国外大学优秀教材——工业工程系列（影印版

Benjamin S. Blanchard
Wolter J. Fabrycky

系统工程与分析

（第3版）

SYSTEMS ENGINEERING AND ANALYSIS

THIRD EDITION

Benjamin S. Blanchard
Wolter J. Fabrycky

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

清华大学出版社
http://www.tup.tsinghua.edu.cn

Pearson Education

国外大学优秀教材——工业工程系列（影印版）

SYSTEMS ENGINEERING AND ANALYSIS

THIRD EDITION

系统工程与分析

(第3版)

BENJAMIN S. BLANCHARD

Virginia Polytechnic Institute and State University

WOLTER J. FABRYCKY

Virginia Polytechnic Institute and State University

清华大学出版社

（京）新登字 158 号

系统工程与分析（第 3 版）
Systems Engineering and Analysis, third edition.
EISBN: 0-13-135047-1

北京市版权局著作权合同登记号：图字：01-2002-3213

图书在版编目（CIP）数据

系统工程与分析：第 3 版 /（美）布兰查德，（美）法布里奇著. —影印本. —北京：清华大学出版社，2002

书名原文：Systems Engineering and Analysis

国外大学优秀教材. 工业工程系列

ISBN 7-302-05657-9

Ⅰ. 系… Ⅱ. ① 布… ② 法… Ⅲ. ① 系统工程—高等学校—教材—英文 ② 系统分析—高等学校—教材—英文 Ⅳ. N94

中国版本图书馆 CIP 数据核字（2002）第 049710 号

出 版 者： 清华大学出版社（北京清华大学学研大厦，邮编 100084）
http:// www.tup.tsinghua.edu.cn
责任编辑： 张秋玲
印 刷 者： 清华大学印刷厂
发 行 者： 新华书店总店北京发行所
开 本： 787×960 1/16 **印张：** 47
版 次： 2002 年 8 月第 1 版 2002 年 8 月第 1 次印刷
书 号： ISBN 7-302-05657-9/TB · 45
印 数： 0001～3000
定 价： 71.00 元

Forward

This textbook series is published at a very opportunity time when the discipline of industrial engineering is experiencing a phenomenal growth in China academia and with its increased interests in the utilization of the concepts, methods and tools of industrial engineering in the workplace. Effective utilization of these industrial engineering approaches in the workplace should result in increased productivity, quality of work, satisfaction and profitability to the cooperation.

The books in this series should be most suitable to junior and senior undergraduate students and first year graduate students, and to those in industry who need to solve problems on the design, operation and management of industrial systems.

Gavriel Salvendy

Department of Industrial Engineering, Tsinghua University

School of Industrial Engineering, Purdue University

April, 2002

前　言

本教材系列的出版正值中国学术界工业工程学科经历巨大发展、实际工作中对工业工程的概念、方法和工具的使用兴趣日渐浓厚之时。在实际工作中有效地应用工业工程的手段将无疑会提高生产率、工作质量、合作的满意度和效果。

该系列中的书籍对工业工程的本科生、研究生和工业界中需要解决工程系统设计、运作和管理诸方面问题的人士最为适用。

加弗瑞尔·沙尔文迪
清华大学工业工程系
普渡大学工业工程学院（美国）
2002 年 4 月

PREFACE

This book is about *systems*. It focuses on the *engineering* of systems and on systems *analysis*. In the first case, emphasis is on the process of bringing systems into being, beginning with the definition of need and extending through requirements analysis, functional analysis and allocation, design synthesis, design evaluation, and system validation. In the second case, concern is with the improvement of systems already in existence. Through the iterative steps of analysis, evaluation, feedback, modification and control, many systems in use today can be improved in their effectiveness, output quality, ownership cost, and user satisfaction. Systems analysis methods and techniques are integrated within the *systems engineering process*, which remains the overarching theme for this book.

Systems may be classified as either "natural" or "human-made." Natural systems are those which came into existence by natural processes. Human-made, or technical systems, are those where people have intervened in the natural order by applying pervasive technologies through system components, attributes, and relationships. The types and variety of human-made systems are numerous and encompass the domains of communications, defense, education, healthcare, manufacturing, transportation, and others. Only human-made systems are the central focus in this book.

Experience in recent decades indicates that properly coordinated and functioning human-made systems, with a minimum of undesirable side effects, require the application of an integrated, life-cycle oriented "systems" approach. The consequences of not applying systems engineering in the design and development and/or reengineering of systems have been disruptive and costly. Accordingly, the main objective of this book is to provide engineers, systems analysts, technical personnel, and managers with the essential systems concepts, methodologies, models, and tools needed to understand and apply *systems engineering* to all types of human-made systems.

