high-level overview to establish the context for contained chapters. Each of the 19 chapters now begins with an expanded introduction. A summary and extensions section has been added to the end of each chapter for review purposes and as a guide for further study. Of special interest in this edition is the inclusion of 35 key web sites as well as a download source for some relevant courseware.

This textbook is intended for use in the classroom at either the advanced undergraduate or graduate level, or by the practicing professional in business, industry, or government. It has become a standard text for continuing education purposes and for personal reference. The book includes more than 300 illustrations and 450 problem exercises arranged in such a way as to guide the reader through the entire systems engineering process. The concepts and techniques presented are applicable to almost any type of system, and the topics discussed may be "tailored" for both large- and small-scale systems. Many of the examples and applications have been developed from industrial and research experience in systems engineering and analysis by these authors over four decades.

Six other Prentice Hall books by the authors provide background and some of the raw material from which this textbook was fashioned. These books cover the subject areas of applied operations research and management science, economic decision analysis, engineering economy, life-cycle cost and economic analysis, logistics engineering and management, and procurement and inventory systems analysis. But, more important to our teaching and authorship is the invaluable motivation, guidance, and critique generously provided by thousands of students and practicing professionals down through the years. We thank each and every individual who has encouraged our publishing endeavors, but acknowledge and accept full responsibility for the usefulness of the final products.

BENJAMIN S. BLANCHARD
WOLTER J. FABRYCKY

Contents

Part I

Introduction to Systems

Two coordinated chapters comprise Part I of this textbook. Systems science and engineering (Chapter 1) provides essential prerequisite material supporting an overview of the process of bringing human-made or technical systems into being (Chapter 2). These chapters introduce systems from both a scientific and an engineering perspective. Together they provide a conceptual foundation for the synthesis, analysis, and evaluation of engineered systems; engineered systems are the overarching theme of this book.

The closely related topics in Chapter 1 begin with fundamental system definitions and end with contemporary definitions of systems engineering. Between these important definition categories is a conceptual discussion of system elements, a high-level classification of systems, a summary of science and system science, a view of technology as the progenitor for technical systems, and insight regarding transition to the systems age. Basic requirements for successful engineering in the systems age are then addressed as a basis for introducing and defining systems engineering.

Chapter 2 begins with a definition and focus on human-made or engineered systems, as distinct from natural systems. Within this concept are the important symbiotic relationships between the product and the system, with special note of the desire for product competitiveness. System life-cycle engineering is then offered as a generic paradigm for bringing engineered systems into being. This paradigm is implemented by designing for the life cycle, all within the systems engineering process. For completeness, other popular systems engineering process models are also introduced. Regardless of the process model chosen, it is essential that design criteria be established and linked to design dependent parameters. Then, a unifying morphology for synthesis, analysis, and evaluation invoking integration and iteration brings order to the process of system realization. Finally, the importance of investing in systems engineering early in the life cycle is emphasized.

Part I of this textbook has the potential to stand alone as a learning module. It provides a high-level introduction to system science and engineering that might be suitable for presentation to engineering and technical managers. Subsequent chapters should be considered only after obtaining an understanding of the fundamentals herein, but study beyond the fundamentals is optional for those who need only an overview of systems engineering and its foundation in systems science.

Chapter 1

System Science and Engineering

Systems are as pervasive as the universe in which they exist. At one extreme, they are as grand as the universe itself. At the other, they are as infinitesimal as the atom. Systems appeared first in natural forms, but with the advent of human beings, a variety of human-made systems have come into existence. Only recently have we begun to understand the underlying structure and characteristics of natural and human-made systems in a scientific way.

In this first chapter, some system definitions and system science concepts are presented to provide a basis for the study of systems engineering and analysis. They include definitions of system characteristics, a classification of systems into various types, consideration of the current state of system science, and a discussion of the transition to the systems age. Finally, this chapter presents technology and the nature of engineering in the systems age, including a number of commonly accepted definitions of systems engineering.

Upon completion of Chapter 1, the reader will have obtained essential insight about systems and system thinking, with an orientation toward systems engineering and analysis. The system definitions, classifications, and concepts presented in this chapter are intended to impart a general understanding about:

- System classifications and a dichotomous contrast of system similarities and dissimilarities;
- The fundamental distinction between natural and human-made, or technical, systems;
- The elements of a system and the position of the system in the hierarchy of systems;
- The domain of system science, with consideration of cybernetics, general system theory, and systemology;