The topics presented in this book have been organized into 6 parts and 19 chapters. Part I presents an introduction to systems and systems engineering in the context of system science and good engineering practice. Part II addresses the system design process as 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 some of the most useful mathematical models and tools for systems analysis. Emphasis is placed upon the application of modeling and analysis techniques as an integral part of the systems engineering process. Part IV addresses "design for operational feasibility " by discussing those characteristics of design found to be most significant for successful system operation and customer satisfaction. Separate chapters are devoted to reliability, maintainability, usability (human factors), supportability (serviceability), producibility, disposability, and affordability (life-cycle cost). Part V presents an overview of systems engineering management, with planning and organization discussed in one chapter and program management and control in another. Part VI contains a set of comprehensive appendices providing supporting topics, checklists, tables, references, and related resource materials.

This third edition is more comprehensive than earlier editions. While the overall organization of material has not changed, a morphology for design synthesis, analysis, and evaluation has been integrated with the system life-cycle concept. The entire life cycle is now covered more comprehensively with the expansion of chapters to include contemporary design tools. Part II has been strengthened in the areas of requirements analysis, the identification and prioritization of technical performance measures, and functional analysis and allocation. Part III is now oriented more toward design evaluation as an essential activity within the systems engineering process. A design evaluation display for multiple criteria is the central unifying construct. Part IV has been expanded to include new chapters dealing with design for producibility, disposability, and affordability.

This book is intended for use in the classroom at either the undergraduate or graduate level, or by the practicing professional in business, industry, or government. The text material includes over 320 illustrations and 430 problem exercises arranged in such a manner as to guide the engineer or analyst through the entire system life cycle. The concepts and techniques presented are applicable to any type of system, and the topics discussed may be "tailored" for both large- and small-scale systems. Much of the material has been developed from industrial and research experience in systems engineering over three decades.

Six other Prentice Hall books by the authors provided some of the raw material from which this text was fashioned. These books cover the subject areas of engineering organization and management, logistics engineering and management, procurement and inventory systems, applied operations research and management science, engineering economy, and life-cycle cost and economic analysis.

Benjamin S. Blanchard
Wolter J. Fabrycky

CONTENTS

PREFACE xiii

Part I: Introduction to Systems 1

1 SYSTEM DEFINITIONS AND CONCEPTS 1

1.1 System Definitions and Elements 1
1.2 Classification of Systems 4
1.3 Science and Systems Science 7
1.4 Transition to the Systems Age 10
1.5 Technology and Technical Systems 12
1.6 Engineering in the Systems Age 14
Questions and Problems 16

2 BRINGING SYSTEMS INTO BEING 17

2.1 Engineering for Product Competitiveness 17
2.2 System Life-Cycle Engineering 19
2.3 Systems Engineering Definitions 23
2.4 The Systems Engineering Process 24

2.5 System Design Evaluation 29
2.6 Implementing Systems Engineering 36
Questions and Problems 43

Part II: The System Design Process **45**

3 CONCEPTUAL SYSTEM DESIGN **45**

3.1 Identification of Need 45
3.2 Accomplishment of Feasibility Analysis 46
3.3 Advance System Planning 47
3.4 System Requirements Analysis 48
3.5 Technical Performance Measures (TPMs) 57
3.6 Functional Analysis and Allocation 61
3.7 Synthesis, Analysis, and Evaluation 67
3.8 System Specification 69
3.9 Conceptual Design Review 71
Questions and Problems 72

4 PRELIMINARY SYSTEM DESIGN **74**

4.1 Subsystem Functional Analysis 74
4.2 Requirements Allocation 80
4.3 Design Requirements (Parameters) 84
4.4 Engineering Design Technologies 86
4.5 Synthesis and Design Definition 93
4.6 System Design Reviews 94
Questions and Problems 96

5 DETAIL DESIGN AND DEVELOPMENT **97**

5.1 Detail Design Requirements 97
5.2 Integrating System Elements 99
5.3 Design Engineering Activities 104

5.4 Detail Design Aids 107
5.5 Detail Design Documentation 108
5.6 System Prototype Development 112
5.7 Detail Design Reviews 114
Questions and Problems 119

6 SYSTEM TEST AND EVALUATION 121

6.1 Requirements for Test and Evaluation 121
6.2 Categories of System/Component Testing 123
6.3 Planning for Test and Evaluation 128
6.4 Preparation for Test and Evaluation 130
6.5 Test Performance and Reporting 132
6.6 System Modification 140
Questions and Problems 140

Part III: Systems Analysis and Design Evaluation 143

7 ALTERNATIVES AND MODELS IN DECISION MAKING 143

7.1 Alternatives in Decision Making 143
7.2 Models in Decision Making 145
7.3 Decision Evaluation Theory 149
7.4 The Decision Evaluation Matrix 153
7.5 Decisions Under Assumed Certainty 155
7.6 Decisions Under Risk 157
7.7 Decisions Under Uncertainty 160
7.8 The Decision Evaluation Display 164
Questions and Problems 166

8 MODELS FOR ECONOMIC EVALUATION 169

8.1 Interest and Interest Formulas 169
8.2 Determining Economic Equivalence 175
8.3 Evaluating a Single Alternative Under Certainty 179

8.4 Evaluating Multiple Alternatives Under Certainty 186

8.5 Evaluations Involving Multiple Criteria 190

8.6 Evaluating Multiple Alternatives with Multiple Features 192

8.7 Break-Even Economic Evaluations 195

8.8 Break-Even Analysis Under Risk 200

Questions and Problems 201

9 OPTIMIZATION IN DESIGN AND OPERATIONS 206

9.1 Classical Optimization Theory 206

9.2 Unconstrained Classical Optimization 213

9.3 Constrained Classical Optimization 231

9.4 Evaluation Involving Optimization and Multiple Criteria 236

9.5 Constrained Optimization by Linear Programming 238

9.6 Constrained Optimization by Dynamic Programming 247

Questions and Problems 256

10 QUEUING THEORY AND ANALYSIS 261

10.1 The Queuing System 261

10.2 Monte Carlo Analysis of Queuing 265

10.3 Single-Channel Queuing Models 268

10.4 Multiple-Channel Queuing Models 278

10.5 Queuing with Nonexponential Service 280

10.6 Finite Population Queuing Models 283

10.7 Repairable Equipment Population Systems 291

Questions and Problems 303

11 CONTROL CONCEPTS AND TECHNIQUES 306

11.1 Some Control Concepts 306

11.2 Statistical Process Control 309

11.3 Optimum Policy Control 320

11.4 Project Control with CPM and PERT 323

11.5 Total Quality Control 334
Questions and Problems 339

Part IV: Design for Operational Feasibility 345

12 DESIGN FOR RELIABILITY 345

12.1 Definition and Explanation of Reliability 345
12.2 Measures of Reliability 347
12.3 Reliability in the System Life Cycle 362
12.4 Reliability Analysis Methods 375
12.5 Design Review and Evaluation 387
12.6 Reliability Test and Evaluation 389
Questions and Problems 396

13 DESIGN FOR MAINTAINABILITY 401

13.1 Definition and Explanation of Maintainability 401
13.2 Measures of Maintainability 402
13.3 Maintainability in the System Life Cycle 417
13.4 Maintainability Analysis Methods 424
13.5 Design Review and Evaluation 447
13.6 Maintainability Demonstration 448
Questions and Problems 454

14 DESIGN FOR USABILITY (HUMAN FACTORS) 459

14.1 Definition and Explanation of Human Factors 459
14.2 The Measures in Human Factors 474
14.3 Human Factors in the System Life Cycle 475
14.4 Human Factors Analysis Methods 478
14.5 Personnel and Training Requirements 485
14.6 Design Review and Evaluation 487
14.7 Personnel Test and Evaluation 488
Questions and Problems 488

15 DESIGN FOR SUPPORTABILITY (SERVICEABILITY) 490

15.1 Definition and Explanation of Supportability 491
15.2 The Elements of Support 492
15.3 The Measures of Supportability 495
15.4 Logistic Support in the System Life Cycle 513
15.5 Supportability Analysis (SA) 521
15.6 Continuous Acquisition and Life-Cycle Support (CALS) 528
15.7 Total Productive Maintenance (TPM) 529
15.8 Supportability Test and Evaluation 531
Questions and Problems 532

16 DESIGN FOR PRODUCIBILITY AND DISPOSABILITY 535

16.1 Introduction to Producibility and Disposability 535
16.2 Producibility and Disposability in the System Life Cycle 539
16.3 Design for Producibility 544
16.4 Modeling Manufacturing Progress 549
16.5 Design for Disposability 550
16.6 Integration of Producibility and Disposability 553
Questions and Problems 554

17 DESIGN FOR AFFORDABILITY (LIFE-CYCLE COST) 557

17.1 Introduction to Life-Cycle Costing 557
17.2 Cost Emphasis in the System Life Cycle 561
17.3 The Life-Cycle Cost Analysis Process 565
17.4 A Life-Cycle Cost Analysis Process Example 567
17.5 Life-Cycle Cost Applications and Benefits 597
Questions and Problems 602

Part V: Systems Engineering Management 609

18 SYSTEMS ENGINEERING PLANNING AND ORGANIZATION 609

18.1 Systems Engineering Planning 610
18.2 System Engineering Management Plan (SEMP) 610

18.3 Organization for Systems Engineering 626
18.4 Summary 638
Questions and Problems 638

19 PROGRAM MANAGEMENT AND CONTROL **640**

19.1 Organizational Goals and Objectives 640
19.2 Direction and Control of Program Activities 642
19.3 Program Evaluation Factors 653
19.4 Program Risk Management 657
Questions and Problems 661

Part VI: Appendices **663**

APPENDIX A: ANALYSIS AND CHECKLIST METHODS **664**

A.1 Functional Analysis 665
A.2 Design Review Checklists 674

APPENDIX B: PROBABILITY THEORY AND ANALYSIS **678**

B.1 Probability Concepts and Theory 678
B.2 Probability Distribution Models 681
B.3 Monte Carlo Analysis 690

APPENDIX C: PROBABILITY AND STATISTICAL TABLES **695**

C.1 Random Rectangular Variates 696
C.2 Cumulative Poisson Probabilities 698
C.3 Cumulative Normal Probabilities 702

APPENDIX D: INTEREST FACTORS TABLES **704**

Tables D.1 to D.8 Interest Factors for Annual Compounding 704

APPENDIX E: FINITE QUEUING TABLES **713**

Table E.1 to E.3 Finite Queuing Factors 713

APPENDIX F: SELECTED BIBLIOGRAPHY 721

F.1 Systems, Systems Theory, Systems Engineering, and Systems Analysis 722

F.2 Concurrent/Simultaneous Engineering 723

F.3 Software/Computer-Aided Systems 724

F.4 Reliability, Maintainability, and Maintenance Engineering 724

F.5 Human Factors and Safety Engineering 725

F.6 Logistics and Logistics Engineering 725

F.7 Quality, Quality Engineering, and Quality Assurance 726

F.8 Production, Producibility, and Environmental Engineering 726

F.9 Operations Research, and Operations Analysis 727

F.10 Engineering Economy, Economic Analysis, and Cost Estimating 727

F.11 Management and Supporting Areas 727

INDEX 729

PART I

INTRODUCTION TO SYSTEMS

1 System Definitions and Concepts

Systems are as pervasive as the universe in which we live. 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 appearance of human beings, a variety of human-made systems have come into existence. Only recently have we come 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 that provide a basis for the study of systems engineering and analysis. This includes definitions of system characteristics, a classification of systems into various types, a discussion of the current state of system science, and a discussion of the transition to the systems age now under way. Finally, this chapter presents technology and the nature of engineering in the systems age.

1.1 SYSTEM DEFINITIONS AND ELEMENTS

A *system* is an assemblage or combination of elements or parts forming a complex or unitary whole, such as a river system or a transportation system; any assemblage or set of correlated members, such as a system of currency; an ordered and comprehensive assemblage of facts, principles, or doctrines in a particular field of knowledge or thought, such as a system of philosophy; a coordinated body of methods or a complex scheme or plan of procedure, such as a system of organization and management; any regular or special method of plan of procedure, such as a system of marking, numbering, or measuring.[1] Not every set of items, facts, methods, or procedures is a system. A

[1] This definition was adapted from *The Random House Dictionary of the English Language*. 2nd ed. (New York: Random House, Inc., 1994).

random group of items in a room would constitute a set with definite relationships between the items, but it would not qualify as a system because of the absence of unity. functional relationship, and useful purpose.

The Elements of a System

Systems are composed of components, attributes, and relationships. These are described as follows:

1. *Components* are the operating parts of a system consisting of input, process, and output. Each system component may assume a variety of values to describe a system state as set by some control action and one or more restrictions.
2. *Attributes* are the properties or discernible manifestations of the components of a system. These attributes characterize the system.
3. *Relationships* are the links between components and attributes.

A system is a set of interrelated components working together toward some common objective or purpose. The set of components has the following properties:

1. The properties and behavior of each component of the set has an effect on the properties and behavior of the set as a whole.
2. The properties and behavior of each component of the set depends on the properties and behavior of at least one other component in the set.
3. Each possible subset of components has the two properties listed previously; the components cannot be divided into independent subsets.

The properties listed earlier ensure that the set of components constituting a system always has some characteristic or behavior pattern that cannot be exhibited by any of its subsets. A system is more than the sum of its component parts. However, the components of a system may themselves be systems, and every system may be part of a larger system in a hierarchy.

The objective or purpose of a system must be explicitly defined and understood so that system components may be selected to provide the desired output for each given set of inputs. Once defined, the objective or purpose makes it possible to establish a measure of effectiveness indicating how well the system performs. Establishing the purpose of a human-made system and defining its measure of effectiveness is often a challenging task.

The purposeful action performed by a system is its *function*. A common system function is that of altering material, energy, or information. This alteration embraces input, process, and output. Some examples are the materials processing in a manufacturing system or a digestive system, the conversion of coal to electricity in a power plant system, and the information processing in a computer system.

Systems that alter material, energy, or information are composed of structural components, operating components, and flow components. *Structural components* are